

Functionality as a Key Concept for Integrated Project Planning and Scheduling Methods

4 Moslem Sheikhhoshkar¹, S.M.ASCE, Hind Bril El-Haouzi², Alexis Aubry³, Farook Hamzeh, A.M.ASCE⁴

6 ¹Research Assistant, Université de Lorraine, CNRS, CRAN, Epinal, France, ORCID: <https://orcid.org/0000->
7 0001-9067-2705. Email: Moslem.sheikhkhoshkar@univ-lorraine.fr

8 ²Professor, Université de Lorraine, CNRS, CRAN, Epinal, France, ORCID: <https://orcid.org/0000-0003-4746->
9 5342. Email: hind.el-haouzi@univ-lorraine.fr

³Associate Professor, Université de Lorraine, CNRS, CRAN, Nancy, France, ORCID: <https://orcid.org/0000-0002-7335-821X>. Email: alexis.aubry@univ-lorraine.fr

2 ⁴Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Alberta, 7-287 Donadeo
3 Innovation Centre for Engineering, 9211 116th St., Edmonton, AB, Canada T6G 1H9. ORCID:
4 <https://orcid.org/0000-0002-3986-9534>. Email: hamzeh@ualberta.ca

6 Abstract

The construction industry has made significant efforts to address the issues of low productivity caused by inefficient construction planning and scheduling. This issue led to more focus on integrating scheduling methods in the existing studies without comprehensively analyzing the integration's goals and objectives. In this regard, this study aims to present and analyze a holistic list of integrated scheduling methods' functionalities in the construction sector. In this paper, the underlying concept and main objective of scheduling methods are considered as their functionality. A multi-step methodology is adopted for this research. First, the authors identified integrated scheduling methods and their functionalities. Second, social network analysis (SNA) and Pareto analysis are used to assess and analyze the significance of the identified functionalities. The findings indicated that improving planning reliability, increasing transparency, identifying and eliminating wastes, and considering the continuous flow of work that follows the lean principles are the most important employed functionalities in the integrated scheduling methods. Also, the last planner system, building information modeling, simulation methods and location-based management system are mainly used common scheduling methods

in the integrated scheduling methods. Eventually, this study will aid project stakeholders in better understanding of integrated scheduling methods by defining the functionality concept of scheduling methods.

Keywords: Functionality Concept, Integrated Scheduling Methods, Common Scheduling Methods, Social Network Analysis (SNA), Pareto Chart Analysis

Introduction

McKinsey group estimated that 98% of construction projects experience more than 30% cost overruns, and 77% are at least 40% late (Ashcraft 2022). Lack of effective planning and scheduling (Salama et al. 2021), inefficient constraint management (Wu et al. 2021), the multi-organizational structure of the construction sector (Mota et al. 2010), the shortage of collaboration between stakeholders (Mota et al. 2010; Viklund Tallgren et al. 2020) and the presence of many uncertainties in the projects (Tokdemir et al. 2019) are some of the significant factors contributing to this rise in project cost and time. Over the previous decades, a vast range of planning and scheduling methodologies, methods, and tools have been developed and used to deal with these challenges (Pellerin and Perrier 2019). Examples of practical methods include the Critical Path Method (CPM) (Antill and Woodhead 1991), Critical Chain Project Management (CCPM) (Raz et al. 2003), Line of Balance (LOB) (Arditi and Albulak 1986), Linear Scheduling Model (LSM) (Yamin and Harmelink 2001), Location-based Management System (LBMS) (Seppänen et al. 2014), Last Planner System (LPS) (Ballard and Tommelein 2016), Takt Time Planning (TTP) (Frandsen et al. 2013), 4DBIM (Martins et al. 2020), Simulation-based Methods (SM) (Zhang et al. 2002), and Tri-Constraint Method (TCM) (Morkos 2014). In this paper, these methods are defined as common scheduling methods. Another approach is mathematical and algorithmic

methods (Ansari et al. 2022; Milat et al. 2021) which were used to model the scheduling problems. In these methods, the defined scheduling problems were solved by one or more objective functions with several constraints. They also applied different meta-heuristic algorithms, including Genetic Algorithms (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO), and others, to optimize different types of project scheduling problems. This approach is more research-oriented, and their application in a complex construction environment is still challenging.

Although the mentioned methods separately have pros, their cons lead to ineffective planning and scheduling (Olivieri et al. 2016). To address this issue, some researchers have tried to combine classical planning and scheduling methods and lean tools and principles with a wide range of objectives to cover the disadvantages of the existing methods. In this line, several studies integrated the Last Planner System (LPS) with Building Information Modelling (BIM) to meet lean principles such as workflow stability, facilitating negotiation and team commitment, pull planning, flow visualization, addressing spatiotemporal conflicts, reducing the time waste of urban highway projects, enhancing process management and flow of work on the construction site, promoting continuous improvement, and enhancing project stakeholder understanding (Bhatla and Leite 2012; Igwe et al. 2019; Sacks et al. 2010; Schimanski et al. 2021). Moreover, some researchers focused on integrating LBMS, LPS, and CPM to address some gaps in conventional scheduling methods, improve planning and control processes, and fulfil lean objectives of reducing waste, increasing productivity, minimizing variability, supporting managers in analyzing delays, and determining the most influential critical path strategy (Olivieri et al. 2016; Seppänen et al. 2010). In modular construction, Salama et al. (2021) developed a new

approach for monitoring and controlling of integrated offsite and on-site activities. The proposed technique combines the last planner system (LPS), critical chain project management (CCPM), and linear scheduling method (LSM) in a structured manner that addresses student syndrome in CCPM, public commitments, non-completion reasons, and monitoring of task completion. Furthermore, to increase productivity, the suggested integrated scheduling method followed the principle of takt time (TT) and Just in Time (JIT). Integration of Building Information Modeling (BIM) and LPS have received the most attention in the literature (Al Hussein 2016; Barkokebas et al. 2021; Burguete 2018; Heigermoser et al. 2019; McHugh et al. 2019; Sacks et al. 2010; Toledo et al. 2016). Moreover, BIM-LPS-Kanban (Sacks et al. 2010; Schimanski et al. 2021), 4D-LPS (Igwe 2021; Lin and Golparvar-Fard 2021), LPS-LBMS (Seppänen et al. 2010), LBMS-LPS-CPM (Olivieri et al. 2016; POLIANI 2020) and BIM-TTP-SM (Abbasi et al. 2020) can be mentioned among the many combined scheduling methods that have been performed in previous studies. In this study, these mixed methods are considered as integrated scheduling methods. Over time, the number of integrated scheduling methods contributing to project performance and success has expanded. Although several integrated scheduling methods have widened the window of opportunity, particularly for contractors, they have also caused confusion on which approach should be chosen and which is best suited for the project. AlNasseri and Aulin (2015) highlighted that despite the availability of advanced planning and scheduling tools and methods, stakeholders prefer to choose traditional methods. Insufficient familiarity and information about the applicability and efficiency of planning and scheduling methods are mentioned as the primary cause of this issue. In order to minimize imbalances between stakeholder requirements and project plans, several studies have suggested that project participants should be aware of key

characteristics and objectives of project scheduling methods (AlNasseri and Aulin 2015; AlNasseri 2015; Walker and Shen 2002). In line with this, this study defines and addresses the concept of functionality to describe the goals and objectives of integrated scheduling methods. In the Longman dictionary, functionality refers to "one or all of the operations that a computer, software program or piece of equipment is able to perform" (Richards and Schmidt 2013). According to this concept, schedule plan functionality is regarded as the operations and the primary objective of each single or integrated scheduling methods. The functionality concept can ease sense-making and the situation awareness of project stakeholders regarding the planning and scheduling requirements.

This research aims to develop a comprehensive list of the functionalities of integrated scheduling methods in the construction industry and guide future research efforts. Eventually, the findings of this paper aim to contribute to a better understanding of integrated scheduling methods' functionalities in the construction industry. Furthermore, they provide new insights for project managers and practitioners regarding the new management strategies, methods, and tools required to enhance the effective use of planning and scheduling concepts in current construction project practices. The following sections present the research methodology, analyses and results, validation, research discussion, and finally, conclusions, limitations and suggestions for future research and development in this domain.

Research Methodology

To achieve this study's objectives, the authors proceeded with a process composed of several interdependent steps, as shown in Fig. 1.

Fig. 1. Summary of the adopted research methodology

The authors (1) performed a systematic review, and content analysis of the literature on integrated planning and scheduling methods in the construction industry, (2) identified the aims and objectives of integrating scheduling methods and defined them as integrated scheduling methods' functionalities, (3) used social network analysis (SNA) to quantify the importance of each of the identified functionalities and validated the results using a simple analytic technique, (4) implemented Pareto chart analysis to determine the main functions of the integrated scheduling methods, (5) identified the literature gaps and determined the future directions. In the following subsections, the components of the research methodology are described in depth.

Conducting a Systematic Literature Review

The authors conducted a systematic literature review and analysis addressing the integrated scheduling methods' functionalities in the construction industry. This study is systematic in the sense that it adheres to a rigorous protocol that permits replication of the selected approach in accordance with the guidelines for conducting systematic reviews (Kitchenham 2004; Thomé et al. 2016). This review is composed of three parts: (1) data acquisition; (2) screening based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline (Ullah 2021); and (3) content analysis which is mainly characterized by a quantitative literature analysis using SNA. The review procedure is illustrated in Fig. 2 and detailed in the following subsections.

Fig. 2. Adopted systematic review procedure

Data Acquisition

For the review phase of this research, peer-reviewed and reputable scholarly construction and manufacturing journal papers as well as conference proceedings were considered reliable sources.

The list of journals and conferences taken into account for this paper is shown in Table 1. The

Web of Science (WoS) database was selected as the search engine, and the search string was

determined using the combination of scheduling methods with "AND" & "OR", as shown in Table

2. To ensure that the essential papers were covered, backward and forward citation searching

were applied. Backward reference searching is finding and analyzing the sources or publications

referenced in an article. In contrast, forward searching focuses on the articles published after the

publication of an article (Gusenbauer and Haddaway 2020). As a result of these citation

searching, one paper matching the inclusion criteria was added to the list. The search was

conducted within the title, abstract and keywords. In addition, no limitations were imposed while

selecting the search's date range, and any entries accessible until November 2022 were reviewed.

The search was conducted by the first author of this research. The first data acquisition stage

resulted in a total of 1499 publications.

Table 1. List of journals and conferences

Table 2. Search query

Screening based on PRISMA guideline

The PRISMA protocol was followed during the screening stage due to broader acceptance. The

authors initially considered several inclusion and exclusion criteria to decrease the sample size

and concentrate the review on the integrated scheduling methods. The criteria for this aim are provided in Table 3. Using these criteria, the sample size was decreased to 57 publications.

Table 3. Inclusion and exclusion criteria for screening

Content Analysis

After the screening phase, 57 retrieved publications were subjected to content analysis to determine the goals, objectives, and outcomes of integrated scheduling methods. In this regard, First, 26 integrated scheduling methods were found relevant and valuable for this paper's purpose. Second, the retrieved articles based on 26 identified integrated scheduling methods were analyzed using Nvivo Qualitative Data Analysis software since this method of analysis is one of the most utilized methodologies in qualitative research (Hajirasouli and Banihashemi 2020). In addition, this kind of data analysis enhances the accuracy and reliability of qualitative research by using both deductive and inductive strategies to find codes and themes within the data (Hajirasouli et al. 2022). Three types of codes were established to extract the functionality of integrated scheduling methods: 1) aims and objectives, 2) research questions, and 3) the benefits of each integrated scheduling method. In the first step, 82 objectives for integrating common scheduling methods were found by analyzing and coding the content of 57 finalized papers. The authors of this paper reviewed identified objectives. Similar objectives were merged, such as eliminating non-value-added activities and identifying and eliminating waste. Consequently, 44 adjectives are collected and considered as integrated scheduling methods' functionalities for further analysis. The following subsections describe the procedure for analyzing the integrated scheduling methods and their functionalities in detail.

Literature Quantitative Analysis

After collecting the publications and conducting a content analysis, the authors identified the functionality of integrated scheduling methods in the construction industry. For the purpose of analyzing the highlighted functionalities, the authors created reference matrix **M**. In this matrix, the rows indicate the recognized functionalities, while the columns represent the integrated scheduling methods. If functionality is included in an integrated method, a value of 1 is entered into the corresponding cell; otherwise, a value of 0 is inserted. Fig. 3 is an example to illustrate the notion of a reference matrix. In this article, F_i is an identified functionality, and T_j is the integrated scheduling method. As seen in Fig. 3, functionality F_k is described in integrated scheduling methods T_j and T_j ; thus, a value of 1 is recorded in the relevant cells, but a value of 0 is recorded for cells below the other integrated scheduling methods. For the generated reference matrix **M**, the authors performed quantitative analysis using the SNA method and validated the findings with the simplified analysis technique. The following subsections give further information on these two methods for analysis.

Fig. 3. An example of a reference matrix

Social Network Analysis

Application of SNA in Quantitative Literature Analysis in Construction Management

Recently, the network analysis method has obtained considerable interest and built outstanding expertise in the knowledge extraction of the construction management fields of study (Assaad and El-Adaway 2020). SNA enables academics to undertake systematic literature-related findings by connecting ideas overlooked in manual review analyses (Hosseini et al. 2018). A current

example of SNA applications in the quantitative literature analysis in the construction management field is the research of (Elsayegh and El-adaway 2021), who studied the factors affecting collaborative planning in the construction industry. Another example is the study of Abdul Nabi and El-adaway (2020), who analyzed a detailed set of decision-making factors and determined future research requirements for modular construction. In addition, Abdul Nabi and El-adaway (2022) utilized SNA for quantitative analysis of the most frequent sources of disputes and their interactions in modular construction projects (Abdul Nabi and El-adaway 2022). Other instances comprise research conducted on construction business failure factors (Assaad and El-Adaway 2020), critical review of off-site construction studies (Hosseini et al. 2018), application of cognitive science focusing on electroencephalography in construction (Saedi et al. 2022), and a study of the literature on the use of dynamic modeling in construction management systems to achieve a holistic view of the direct and indirect effects of various project parameters (Abotaleb and El-adaway 2018).

Justifications for SNA Selection

Meanwhile, several methods have been suggested for extracting relevant characteristics, factors, features, attributes and functionalities from accessible previous research findings. Existing methods for identifying factors in the literature rely on qualitative assessments, while SNA emphasizes a quantitative approach. To do this, SNA was used because of its (1) quantitative strength, (2) capability to examine the interrelationships among the various factors (Elsayegh and El-adaway 2021), (3) value in comparing the relative importance of the factors, and (4) value in identifying understudied domains that could benefit from further research (Assaad and El-Adaway 2020). The primary objective of this study is to determine the essential functionalities

utilized in integrated scheduling methods by analyzing their interdependence. The authors ultimately selected SNA as the best approach to find the most prevalent functionalities leading to integrated scheduling methods in construction projects.

Developing the Social Network

SNA was utilized to discover knowledge gaps and determine factors' importance in many applications and domains (Abdul Nabi and El-adaway 2020). In this study, the same methodology is applied to understand the functionality of integrated scheduling methods. To do this, The authors sought a metric that can quantify the importance of integrated scheduling methods' functionalities based on their frequency of integration and co-occurrences with other functionalities. Consequently, the Degree Centrality (DC) was used since it reflects the number of instances in which it happened in combination with other functionality in the same integrated scheduling method (Freeman 1980). Computing the DC of SNA nodes implies creating a weighted adjacency matrix (WAM) for the network under study.

Therefore, the authors developed a WAM for network **M**, constructed during the functionalities' analysis (**M**_{44×26}). Multiplying the reference matrix **M** by its transpose and then eliminating and replacing the values in the diagonal cells of the resultant matrix with zeros generates a WAM. The WAM is a matrix representation of a network in which (1) the matrix columns and rows represent n nodes representing the functionality of integrated scheduling methods and (2) the matrix records represent a set of edge weights which correspond to the strength of the connection between each pair of functionalities. This matrix is calculated using Equation (1).

$$WAM_{f \times f} = \begin{cases} M_{f \times t} \times M_{f \times t}^T & \text{for } k \neq j \\ 0 & \text{for } k = j \end{cases} \quad (1)$$

where $WAM_{f \times f}$ = weighted adjacency matrix; $M_{f \times t}$ = reference matrix; $M_{f \times t}^T$ = transpose of the reference matrix; f = number of identified functionalities(i.e., 44); and t = number of integrated scheduling methods (i.e., 26). Fig. 4 and Fig. 5 show an example of creating and visualizing a WAM for a reference matrix with four integrated methods and four functionalities. Fig. 4 illustrates how the adjacency matrix is developed, while Fig. 5 presents a visual representation of the references and adjacency matrix. As can be seen in the reference matrix, for instance, the functionality F1 and F4 are addressed in integrated method 1. Therefore, these functionalities are linked by an edge when a diagram of this integrated method is created. An adjacency matrix is used to depict a single network for the reference matrix rather than a network for each functionality in the reference matrix. The adjacency matrix shows the interconnections between the functionalities. It demonstrates that F1 is referenced simultaneously with F4 twice and F2 simultaneously with F3 once. The adjacency matrix's calculated values, also referred to as the link strength, indicate how directly connected the functionalities are to one another.

Fig. 4. An illustration of an adjacency matrix

Fig. 5. Visual representation of reference and adjacency matrix

After developing the WAM, The DC for each functionality of integrated scheduling methods is calculated based on Equation 2.

$$DC_k = \sum_{j; j \neq k} M_{k,j} \quad (2)$$

Where DC_k indicates the degree centrality for functionality k and $M_{k,j}$ is the cell's value in row k and column j of the investigated adjacency matrix. Moreover, as the calculated DC depends on the relevant network's size, the authors decided to normalize it. As shown in Equation3., the

266 normalized DC of a functionality k in a network is simply the DC of the evaluated functionality
 267 divided by the highest DC in the studied network.

$$268 \quad \overline{DC_k} = \frac{DC_k}{\max\{DC_k\}} \quad (3)$$

269 Thus, the normalized DC_k range from 0 to 1 for all functionalities.

270 ***Validation Method: Simplified Analysis***

271 The simplified analysis was considered in the research of Elsayegh and El-adaway (2021) for
 272 validation of SNA results. In this research, the same approach was carried out to verify the SNA
 273 and assess whether or not it is working as expected. In this method, a score for each identified
 274 functionality is calculated by summing up all the cells in the row that belong to that functionality
 275 using Equation 4. For instance, a score of 11 for a functionality F15 in matrix **M** indicates that this
 276 functionality is addressed in 15 integrated scheduling methods.

$$277 \quad Score_k = \sum_{z=1}^{26} M_{k,z} \quad (4)$$

278 where $Score_k$ is the frequency of referencing functionality k , $M_{k,z}$ is the cell's value in the
 279 reference matrix (either 0 or 1) that corresponds to functionality k and the integrated scheduling
 280 method z . Similar to SNA normalization according to Equation 5, functionalities are assigned a
 281 normalized score in the simplified analysis method. Therefore, the normalized score varies from
 282 0 to 1 for each functionality in the reference matrix.

$$283 \quad \overline{Score_k} = \frac{Score_k}{\max\{Score_k\}} \quad (5)$$

284

285

Pareto Chart Analysis

After analyzing the functionality of integrated scheduling methods in the construction project using the SNA approach, a statistical analysis using Pareto diagrams was conducted to determine the most important functionalities of integrating scheduling methods. The Pareto chart is a commonly adopted approach primarily used to identify the most significant issues and assist management and decision-makers in decision-making (Moktadir et al. 2021). A Pareto chart comprises both a bar graph and a line graph. The bar in this study displayed analyzed functionalities using SNA, and the line reflects the cumulative percentage of the occurrence of the functionalities. When there are a significant number of functions to be evaluated, such as in this research, the benefit of employing Pareto chart analysis is that it helps emphasize the most significant ones. Second, the diagrammatic depiction is straightforward to comprehend and allows researchers to concentrate on the few most critical functionalities by directly displaying their degree of influence (Viles et al. 2019). Thus, Pareto chart analysis was implemented to understand the essential functionalities of integrated scheduling methods.

Results and Analysis

Data Collection Efforts

As described in the methodology, the authors used a systematic approach based on search queries to extract journal and conference publications relating to integrated scheduling methods in the construction industry. This meta-analysis search and screening efforts retrieved 57 journal and conference articles are shown in Table 4 and were approved for further analysis. Table 4 reveals the published papers in three decades and shows that most publications were carried out

after 2013. This highlights that current research efforts in this domain have focused on integrating scheduling methods. The shortcomings of scheduling methods, such as ignoring uncertainties in some methods (Al Nasser et al. 2016), inadequate management of daily activities (Olivieri et al. 2016), lack of integration between different levels of the schedule plan (Dave et al. 2016), lack of supply chain integration (Aslam et al. 2020), lack of consideration to all flows (Aslam et al. 2020), high effort and investment requirements to produce a sufficiently detailed 4D model (Ortenburger and Hartmann 2021) and the popularity of off-site construction (Salama et al. 2021) have increased interests on integrated scheduling methods (POLIANI 2020).

Table 4. Full-text reviewed articles

Fig. 6 more clearly depicts the distribution of the papers across the years of the research period. The number of papers addressing integrated scheduling methods in the construction industry has been on a trend since 2014 and reached its peak in 2021.

Fig. 6. Distribution of the papers across the years

Integrated Scheduling Methods and their Functionalities in the Construction Industry

By analyzing the content of the publications in Table 4, the authors identified 26 integrated scheduling methods and 44 scheduling methods' functionalities listed in Table 5 and Table 6. The 26 identified integrated scheduling methods were developed by combining 14 common scheduling methods and lean principles illustrated in a Sankey diagram in Fig. 7. Also, Fig. 8 clearly indicates the distribution of utilized common scheduling methods in integrated scheduling methods. As it can be seen, the Last Planner System (LPS), Building Information Modeling (BIM), Simulation Modeling (SM) and Location-based Management System (LBMS) have been

considered the most with 24%, 16%, 13% and 9%, respectively. Furthermore, BIM-LPS was the most used integrated scheduling method in the literature. Notably, although 4D is one of the BIM applications, some researchers have just utilized it as a visual representation tool. Thus, the authors distinguish between 4D, and BIM approaches in project scheduling.

Moreover, Fig. 9, matrix **M**, represents the mapping between the identified project scheduling methods' functionalities and the analyzed integrated scheduling methods based on the literature. A red-colored cell indicates that the respective integrated scheduling methods have addressed the functionalities. As can be seen, the integrated scheduling methods, including BIM-LPS, BIM-LPS-Kanban, LBMS-LPS-CPM and BIM-LPS-SM, have the most combination of functionalities in their structure. Furthermore, F1(improving the reliability of the planning), F39(increasing transparency), F15(improving managerial practices), and F19 (managing uncertainties) are the most utilized functionalities in the integrated scheduling methods.

Table 5. Identified integrated scheduling methods

Table 6. Scheduling methods' functionalities

Fig. 7. Sankey diagram of integrated scheduling methods

Fig. 8. Distribution of utilized common scheduling methods in integrated scheduling methods

Fig. 9. Mapping between the identified functionalities and analyzed integrated scheduling methods

As mentioned earlier, several papers integrated common scheduling methods to address the challenges of low construction productivity resulting from inefficient planning and scheduling. Some investigations were conducted at the level of the conceptual framework, and implementing a case study for validation. In addition to the conceptual model and case study, some have

developed tools, software, or decision support systems (DSS) for practical deployment in the construction industry. Analyzing the various abstraction levels of common scheduling methods utilized in integrated ones from a conceptual framework to implementation can be advantageous in two dimensions. On the one hand, having information about methods with conceptual models and promoting them into practical tools and software may substantially aid researchers in selecting future research directions. On the other hand, it can help the industry to adopt more practical methods for project scheduling and planning. To do this, the final articles considered for content analysis were classified as follows:

Class 1 (C1): These articles give either a conceptual framework, a case study implementation, or a mix of both. The study conducted by Abdelmegid et al. (2021) is regarded as class 1 since it addressed the connections between simulation modelling and construction production planning and control by developing a conceptual framework and putting it to the validation in a case study.

Class 2 (C2): These papers concentrate on developing a model/tools/ Decision Support System(DSS) or integrating existing tools and software solutions combined with a conceptual framework or case study implementation. The research project by Heigermoser et al. (2019) is categorized as class 2 since it developed a BIM-based Last Planner System tool for construction management throughout the construction phase.

After classifying the papers into two classes, 26 integrated scheduling methods were studied within each class, and the number of papers associated with each integrated method was determined. The number of articles that addressed each common scheduling method in integrated methods was used to calculate the normalized score for each common scheduling

method within each class. Fig. 10 displays the findings of the analysis's common scheduling methods used in each class based on differences between class 2 and class 1 (C2-C1). For each method, a positive value in Fig. 10 shows that it is used more often in class 2 research, which is primarily concerned with creating a model, tool, or decision-support tool for integrating the common scheduling methods.

In contrast, a negative score indicates that the scheduling method is used more in class 1 with an emphasis on conceptual model development. As can be seen, BIM and Simulation Methods (SM) are considered more in conceptual framework-based studies. The applications of Takt time planning (TTP), Last Planner System (LPS), and Location-based Management System (LBMS) in integrated scheduling methods are almost identical for both classes. Moreover, Critical Chain Project Management (CCPM) and Linear Scheduling Methods (LSM) are used more in studies focusing on developing tools/models and decision-support systems or integrating existing tools and software solutions. This finding may be due to the fact that, even though BIM and SM have received a great deal of attention in recent years in scientific studies, the maturity and readiness of construction companies to use these technologies, particularly during the construction phase, is still low. Therefore, researchers who have concentrated more on the practical aspects of scheduling methods have paid less attention to BIM and SM and given more emphasis to conventional methods such as CCPM, LSM, and CPM.

Fig. 10. Derived differences in the scores of C1 and C2 studies for common scheduling methods

Quantitative Analysis of the Integrated Scheduling Methods' Functionalities

After reviewing the publications listed in Table 3 and finding the integrated scheduling methods' functionalities, the authors developed a reference matrix **M** based on the identified functionalities and integrated scheduling methods based on the described detail in the methodology. The reference matrix **M** has a dimension of 44 by 26 and comprises 26 integrated scheduling methods and 44 functionalities. The following subsections provide a detailed explanation of the findings.

Social Network Analysis

After evaluating the acquired data and developing the reference matrix **M_{44×26}**, the authors produced the weighted adjacency matrix **WAM_{44×44}** to calculate the DCs of the indicated functionalities. The DCs measure, as was previously mentioned, highlights the value of a given functionality by emphasizing its frequency and mention alongside other functionality in integrated scheduling methods. The functionalities network shown in Fig. 11 consists of 44 nodes (representing 44 integrated scheduling methods' functionalities) and 1248 corresponding edges. The network's nodes represent the functionality, while the edges reflect the interconnection or co-occurrence between each pair of functionalities. The node's radial location is inversely proportional to the normalized DC of the respective functionality. In other words, when the node moves closer to the center, the normalized DC of this functionality increases compared to other nodes that are farther from the center. The color difference of the nodes is proportional to the calculated normalized DC of each functionality in terms of radial position. Another way of putting it, red, orange, and yellow nodes are linked with greater DC values than nodes of other colors.

413 Clearly, the network has a significant number of nodes and connections. As a result, a color-coded
414 matrix was provided in Fig. 12 to illustrate the degree of connectivity between nodes. Both rows
415 and columns of the matrix represent the functionality of integrated planning methods.

416 The matrix is color-coded according to the intensity of the link between any two functionalities.
417 As shown in Fig.12, the white-colored cells for a pair of functionalities imply that they have never
418 co-occurred in any of the studied integrated scheduling methods. On the other hand, some pairs
419 of functionalities contain dark purple cells, suggesting high weights and, thereby, a high
420 frequency of co-occurrence in the integrated scheduling methods. An example of the former
421 would be F3 (considering the continuous flow of work) and F44 (applying creativity techniques
422 to planning and scheduling). The latter is represented in the weights of edges between F1
423 (improving the reliability of the planning) and F39 (increasing transparency).

424 The functionalities can be discussed from two points of view: (1) the functionalities that have
425 been applied the most in the integrated scheduling methods and (2) the functionalities that have
426 received the least attention in the integrated scheduling methods.

427 Concerning the first perspective, Fig. 11 shows that F1 (improving the reliability of the planning),
428 F39 (increasing transparency), F11 (identifying and eliminating wastes), and F3 (considering the
429 continuous flow of work) are the most often used functionalities of integrated scheduling
430 methods in combination with other functionalities in construction projects. As also seen in Fig. 9,
431 F15 (improving managerial practices) and F19 (managing uncertainties) have been among the top
432 four used functionalities in integrated scheduling methods. Nevertheless, according to SNA
433 analysis, F11 (identifying and eliminating wastes) and F3 (considering the continuous flow of

work) have gotten the most DC, showing greater interconnectivity with other functionalities. Here, the significance of SNA analysis in this study is fully acknowledged. Considering the multifunctional nature of integrated scheduling methods, it can be claimed that functionalities that interact more with other functionalities are more valuable in these methods. Since, as previously indicated, the primary objective of integrated scheduling methods is to combine the functionalities of conventional scheduling methods to compensate for their deficiencies, assessing the combination of functionalities employed in integrated scheduling methods conducted in this research is necessary. Regarding the combination analysis of functionalities, according to Fig. 12, the combination of F1 (improving the reliability of the planning) and F39 (increasing transparency), F3 (considering the continuous flow of work) and F4 (decreasing workflow variability), F15 (improving managerial practices) and F4 (decreasing workflow variability), F14 (detecting and solving spatiotemporal conflicts) and F40 (enabling the coordination of the look-ahead plans), and F27 (applying analytical method) and F15 (improving managerial practices) have been utilized the most in integrated scheduling methods.

Following the second perspective, Fig. 11 illustrates that F30 (eliminating the root causes of variability), F38 (increasing safety on construction sites), F24 (scheduling of modular and offsite construction), and F31 (integrating offsite and onsite planning for modular and offsite construction) have earned the least consideration in the integrated scheduling methods.

Fig. 11. Functionalities network

Fig. 12. Color-coded matrix of functionalities

Pareto Analysis of Main Functionalities

For the Pareto analysis, the score for each functionality was calculated using SNA, and after that, the cumulative percentage was derived. 43% of the forty-four functionalities are employed in 80% of integrated scheduling methods, as illustrated by the Pareto chart in Fig. 13. As shown in Figure 9, integrated scheduling methods and even conventional scheduling methods (CPM, LPS, LBMS, and so on) are multi-functional. In addition, the construction industry's multi-organizational nature and its complexities and uncertainties have led to using a combination of functionalities in project scheduling. This argument may explain why the proportion of crucial functionalities exceeds the Pareto principle (80/20).

F1(improving the reliability of the planning), F39 (increasing transparency), F11 (identifying and eliminating wastes), F3 (considering the continuous flow of work), F14 (detecting and solving spatiotemporal conflicts), F15 (improving managerial practices), F4 (decreasing workflow variability), F40 (enabling the coordination of the look-ahead plans), F28 (supporting human decision making), F10 (increasing teamwork, and communication between all stakeholders), F5 (Analyzing constraints more effectively), F7(visualizing of the schedules to understand and communicate content to a variety of stakeholders), F16(considering the supply chain instability), F18(understanding of the subprocesses more accurately), and F33 (linking the supply chain and construction process) are considered in 60% of integrated scheduling methods.

Fig. 13. Pareto Analysis of Functionalities

Validation

This study used a simplified analysis to verify the SNA values. After analyzing the normalized DC values for the functionalities outlined in the methodology, the authors calculated the normalized scores using simplified analysis to compare the findings of these two approaches. The differences in normalized scores between the SNA and the simplified analysis are shown in Fig. 14. The results indicate that the simplified analysis outputs are comparable to those of the SNA. The slight deviations between the outcomes of the two kinds of analysis may be explained by the fact that the SNA employs more sophisticated criteria to examine the interrelationships and interdependencies between the various functionalities (Elsayegh and El-adaway 2021). On the contrary, the simplified analysis is calculated mainly on the simple frequency of the co-occurrence of functionalities in the analyzed integrated scheduling methods. In Table 7, Spearman correlation, variance, and standard deviation have been applied to examine the relationship between these two approaches' outcomes and validate the SNA values. Given the fundamental features of the two investigations and the statistical test results, the differences are thus deemed acceptable. Accordingly, the findings shown in Table 7 demonstrate that the SNA is acting as anticipated. For a thorough validation of the results, however, the authors suggest that future research investigates the interactions between the 44 functionalities using real case studies or experts' points of view.

Table 7. Statistical test results on the simplified analysis and SNA

Fig. 14. Comparison results between simplified analysis and SNA

498 **Discussions of the Research Findings**

499 Using the insights from the literature analysis of this study, this section describes in-depth
500 discussions of the main findings of this article in light of the recognized integrated scheduling
501 methods' functionalities. This is conducted by highlighting areas where the extensive focus has
502 previously been received, as well as those that have paid the least attention to lead the future
503 directions.

504 This study identified and analyzed the integrated scheduling methods' functionalities to the
505 project team can choose the project scheduling method according to the needs and
506 characteristics of the project with a better understanding. Functionalities were considered due
507 to the insufficient understanding and awareness of project scheduling theories and methods on
508 behalf of project stakeholders and participants (AlNasseri and Aulin 2015). This implies that these
509 methods address a broader range of project planning, scheduling, and control issues. Between
510 identified integrated scheduling methods, BIM-LPS, BIM-LPS-Kanban, LBMS-LPS-CPM and BIM-
511 LPS-SM have utilized the most combination of functionalities. The combination of common
512 scheduling methods with BIM demonstrates the attention of researchers and the industry to the
513 use of semantic information of BIM models as well as its visualization capability in the form of 4D
514 modeling to improve communication between stakeholders in the project. Furthermore, the last
515 planner system is employed more often, according to the distribution of common scheduling
516 methods in integrated scheduling methods.

517 Although simulation methods are not practical project scheduling methods, different types of it
518 (such as System Dynamic (SD), Discrete Event Simulation (DES), Agent-based Modeling (ABM)

and Monte Carlo) have contributed several functions to common scheduling methods, including uncertainty modeling (Alhussein et al. 2022; Himmiche et al. 2018; Tokdemir et al. 2019), applying creativity techniques to planning and scheduling (Abdelmegid et al. 2019; Abdelmegid et al. 2021), understanding the behaviour of the performance indicators (Shehab et al. 2020) and scenario analysis (König 2011).

The results of the network analysis indicated that F1 (improving the reliability of the planning), F39 (increasing transparency), F11 (identifying and eliminating wastes), and F3 (considering the continuous flow of work) are the most often used functionalities of integrated scheduling methods in combination with other functionalities in construction projects. These findings significantly emphasize lean construction principles, such as planning reliability, transparency, waste elimination, and continuous workflow in integrated scheduling methods. In other words, these methods have integrated lean thinking into the planning and control process. Therefore, lean planners must address the planning and control process before the project execution process. In addition, these functionalities are remarkable for enhancing medium-term and short-term planning (Emdanat and Azambuja 2016; Soman and Molina-Solana 2022; Tezel et al. 2020), indicating that integrated scheduling methods pay greater attention to these two planning levels. Integrated methods that have included CPM in their structure have emphasized long-term planning and management. Hence, despite the efforts of academics to compensate for the shortcomings of common scheduling methods by using integrated scheduling methods, there is still a research gap between the alignment of short-term and long-term planning (Amer et al. 2021; Emdanat and Azambuja 2016; Tezel et al. 2020).

540 Regarding the combination analysis of integrated scheduling methods' functionalities, the
541 combination of F1 (improving the reliability of the planning) and F39 (increasing transparency),
542 F3 (considering the continuous flow of work) and F4 (decreasing workflow variability), F15
543 (improving managerial practices) and F4 (decreasing workflow variability), F14 (detecting and
544 solving spatiotemporal conflicts) and F40 (enabling the coordination of the look-ahead plans),
545 and F27 (applying analytical method) and F15 (improving managerial practices) have been
546 considered the most in integrated scheduling methods. These analyses demonstrate that
547 integrated scheduling methods are developed to address the aforementioned concerns
548 regarding low productivity caused by inefficient construction planning and scheduling. In
549 addition, they will be able to manage the whole scheduling process, including long-term,
550 medium-term, and short-term planning.

551 The SNA analysis shows that little attention had been paid to the required functionalities in the
552 scheduling methods for offsite construction. This issue can be concluded from the lack of
553 consideration given to F24 (scheduling of modular and offsite construction) and F31 (integrating
554 offsite and onsite planning for modular and offsite construction). Although there have been
555 advances in industrialization and offsite construction in the industry and academic studies, more
556 attention should be paid to scheduling methods and the associated functionalities of integrated
557 scheduling methods.

558 Following the results in Figures 7 and 8, the last planner system has gained the most attention
559 among integrated scheduling methods. Several integrated scheduling technologies, such as LPS-
560 BIM and LPS-CPM-LBMS, have attempted to account for the shortcomings of the last planner
561 system, which included inadequate visualization capabilities (Aslam et al. 2020) and a lack of

involvement in the management of construction delays, changes, and contracts (Olivieri et al. 2019). However, Integrated scheduling methods have paid little attention to one of the LPS' key drawbacks, namely the nonperformance of root cause analysis and corrective actions (Aslam et al. 2020). This finding is evident from the network in Fig. 11, which demonstrates that F30 (eliminating the root causes of variability) had the lowest DC between integrated scheduling methods' functionalities. This functionality is only considered in LPS-SS integrated methods. Consequently, there is a need for further study in this area.

Conclusion, Limitations, and Future Directions

Understanding the functionality of integrated scheduling methods in the construction industry is necessary for selecting the most appropriate planning and scheduling approach based on the required project's goals and objectives. As such, this research conducted a multi-step methodology to collect and analyze 26 integrated scheduling methods and 44 associated functionalities using SNA. Accordingly, 14 common scheduling methods and lean principles were included to create 26 identified integrated scheduling methods. The Last Planner System (LPS), Building Information Modeling (BIM), Simulation Modeling (SM) and Location-based Management System (LBMS) are utilized , as common scheduling methods, more often in integrated scheduling methods. Moreover, It has been demonstrated, as well, that studies focusing on the practical application of scheduling methods have tended to emphasize traditional methods such as CCPM, LSM, and CPM while focusing less on BIM and SM. Regarding the integrated scheduling methods, BIM-LPS, BIM-LPS-Kanban, LBMS-LPS-CPM, and BIM-LPS-SM have used the highest combination of functionalities. Also, the findings revealed that F1 (improving planning reliability), F39 (increasing transparency), F11 (identifying and eliminating

584 wastes), and F3 (considering the continuous flow of work) are the main functionalities employed
585 in integrated scheduling methods. These results also underline the importance of lean
586 construction principles, such as planning reliability, transparency, waste elimination, and
587 continuous workflow in integrated scheduling techniques. In contrast, the findings indicate that
588 integrated scheduling methods need to pay more attention to one of the LPS's significant flaws,
589 non-performance of root cause analysis and corrective actions. Furthermore, although offsite
590 and modular construction is receiving a great deal of attention in practice and academia, more
591 focus should be given to the required functionalities of the scheduling methods for offsite
592 construction.

593 Another finding illustrates several combinations of functionalities have been considered most
594 often. These include F1 (improving the reliability of the planning) and F39 (increasing
595 transparency), F3 (considering the continuous flow of work) and F4 (decreasing workflow
596 variability), F15 (improving managerial practices) and F4 (decreasing workflow variability), F14
597 (detecting and solving spatiotemporal conflicts) and F40 (enabling the coordination of the look-
598 ahead plans), and F27 (applying analytical method) and F15 (improving managerial practices).
599 These results indicate that integrated scheduling methods can handle the requirement of multi-
600 levels of schedule plan, including long-term, medium-term, and short-term planning. Moreover,
601 the pareto chart analysis applied to determine the most important functionalities in integrated
602 scheduling methods. 80% of integrated scheduling methods utilize 43% of the forty-four
603 functionalities. To validate the SNA method's findings, a simplified analysis approach is used. The
604 spearman correlation, variance, and standard deviation results reveal that minor differences
605 between the two approaches are acceptable.

Ultimately, this research contributes to the body of knowledge by providing a better understanding the integrated scheduling methods' functionalities in the construction sector.

One of the limitations of this article is that the analyses were conducted solely based on the literature review; however, given the practical aspect of project planning and scheduling, it is crucial to consider experts' opinions for a more effective and comprehensive analysis. In this regard, Future research should focus on studying the understanding of scheduling methods in light of the perspectives of experts. In addition, Due to a large number of identified functionalities and some conceptual overlap between them, their clustering and sorting out according to underlying concepts and taking expert opinion into account could be another future direction.

Data Availability Statement

All data and code generated or used during the study appear in the published article.

Acknowledgements

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

References

- Abbasi, S., Taghizade, K., and Noorzai, E. (2020). "BIM-based combination of takt time and discrete event simulation for implementing just in time in construction scheduling under constraints." *Journal of construction engineering and management*, 146(12), 04020143.
- Abdelmegid, M. A., González, V. A., O'Sullivan, M., Walker, C. G., Poshdar, M., and Alarcón, L. F. "Establishing a link between the last planner system and simulation: a conceptual framework." *Proc., 27th Annual Conference of the International Group for Lean Construction (IGLC)*, 335-246.
- Abdelmegid, M. A., González, V. A., O'Sullivan, M., Walker, C. G., Poshdar, M., and Alarcón, L. F. (2021). "Exploring the links between simulation modelling and construction production planning and control: a case study on the last planner system." *Production Planning & Control*, 1-18.

- Abdul Nabi, M., and El-adaway, I. H. (2020). "Modular construction: Determining decision-making factors and future research needs." *Journal of management in engineering*, 36(6), 04020085.
- Abdul Nabi, M., and El-adaway, I. H. (2022). "Understanding Disputes in Modular Construction Projects: Key Common Causes and Their Associations." *Journal of Construction Engineering and Management*, 148(1), 04021184.
- Abotaleb, I. S., and El-adaway, I. H. (2018). "Managing construction projects through dynamic modeling: Reviewing the existing body of knowledge and deriving future research directions." *Journal of management in engineering*, 34(6), 04018033.
- Al Hussein, Z. K. (2016). "Using Building Information Modeling (BIM) and the Last Planner System (LPS) to Reduce Construction Process Delay." Masters Thesis, Western Kentucky University.
- Ajweh, Z. (2014). "A framework for design of panelized wood framing prefabrication utilizing multi-panels and crew balancing." Master of Science, University of Alberta.
- Al Nasser, H. A., Widen, K., and Aulin, R. (2016). "A taxonomy of planning and scheduling methods to support their more efficient use in construction project management." *Journal of Engineering, Design and Technology*.
- Alhussein, H., Shehab, L., and Hamzeh, F. (2022). "Improvisation in Construction Planning: An Agent-Based Simulation Approach." *Buildings*, 12(10), 1608.
- AlNasser, H., and Aulin, R. (2015). "Assessing understanding of planning and scheduling theory and practice on construction projects." *Engineering Management Journal*, 27(2), 58-72.
- AlNasser, H. A. (2015). *Understanding applications of project planning and scheduling in construction projects*, Department of Construction Sciences, Lund University.
- Amer, F., Jung, Y., and Golparvar-Fard, M. (2021). "Transformer machine learning language model for auto-alignment of long-term and short-term plans in construction." *Automation in Construction*, 132, 103929.
- Ammar, M. A. (2013). "LOB and CPM integrated method for scheduling repetitive projects." *Journal of construction engineering and management*, 139(1).
- Andújar-Montoya, M. D., Galiano-Garrigós, A., Echarri-Iribarren, V., and Rizo-Maestre, C. (2020). "BIM-LEAN as a Methodology to Save Execution Costs in Building Construction—An Experience under the Spanish Framework." *Applied Sciences*, 10(6), 1913.
- Ansari, R., Khalilzadeh, M., and Hosseini, M. R. (2022). "A Multi-objective Dynamic Optimization Approach to Project Schedule Management: A Case Study of a Gas Field Construction." *KSCE Journal of Civil Engineering*, 26(3), 1005-1013.
- Antill, J. M., and Woodhead, R. W. (1991). *Critical path methods in construction practice*, John Wiley & Sons.
- Arditi, D., and Albulak, M. Z. (1986). "Line-of-balance scheduling in pavement construction." *Journal of Construction Engineering and Management*, 112(3), 411-424.
- Ashcraft, H. (2022). "Transforming project delivery: integrated project delivery." *Oxford Review of Economic Policy*, 38(2), 369-384.
- Aslam, M., Gao, Z., and Smith, G. (2020). "Development of innovative integrated last planner system (ILPS)." *International Journal of Civil Engineering*, 18(6), 701-715.
- Assaad, R., and El-Adaway, I. H. (2020). "Enhancing the knowledge of construction business failure: A social network analysis approach." *Journal of construction engineering and management*, 146(6), 04020052.
- Ballard, G., and Tommelein, I. (2016). "Current process benchmark for the last planner system." *Lean Construction Journal*, 89, 57-89.
- Barkokebas, B., Khalife, S., Al-Hussein, M., and Hamzeh, F. (2021). "A BIM-lean framework for digitalisation of premanufacturing phases in offsite construction." *Engineering, Construction and Architectural Management*, 28(8), 2155-2175.

- Bhatla, A., and Leite, F. "Integration framework of bim with the last planner systemtm." *Proc., IGLC 2012-20th Conference of the International Group for Lean Construction*.
- Boton, C., Pitti, Y., Forgues, D., and Iordanova, I. (2021). "Investigating the challenges related to combining BIM and Last Planner System on construction sites." *Frontiers of Engineering Management*, 8(2), 172-182.
- Büchmann-Slorup, R. (2014). "Applying critical chain buffer management theory in location-based management." *Construction management and economics*, 32(6), 506-519.
- Burguete, M. G. (2018). "Project optimization through the combination of BIM and last planner system." Aalborg University.
- Dave, B., Seppänen, O., and Modrich, R.-U. "Modeling information flows between last planner and location based management system." *Proc., Proceedings of the 24th Annual Conference of the International Group for Lean Construction, Boston, EE. UU*.
- Elsayegh, A., and El-adaway, I. H. (2021). "Holistic study and analysis of factors affecting collaborative planning in construction." *Journal of Construction Engineering and Management*, 147(4), 04021023.
- Emdanat, S., and Azambuja, M. (2016). "Aligning near and Long Term Planning for LPS implementations: a review of existing and new metrics." *Lean Construction Journal*, 101, 90-101.
- Etges, B. M., Reck, R. H., Fireman, M. T., Rodrigues, J. L., and Isatto, E. L. (2020). "USING BIM WITH THE LAST PLANNER® SYSTEM TO IMPROVE CONSTRAINTS ANALYSIS." *28th Annual Conference of the International Group for Lean Construction (IGLC28)*Berkeley, California.
- Frandsen, A. (2019). "Takt time planning as a work structuring method to improve construction work flow." University of California, Berkeley.
- Frandsen, A., Berghede, K., and Tommelein, I. D. "Takt time planning for construction of exterior cladding." *Proc., 21st Annual Conference of the International Group for Lean Construction. Fortaleza, Brazil, Citeseer*, 21-22.
- Freeman, L. C. (1980). "A Set of Measures of Centrality Based on Betweenness." *Sociometry* 40: 35-41. 1979." *Centrality in Social Networks: Conceptual Clarification.*" *Social Networks*, 1, 215-239.
- Gusenbauer, M., and Haddaway, N. R. (2020). "Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources." *Research synthesis methods*, 11(2), 181-217.
- Hajirasouli, A., and Banihashemi, S. (2020). "The Unfolding Tragedy of Kandovan: The Loss of the last inhabited cone-shaped settlement in the world." *Habitat International*, 102, 102211.
- Hajirasouli, A., Banihashemi, S., Drogemuller, R., Fazeli, A., and Mohandes, S. R. (2022). "Augmented reality in design and construction: thematic analysis and conceptual frameworks." *Construction Innovation*(ahead-of-print).
- Hamzeh, F. R., Saab, I., Tommelein, I. D., and Ballard, G. (2015). "Understanding the role of "tasks anticipated" in lookahead planning through simulation." *Automation in Construction*, 49, 18-26.
- Hamzeh, F. R., Zankoul, E., and Rouhana, C. (2015). "How can 'tasks made ready'during lookahead planning impact reliable workflow and project duration?" *Construction management and economics*, 33(4), 243-258.
- Heigermoser, D., de Soto, B. G., Abbott, E. L. S., and Chua, D. K. H. (2019). "BIM-based Last Planner System tool for improving construction project management." *Automation in Construction*, 104, 246-254.
- Himmiche, S., Aubry, A., Marangé, P., DufLOT-Kremer, M., and Pétin, J.-F. (2018). "Using statistical-model-checking-based simulation for evaluating the robustness of a production schedule." *Service Orientation in Holonic and Multi-Agent Manufacturing*, Springer, 345-357.
- Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., and Chileshe, N. (2018). "Critical evaluation of off-site construction research: A Scientometric analysis." *Automation in Construction*, 87, 235-247.

- Huber, B., and Reiser, P. "The marriage of CPM and lean construction." *Proc., ANNUAL CONFERENCE OF THE INTERNATIONAL GROUP FOR LEAN CONSTRUCTION*, Citeseer.
- Igwe, C., Hammad, A., and Nasiri, F. (2019). "USING LEAN CONSTRUCTION TOOLS AND 4D MODELLING FOR EQUIPMENT WORKSPACE PLANNING." *CSCE Annual Conference*.
- Igwe, C. N. (2021). "A Process-Based Approach for Integrating the Last Planner System In 4D Modeling for Equipment Workspace Planning in Elevated Urban Highway." Concordia University.
- Jeong, W., Chang, S., Son, J., and Yi, J.-S. (2016). "BIM-integrated construction operation simulation for just-in-time production management." *Sustainability*, 8(11), 1106.
- Jongeling, R., and Olofsson, T. (2007). "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." *Automation in construction*, 16(2), 189-198.
- Kim, Y.-W., and Ballard, G. (2010). "Management thinking in the earned value method system and the last planner system." *Journal of management in engineering*, 26(4), 223.
- Kitchenham, B. (2004). "Procedures for performing systematic reviews." *Keele, UK, Keele University*, 33(2004), 1-26.
- König, M. (2011). "Robust construction scheduling using discrete-event simulation." *Computing in Civil Engineering (2011)*, 446-453.
- König, M., Koch, C., Habenicht, I., and Spieckermann, S. "Intelligent BIM-based construction scheduling using discrete event simulation." *Proc., Proceedings of the 2012 Winter Simulation Conference (WSC)*, IEEE, 1-12.
- Lin, J. J., and Golparvar-Fard, M. (2021). "Visual and virtual production management system for proactive project controls." *Journal of Construction Engineering and Management*, 147(7), 04021058.
- Lu, M., and AbouRizk, S. (2000). "Simplified CPM/PERT simulation model." *Journal of Construction Engineering and Management*, 126(3), 219-226.
- Lu, W., and Olofsson, T. (2014). "Building information modeling and discrete event simulation: Towards an integrated framework." *Automation in Construction*, 44, 73-83.
- Martins, S. S., Evangelista, A. C. J., Hammad, A. W., Tam, V. W., and Haddad, A. (2020). "Evaluation of 4D BIM tools applicability in construction planning efficiency." *International Journal of Construction Management*, 1-14.
- McHugh, K., Dave, B., and Craig, R. "Integrated lean and BIM processes for modularised construction." *Proc., 27th Annual Conference of the International Group for Lean Construction*
- Melzner, J. "BIM-based takt-time planning and takt control: Requirements for digital construction process management." *Proc., ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, IAARC Publications, 50-56.
- Milat, M., Knezić, S., and Sedlar, J. (2021). "Resilient scheduling as a response to uncertainty in construction projects." *Applied Sciences*, 11(14), 6493.
- Moktadir, M. A., Dwivedi, A., Khan, N. S., Paul, S. K., Khan, S. A., Ahmed, S., and Sultana, R. (2021). "Analysis of risk factors in sustainable supply chain management in an emerging economy of leather industry." *Journal of Cleaner Production*, 283, 124641.
- Morkos, R. (2014). *Operational efficiency frontier: Visualizing, manipulating, and navigating the construction scheduling state space with precedence, discrete, and disjunctive constraints*, Stanford University.
- Mota, B. P., Viana, D. D., and Isatto, E. L. "Simulating the last planner with systems dynamic." *Proc., ANNUAL CONFERENCE OF THE INTERNATIONAL GROUP FOR LEAN CONSTRUCTION*, Citeseer.
- Novinsky, M., Nesensohn, C., Ihwas, N., and Haghsheno, S. "Combined application of earned value management and last planner system in construction projects." *Proc., Proceedings of the 26th Annual Conference of the International Group for Lean Construction, Chennai, India*, 16-22.

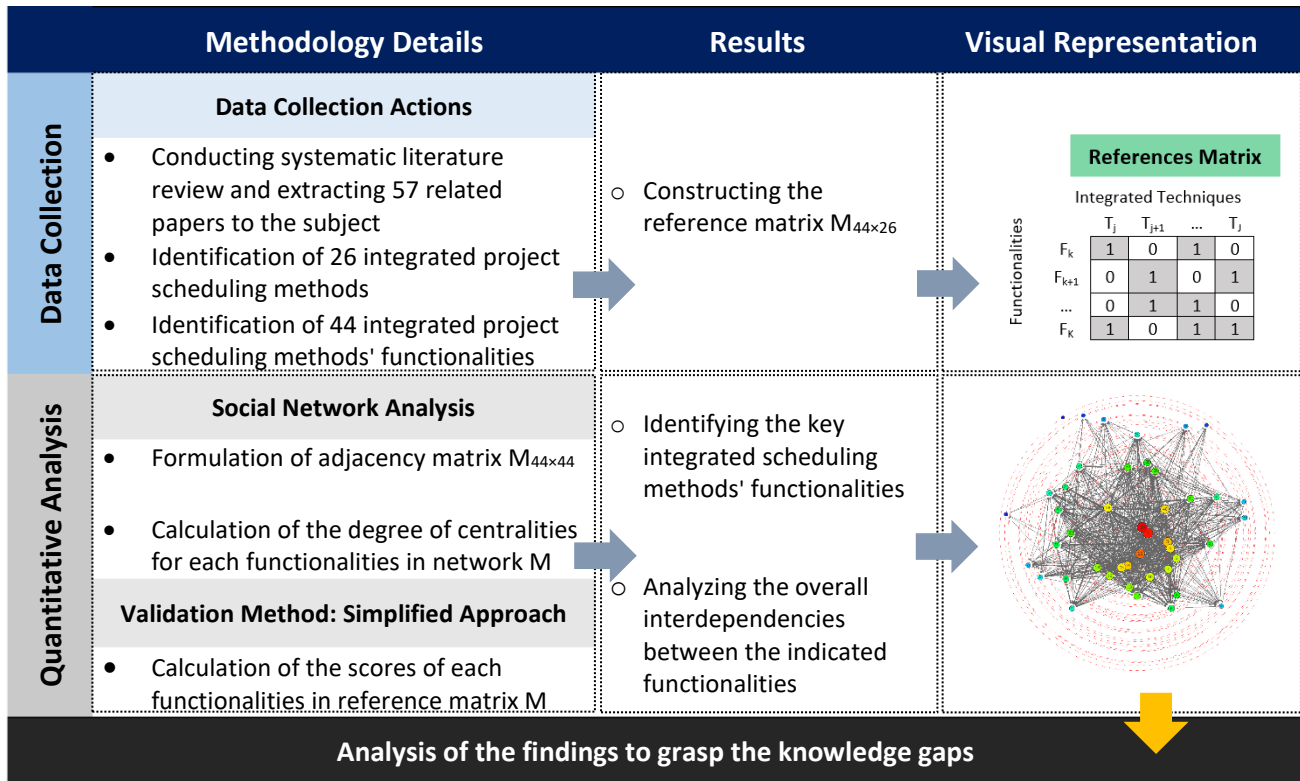
- Olivieri, H., Seppänen, O., Alves, T. d. C., Scala, N. M., Schiavone, V., Liu, M., and Granja, A. D. (2019). "Survey comparing critical path method, last planner system, and location-based techniques." *Journal of construction engineering and management*, 145(12), 04019077.
- Olivieri, H., Seppänen, O., and Denis Granja, A. (2018). "Improving workflow and resource usage in construction schedules through location-based management system (LBMS)." *Construction management and economics*, 36(2), 109-124.
- Olivieri, H., Seppänen, O., and Granja, A. D. "Integrating Lbms, Lps and Cpm: a practical process." *Proc., Proceedings of the 24th Annual Conference of the International Group for Lean Construction, Boston, EE. UU.*
- Ortenburger, S., and Hartmann, T. (2021). "Supporting the Last Planner System with 4D BIM." *Technische Universität Berlin*.
- Pellerin, R., and Perrier, N. (2019). "A review of methods, techniques and tools for project planning and control." *International Journal of Production Research*, 57(7), 2160-2178.
- POLIANI, R. (2020). "Planning and control in construction: analysis and integrations of three methodological approaches. Location-based management system (LBMS), last planner system (LPS) and critical path method (CPM)." *POLITECNICO DI MILANO*.
- Ratajczak, J., Riedl, M., and Matt, D. T. (2019). "BIM-based and AR application combined with location-based management system for the improvement of the construction performance." *Buildings*, 9(5), 118.
- Raz, T., Barnes, R., and Dvir, D. (2003). "A critical look at critical chain project management." *Project management journal*, 34(4), 24-32.
- Richards, J. C., and Schmidt, R. W. (2013). *Longman dictionary of language teaching and applied linguistics*, Routledge.
- Russell, A., Staub-French, S., Tran, N., and Wong, W. (2009). "Visualizing high-rise building construction strategies using linear scheduling and 4D CAD." *Automation in Construction*, 18(2), 219-236.
- Sacks, R., Radosavljevic, M., and Barak, R. (2010). "Requirements for building information modeling based lean production management systems for construction." *Automation in construction*, 19(5), 641-655.
- Saedi, S., Fini, A. A. F., Khanzadi, M., Wong, J., Sheikhhoshkar, M., and Banaei, M. (2022). "Applications of electroencephalography in construction." *Automation in Construction*, 133, 103985.
- Salama, T., Salah, A., and Moselhi, O. "Alternative scheduling and planning processes for hybrid offsite construction." *Proc., Proceedings of the 33rd International Symposium on Automation and Robotics in Construction, International Association for Automation and Robotics in Construction, Auburn, AL, USA*, 18-21.
- Salama, T., Salah, A., and Moselhi, O. (2018). "Integration of linear scheduling method and the critical chain project management." *Canadian Journal of Civil Engineering*, 45(1), 30-40.
- Salama, T., Salah, A., and Moselhi, O. (2021). "Integrating critical chain project management with last planner system for linear scheduling of modular construction." *Construction Innovation*.
- Sbiti, M., Beddiar, K., Beladjine, D., Perrault, R., and Mazari, B. (2021). "Toward BIM and LPS Data Integration for Lean Site Project Management: A State-of-the-Art Review and Recommendations." *Buildings*, 11(5), 196.
- Schimanski, C. P., Marcher, C., Pasetti Monizza, G., and Matt, D. T. (2020). "The Last Planner® system and building information modeling in construction execution: From an integrative review to a conceptual model for integration." *Applied Sciences*, 10(3), 821.
- Schimanski, C. P., Pasetti Monizza, G., Marcher, C., and Matt, D. T. (2021). "Development of a BIM-based production planning and control system for Lean Construction through advancement and integration of existing management techniques." *Frontiers of engineering management*, 8(3), 429-441.

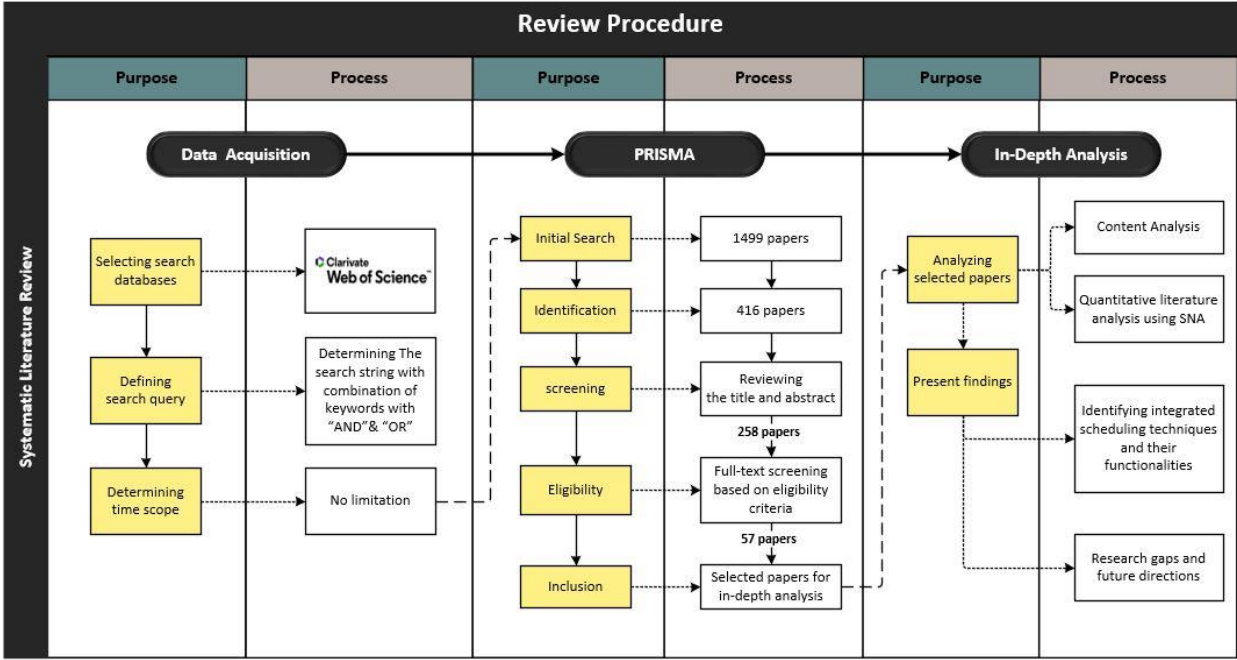
- Schimanski, C. P., Pradhan, N. L., Chaltsev, D., Monizza, G. P., and Matt, D. T. (2021). "Integrating BIM with Lean Construction approach: Functional requirements and production management software." *Automation in Construction*, 132, 103969.
- Seppänen, O., Ballard, G., and Pesonen, S. (2010). "The combination of last planner system and location-based management system." *Lean construction journal*.
- Seppänen, O., Evinger, J., and Mouflard, C. (2014). "Effects of the location-based management system on production rates and productivity." *Construction management and economics*, 32(6), 608-624.
- Shehab, L., Ezzeddine, A., Hamzeh, F., Power, W., Tommelein, I., and Daniel, E. "Agent-Based Modelling and Simulation of Construction Crew Performance." *Proc., Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC28)*.
- Shen, L., and Chua, D. K. (2008). "An investigation of critical chain and lean project scheduling." *16th Annual Conference of the International Group for Lean Construction (IGLC16)*.
- Silveira, B. F., and Costa, D. B. (2023). "Method for automating the processes of generating and using 4D BIM models integrated with location-based planning and Last Planner® System." *Construction Innovation*(ahead-of-print).
- Simmons, L. F. "Project management-critical path method (CPM) and PERT simulated with ProcessModel." *Proc., Proceedings of the Winter Simulation Conference, IEEE*, 1786-1788.
- Soman, R. K., and Molina-Solana, M. (2022). "Automating look-ahead schedule generation for construction using linked-data based constraint checking and reinforcement learning." *Automation in Construction*, 134, 104069.
- Sriprasert, E., and Dawood, N. (2002). "Next generation of construction planning and control system: the LEWIS approach." *Z. Turk. & R. Scherer, eWork and eBusiness in Architecture, Engineering and Construction*, 175-182.
- Sriprasert, E., and Dawood, N. (2003). "Multi-constraint information management and visualisation for collaborative planning and control in construction." *Journal of Information Technology in Construction*, 8, 341-366.
- Staub-French, S., Russell, A., and Tran, N. (2008). "Linear scheduling and 4D visualization." *Journal of Computing in Civil Engineering*, 22(3), 192-205.
- Suhail, S. A., and Neale, R. H. (1994). "CPM/LOB: New methodology to integrate CPM and line of balance." *Journal of construction Engineering and management*, 120(3), 667-684.
- Tezel, A., Taggart, M., Koskela, L., Tzortzopoulos, P., Hanahoe, J., and Kelly, M. (2020). "Lean construction and BIM in small and medium-sized enterprises (SMEs) in construction: a systematic literature review." *Canadian journal of civil engineering*, 47(2), 186-201.
- Thomé, A. M. T., Scavarda, L. F., and Scavarda, A. J. (2016). "Conducting systematic literature review in operations management." *Production Planning & Control*, 27(5), 408-420.
- Tokdemir, O. B., Erol, H., and Dikmen, I. (2019). "Delay risk assessment of repetitive construction projects using line-of-balance scheduling and Monte Carlo simulation." *Journal of Construction Engineering and Management*, 145(2), 04018132.
- Toledo, M., Olivares, K., and González, V. "Exploration of a Lean-BIM planning framework: A Last Planner System and BIM-based case study." *Proc., 24th Annual Conference of the International Group for Lean Construction*, Citeseer, 2016.
- Ullah, F. (2021). "A beginner's guide to developing review-based conceptual frameworks in the built environment." *Architecture*, 1(1), 5-24.
- Viklund Tallgren, M., Roupé, M., Johansson, M., and Bosch-Sijtsema, P. (2020). "BIM-tool development enhancing collaborative scheduling for pre-construction." *J. Inf. Technol. Constr.(ITcon)*, 25, 374-397.
- Viles, E., Rudeli, N. C., and Santilli, A. (2019). "Causes of delay in construction projects: a quantitative analysis." *Engineering, Construction and Architectural Management*.

- Walker, D. H., and Shen, Y. J. (2002). "Project understanding, planning, flexibility of management action and construction time performance: two Australian case studies." *Construction Management & Economics*, 20(1), 31-44.
- Wickramasekara, A. N., Gonzalez, V., O'Sullivan, M., Walker, C., Poshdar, M., and Ying, F. "Exploring the Integration of Last Planner® System, Bim, and Construction Simulation." *Proc., Annual Conference of the International. Group for Lean Construction*.
- Wu, C., Wang, X., Wu, P., Wang, J., Jiang, R., Chen, M., and Swapan, M. (2021). "Hybrid deep learning model for automating constraint modelling in advanced working packaging." *Automation in Construction*, 127, 103733.
- Yamin, R. A., and Harmelink, D. J. (2001). "Comparison of linear scheduling model (LSM) and critical path method (CPM)." *Journal of construction engineering and management*, 112(4), 476-491.
- Zhang, H., Tam, C., and Shi, J. J. (2002). "Simulation-based methodology for project scheduling." *Construction Management & Economics*, 20(8), 667-678.

Figures Caption List

- Fig. 1. Summary of the adopted research methodology
- Fig. 2. Adopted systematic review procedure
- Fig. 3. An example of a reference matrix
- Fig. 4. An illustration of an adjacency matrix
- Fig. 5. Visual representation of reference and adjacency matrix
- Fig. 6. Distribution of the papers across the years
- Fig. 7. Sankey diagram of integrated scheduling methods
- Fig. 8. Distribution of utilized common scheduling methods in integrated scheduling methods
- Fig. 9. Mapping between the identified functionalities and analyzed integrated scheduling methods
- Fig. 10. Derived differences in the scores of C1 and C2 studies for common scheduling methods
- Fig. 11. Functionalities network
- Fig. 12. Color-coded matrix of functionalities
- Fig. 13. Pareto Analysis of Functionalities
- Fig. 14. Comparison results between simplified analysis and SNA

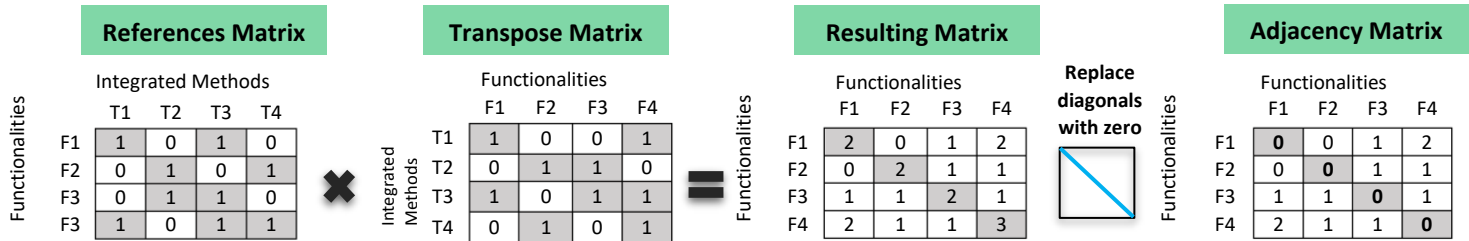


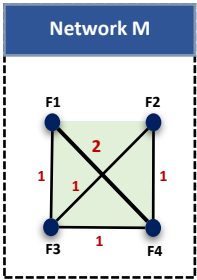
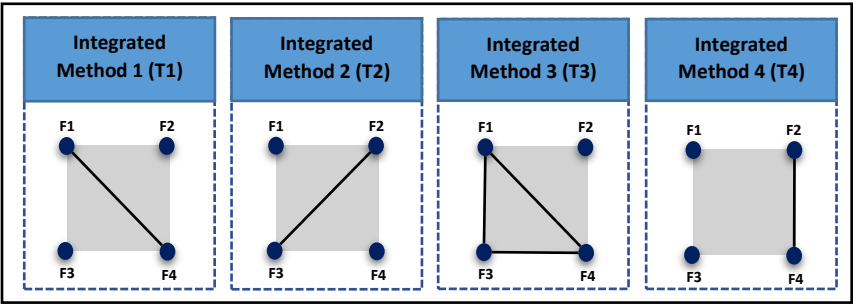


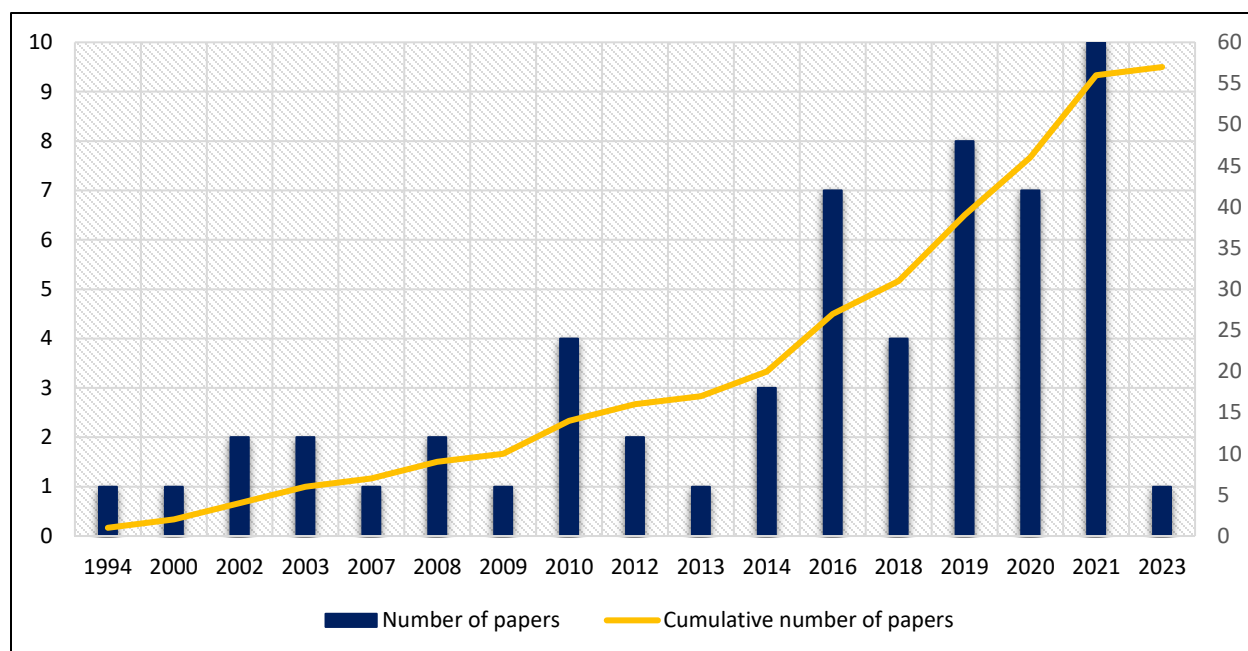
References Matrix M

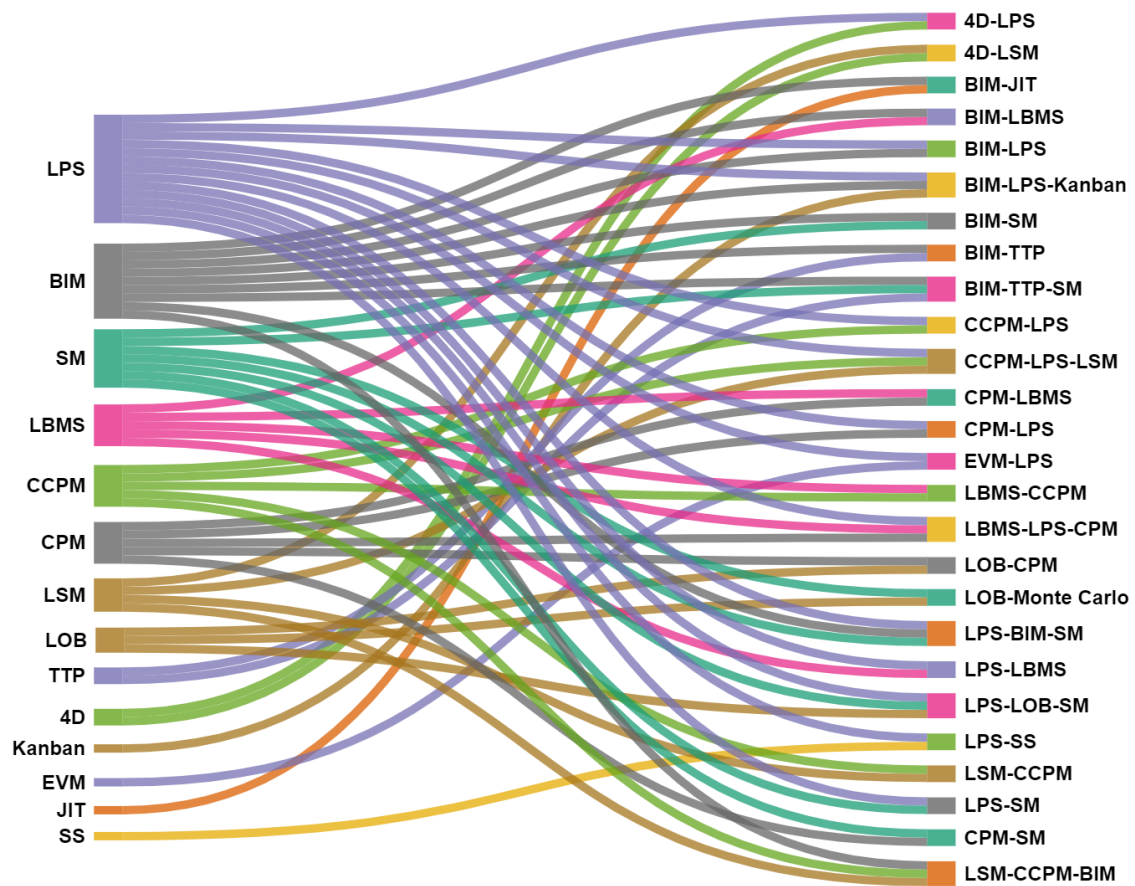
Integrated Techniques

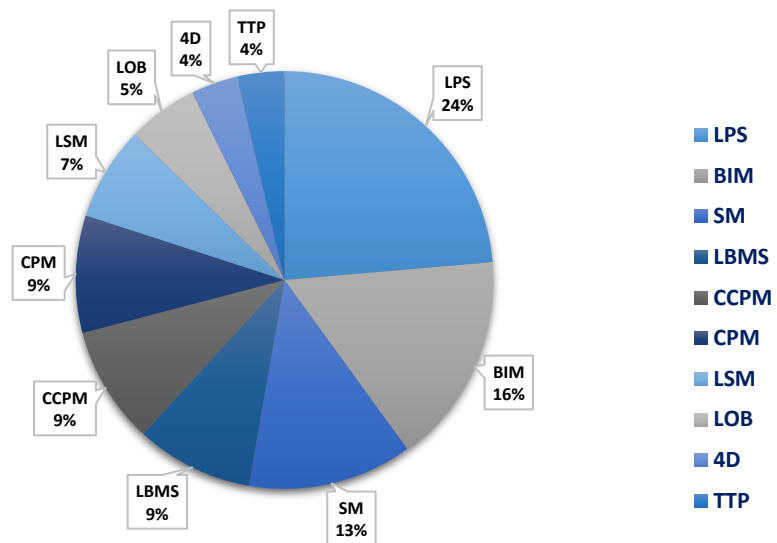
	T_j	T_{j+1}	...	T_j
F_k	1	0	1	0
F_{k+1}	0	1	0	1
...	0	1	1	0
F_K	1	0	1	1





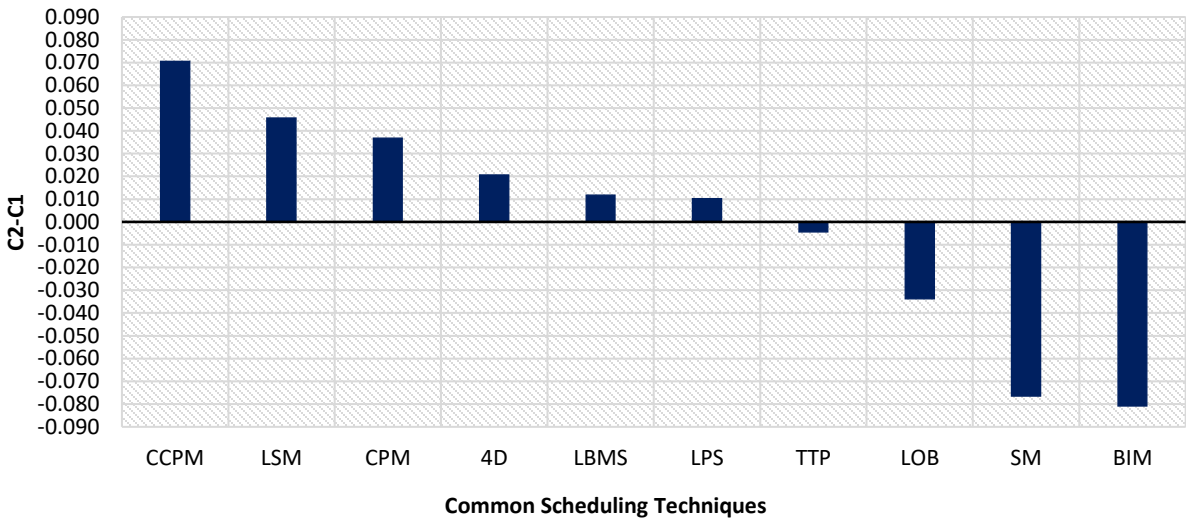


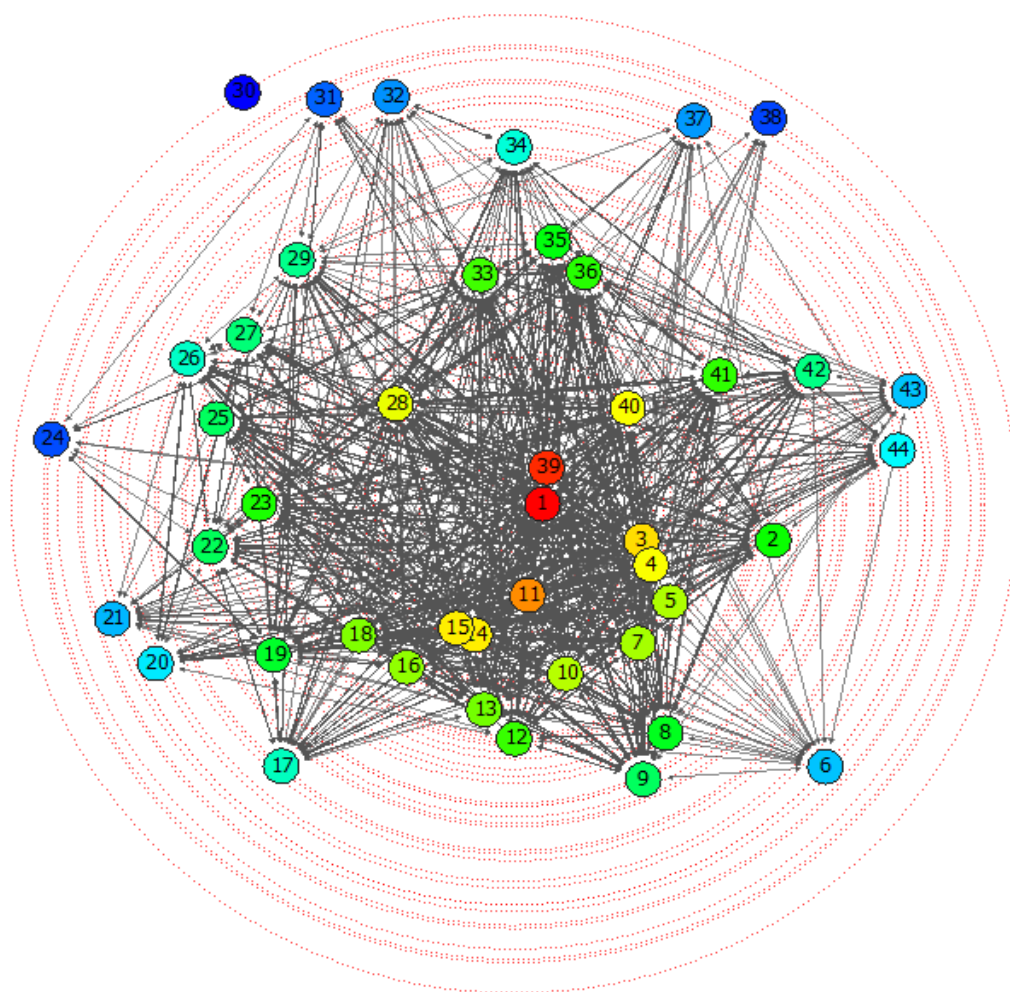


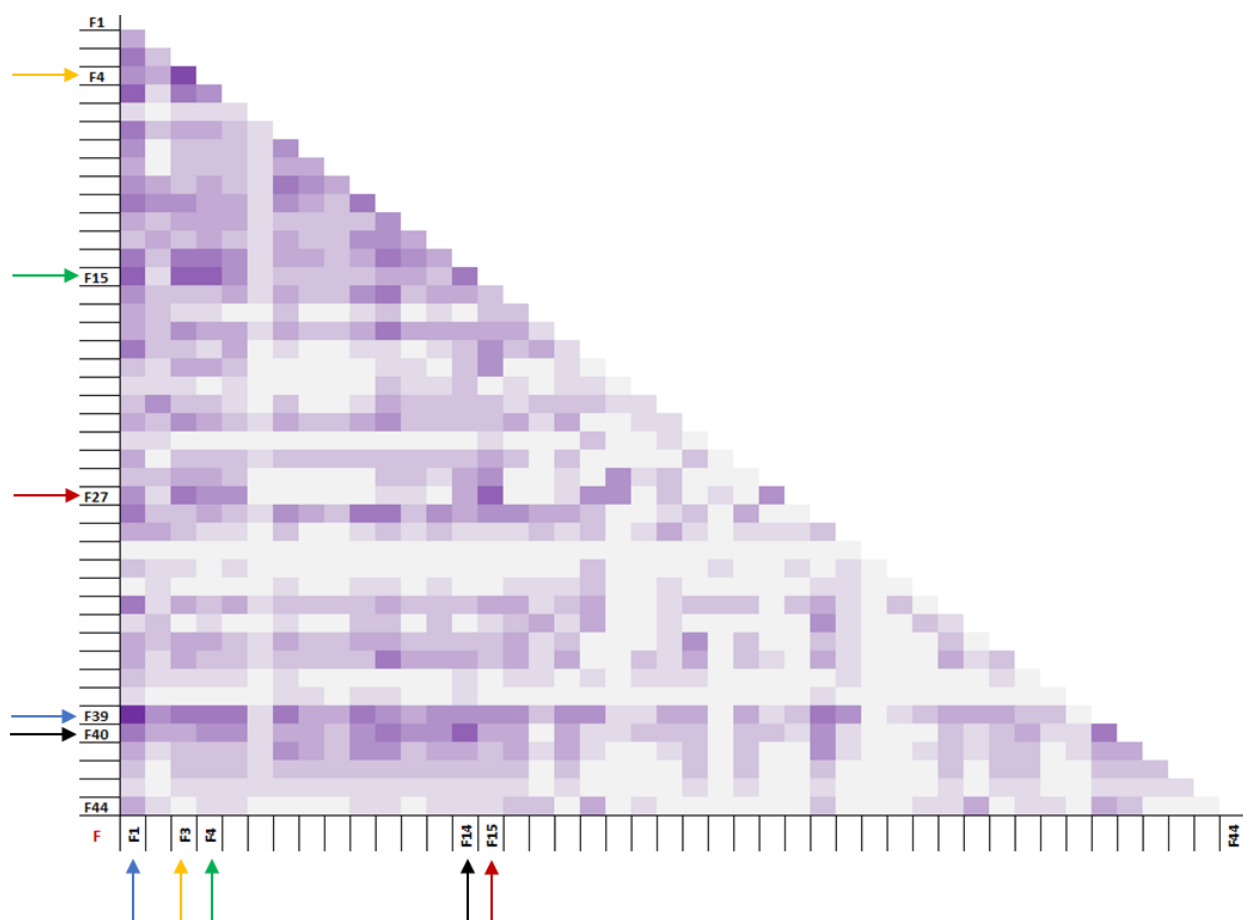


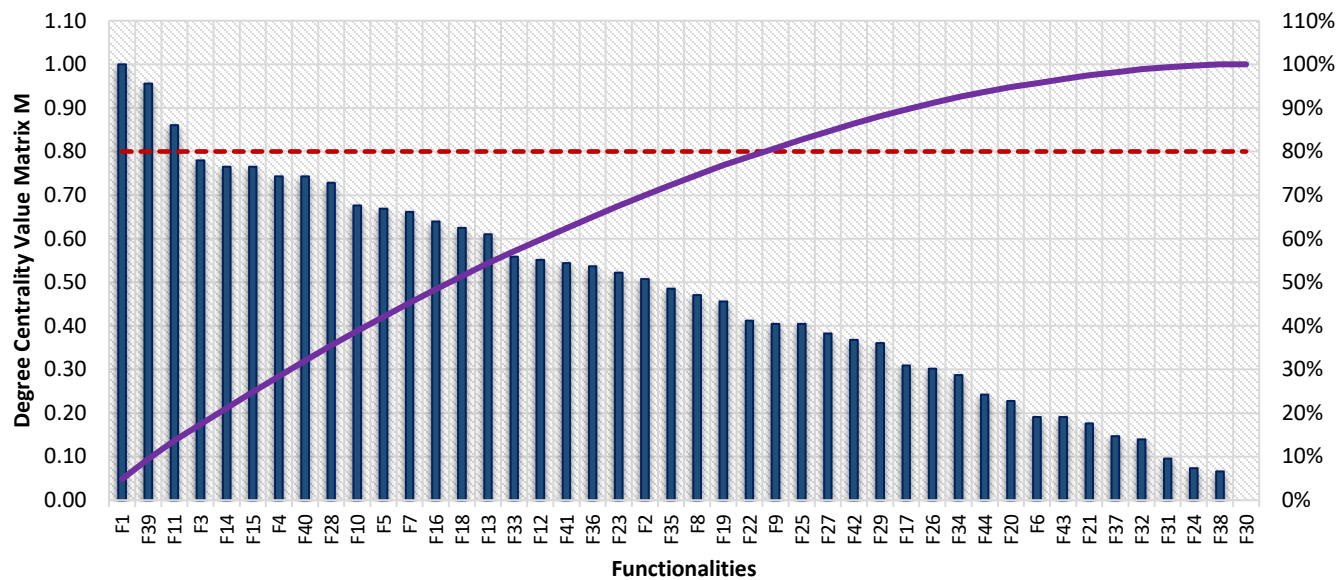
[illegible]

Difference between normalized C2 & C1









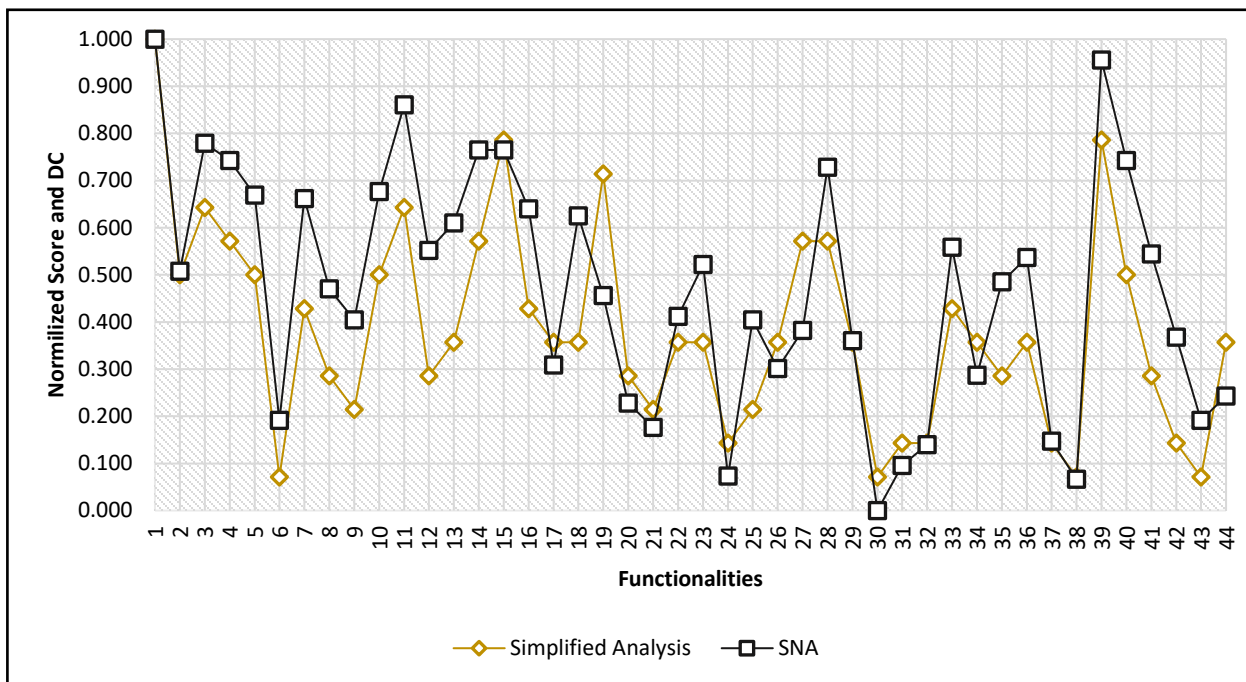


Table1. List of journals and conferences

Journal name	
Journal of Construction Engineering and Management	International Journal of Production Research
Automation in Construction	Journal of Information Technology in Construction (ITcon)
Journal of Management in Engineering	Production Planning & Control
Engineering, Construction and Architectural Management	Construction Management and Economics
Journal of Computing in Civil Engineering	Journal of Engineering, Design and Technology
International Journal of Project Management	Lean Construction Journal (LCJ)
International Journal of Construction Management	Construction Innovation
Journal of Building Engineering	Applied Sciences
Canadian Journal of Civil Engineering	Buildings
Advanced Engineering Informatics	Frontiers of Engineering Management
Conference name	
International Symposium on Automation and Robotics in Construction (ISARC)	
European Conference of Computing in Construction (EC3)	
International Group for Lean Construction (IGLC)	
Construction Research Congress (CRC)	

Table2. Search query

String
("CPM" OR "Critical Path Method" OR "CCPM" OR "Critical Chain Management system" OR "Critical chain method" OR "LPS" OR "Last Planner System" OR "Takt Planning" OR "Takt time planning" OR "LBMS" OR "Location Based Management System" OR "LBS" OR "Location-based system" OR "LOB" OR "Line of Balance" OR "BIM" OR "Building Information Modeling" OR "4D" OR "4DBIM" OR "Linear Scheduling Method" OR "LSM" OR "Simulation" OR " Monte-Carlo" OR "PERT") AND ("Project Planning" OR "Project Scheduling" OR "Project Control" OR "Construction Planning" OR "Construction Scheduling")

Table3. Inclusion and exclusion criteria for screening

Inclusion	Exclusion
- Written in English - Peer-reviewed articles that have been published in reputable scholarly construction and manufacturing journals and conferences - Act towards at least one combination of scheduling methods (LPS-4D)	- Written in a different language than English - Not peer-reviewed; book, book chapter, technical reports - Deals only one scheduling method (LOB OR LPS) - Outside the scope of the construction industry

Table4. Full-text reviewed articles

Year	Full-text analyzed papers	Number of papers
1994-2003	(Suhail and Neale 1994), (Lu and AbouRizk 2000), (Simmons 2002), (Sriprasert and Dawood 2002), (Huber and Reiser 2003), and (Sriprasert and Dawood 2003)	6
2004-2013	(Jongeling and Olofsson 2007), (Shen and Chua 2008), (Staub-French et al. 2008), (Russell et al. 2009), (Kim and Ballard 2010), (Mota et al. 2010), (Sacks et al. 2010), (Seppänen et al. 2010), (Bhatla and Leite 2012), (König et al. 2012), and (Ammar 2013)	11
2014-2023	(Ajweh 2014), (Büchmann-Slorup 2014), (Lu and Olofsson 2014), (Al Hussein 2016), (Al Nasser et al. 2016), (Dave et al. 2016), (Jeong et al. 2016), (Olivieri et al. 2016), (Salama et al. 2016), (Toledo et al. 2016), (Burguete 2018), (Novinsky et al. 2018), (Olivieri et al. 2018), (Salama et al. 2018), (Abdelmegid et al. 2019), (Frandsen 2019), (Heigermoser et al. 2019), (Igwe et al. 2019), (McHugh et al. 2019), (Melzner 2019), (Ratajczak et al. 2019), (Tokdemir et al. 2019), (Abbasi et al. 2020), (Andújar-Montoya et al. 2020), (Aslam et al. 2020), (Etges et al. 2020), (POLIANI 2020), (Schimanski et al. 2020), (Wickramasekara et al. 2020), (Abdelmegid et al. 2021), (Barkokebas et al. 2021), (Boton et al. 2021), (Igwe 2021), (Lin and Golparvar-Fard 2021), (Ortenburger and Hartmann 2021), (Salama et al. 2021), (Sbiti et al. 2021), (Schimanski et al. 2021), (Schimanski et al. 2021), (Silveira and Costa 2023)	40

Table 5. Identified integrated scheduling methods

ID	Integrated Scheduling Methods	Abbreviations	References
1	4D BIM-Last Planner System	4D-LPS	(Igwe et al. 2019; Igwe 2021; Lin and Golparvar-Fard 2021; Ortenburger and Hartmann 2021)
2	4D BIM-Linear Scheduling Method	4D-LSM	(Russell et al. 2009; Staub-French et al. 2008)
3	BIM-Just In Time	BIM-JIT	(Abbasi et al. 2020; Jeong et al. 2016)
4	BIM-Location-Based Management System	BIM-LBMS	(Jongeling and Olofsson 2007; Ratajczak et al. 2019)
5	BIM-Last Planner System	BIM-LPS	(Al Hussein 2016; Barkokebas et al. 2021; Bhatla and Leite 2012; Etges et al. 2020; Heigermoser et al. 2019; McHugh et al. 2019; Sacks et al. 2010; Sbiti et al. 2021; Schimanski et al. 2020; Schimanski et al. 2021; Schimanski et al. 2021; Sriprasert and Dawood 2002; Sriprasert and Dawood 2003; Toledo et al. 2016)
6	BIM-Last Planner System-Kanban	BIM-LPS-Kanban	(Sacks et al. 2010; Schimanski et al. 2021)
7	BIM-Simulation Modeling	BIM-SM	(Abbasi et al. 2020; Jeong et al. 2016; König et al. 2012; Lu and Olofsson 2014)
8	BIM-Takt Time Planning	BIM-TTP	(Abbasi et al. 2020; Frandson 2019; Melzner 2019)
9	BIM-Takt Time Planning- Simulation Modeling	BIM-TTP-SM	(Abbasi et al. 2020; Aslam et al. 2020; Frandson 2019)
10	Critical Chain Project Management- Last Planner System	CCPM-LPS	(Shen and Chua 2008)
11	Critical Chain Project Management- Last Planner System- Linear Scheduling Method	CCPM-LPS-LSM	(Salama et al. 2021)
12	Critical Path Method- Location-Based Management System	CPM-LBMS	(Olivieri et al. 2018; POLIANI 2020)
13	Critical Path Method- Last Planner System	CPM-LPS	(Huber and Reiser 2003; POLIANI 2020)
14	Earn Value Management- Last Planner System	EVM-LPS	(Kim and Ballard 2010; Novinsky et al. 2018)
15	Location-Based Management System- Critical Chain Project Management	LBMS-CCPM	(Büchmann-Slorup 2014)
16	Location-Based Management System- Last Planner System- Critical Path Method	LBMS-LPS-CPM	(Olivieri et al. 2016; POLIANI 2020)
17	Line of Balance - Critical Path Method	LOB-CPM	(Ammar 2013; Suhail and Neale 1994)
18	Line of Balance- Monte Carlo Simulation	LOB-Monte Carlo	(Tokdemir et al. 2019)
19	Last Planner System-BIM-Simulation Modeling	LPS-BIM-SM	(Wickramasekara et al. 2020)
20	Last Planner System- Location-Based Management System	LPS-LBMS	(Dave et al. 2016; Salama et al. 2021; Seppänen et al. 2010)
21	Last Planner System- Line of Balance- Simulation Modeling	LPS-LOB-SM	(Ajweh 2014; Salama et al. 2021)
22	Last Planner System- Six Sigma	LPS-SS	(Aslam et al. 2020)
23	Linear Scheduling Method- Critical Chain Project Management	LSM-CCPM	(Salama et al. 2018; Salama et al. 2021)
24	Last Planner System- Simulation Modeling	LPS-SM	(Abdelmegid et al. 2019; Abdelmegid et al. 2021; Hamzeh et al. 2015; Hamzeh et al. 2015; Mota et al. 2010)
25	Critical Path Method- Simulation Modeling	CPM-SM	(Simmons 2002; Tokdemir et al. 2019)
26	Linear Scheduling Method- Critical Chain Project Management- BIM	LSM-CCPM-BIM	(Salama et al. 2016)

Table6. scheduling methods' functionalities

ID	Functionalities
F1	Improving the reliability of the planning
F2	Increasing productivity
F3	Considering the continuous flow of work
F4	Decreasing workflow variability
F5	Analyzing constraints more effectively
F6	Visualizing the status of work-in-progress
F7	Visualizing the schedules to understand and communicate content to a variety of stakeholders
F8	Avoiding omissions and sequencing mistakes
F9	Analyzing schedule constructability
F10	Increasing teamwork, and communication between all stakeholders
F11	Identifying and elimination wastes
F12	Decreasing meeting durations
F13	Enhancing the performance of construction project management
F14	Detecting and solving spatiotemporal conflicts
F15	Improving managerial practices
F16	Considering Supply chain instability
F17	Improving predictability
F18	understanding of the subprocesses more accurately
F19	Managing uncertainties
F20	Considering contractual requirement
F21	Managing work density
F22	Maintaining continuity of resources
F23	Automatically determines the resources quantities
F24	Scheduling of modular and offsite construction
F25	Improving the understanding of the project's progress
F26	Filling gaps related to delay analysis
F27	Applying analytical method
F28	Supporting human decision making
F29	Improving production tracking, forecasting and control
F30	Eliminating the root causes of variability
F31	Integrating offsite and onsite planning for modular and offsite construction
F32	Understanding the behaviour of the performance indicators
F33	Linking the supply chain and construction process
F34	Testing research hypotheses and improving understanding of the schedule
F35	Automating the generation of schedule
F36	Reducing of production cycle time
F37	Improving the usability of the 4D BIM for workflow analyses
F38	Increasing safety on construction sites
F39	Increasing transparency
F40	Enabling the coordination of the look-ahead plans
F41	Promoting the reliability of the Commitment Plan
F42	Providing more valuable handouts to the planning meetings' participants
F43	Implementing of pull flow control
F44	Applying creativity techniques to planning and scheduling

Table 7. Statistical test results on the simplified analysis and SNA

	Simplified Analysis	SNA
Mean	0.381	0.469
Variance	0.046	0.0640
Standard Deviation	0.214	0.253
Pearson Correlation	0.845	