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THÈSE

présentée et soutenue publiquement le 25 Octobre 2024 pour

l'obtention du grade de

Docteur de l' Université de Lorraine

(mention **Automatique**, Traitement du signal et des images, Génie informatique)

par

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Planification et contrôle multi-niveaux et collaboratifs des chantiers de construction à l'aide de la BIM et du Lean

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DEDICATION

I dedicate this thesis to:

My precious gem, my lifelong companion, and my beloved partner, Nazanin. You have revealed to me the true essence of love and have profoundly transformed my life. Your presence fills my heart with joy each time I see you. Thank you for being my soul mate and for surrounding me with your love. Without your love, sacrifice, patience, and support over the past years, this would not have been possible.

My parents (Ezzatollah & Shokoufeh), my sister, my brothers and my in-law family. Your unconditional love and support have been my driving force.

My beloved grandfather, Azizollah, whose endless love and support remain with me always, even though he is no longer here. His memory continues to inspire me every day.

ACKNOWLEDGMENTS

This dissertation marks the conclusion of my PhD journey. Completing this endeavour would not have been possible without the support and assistance of several individuals, whom I would like to acknowledge.

First and foremost, I would like to express my deepest gratitude to my thesis exceptional supervisor, **Prof. Hind BRIL EL HAOUZI**. Your invaluable guidance, endless support, and expertise have been instrumental in the completion of this thesis. Your insightful feedback and constant encouragement have profoundly shaped my research journey. I would also like to express my gratitude to my co-supervisors, **Dr. Alexis Aubry** and **Prof. Farook Hamzeh**, for their understanding, trust, innovative ideas, and guidance. Their support and encouragement have introduced me to new perspectives on conducting and developing research, making the entire process thoroughly enjoyable. Their invaluable experience and insights were crucial to the completion of this research, shaping both its outcomes and my development as a researcher.

I am also grateful to the **IAEM Doctoral School** for awarding me the DrEAM program scholarship, and to the **CRAN Laboratory** for providing funding through the 2024 incentives program. These opportunities enabled me to spend six months as a visiting researcher at the Engineering School of the University of Greenwich, UK. This experience has been invaluable, allowing me to immerse myself in a vibrant academic environment, engage with esteemed faculty members, and facilitate the exchange of knowledge and ideas with fellow researchers. I am grateful to the Engineering School of the University of Greenwich for their hospitality and support during my visit. I extend my heartfelt thanks to **Dr. Mohammad Sakikhales**, **Dr. Nnedinma Umeokafor**, **Dr. Wim J.C. Melis**, and **Dr. Ahmed Elamin** for their invaluable guidance and assistance.

I would like to extend my gratitude to the committee members of this thesis for their valuable time and dedication, particularly acknowledging **Prof. Robert Pellerin** and **Prof. Élise Vareilles**, for agreeing to review this thesis as well as **Prof. Hervé Panetto**, **Dr. Qian Chen**, and **Prof. Farzad Rahimian** for agreeing to serve as examiners for this thesis. I am deeply thankful to **Prof. Hervé Panetto** and **Dr. Demesure Guillaume** for their generous time and recommendations as members of my thesis monitoring committee over the past three years.

I would also like to express my appreciation to my colleagues and friends at CRAN laboratory, Epinal office, particularly **Dr. Emmanuel Zimmermann**. Working alongside you all has been a privilege, enriching my journey with your presence and collaboration. Thank you for your invaluable contributions.

I am thankful to all the co-authors who collaborated on the published papers during the course of this thesis, generously sharing their time and invaluable insights. Special appreciation goes to **Prof. Farzad Rahimian**, **Dr. Mohammad Sakikhales**, and **Dr. Mani Poshdar**.

This research was conducted at the Nancy Automation Research Center (CRAN) laboratory with financial support from the National Research Agency of France (ANR-20-CE10-0011) for the ISoBIM project. I would like to express my gratitude to the **National Research Agency of France (ANR)** for their financial support and to the **CRAN laboratory** for providing the facilities and making this research possible.

I also extend my gratitude to all academic and industry professionals whose contribution, insightful suggestions, and generous time for interviews and data collection have been invaluable to this study.

Finally, I am indebted to my wife, family, friends, and colleagues who have been a constant source of support and motivation to progress through this academic journey—thank you all.

Abstract

The effective management of construction projects is essential due to their inherent complexity and substantial financial implications. In this regard, the project planning and control domain plays a vital role in successful project execution, which requires data-driven and knowledge-based decisions to navigate these complexities and ensure successful project outcomes. Despite the presence of various planning and control systems, ineffective planning and control remain major causes of low productivity, budget overruns, and delays in construction projects. Integrating existing planning and control systems can address these issues by aggregating the advantages of each. However, a significant gap exists due to the lack of a multi-level and integrated framework that combines different planning methods and control metrics across various schedule levels, leveraging the strengths of each to offer a more effective solution. Furthermore, there is a deficiency in data-driven and knowledge-based systems that address the specific needs and applications of project teams regarding a planning and control system, proposing optimized multi-level solutions. This study aims to bridge this gap by first developing a multi-level and integrated framework for project planning and control. Subsequently, it develops and implements a data-driven and knowledge-based decision support system (DSS) that leverages a knowledge database built from experts' experiences. This system proposes multi-level and integrated solutions for the planning and control of construction projects, enhancing both theoretical frameworks and practical applications. The developed DSS simplifies the decision-making process by posing straightforward and relevant questions tailored to the project team's requirements, thereby suggesting the most suitable approaches for project planning and control. The developed framework and decision support system were validated by applying them to a renovation case study and receiving positive feedback from experts.

Eventually, a detailed methodological guideline was crafted to facilitate the implementation of the DSS-recommended multi-level planning and control system for renovation projects. This guideline offers clear, step-by-step instructions to ensure straightforward adoption and effective integration into project management practices. This versatile tool can be applied across various project types during the preconstruction phase, determining the most effective planning and control strategies based on the functional requirements of the project team.

Keywords: Multi-level framework, Decision support system, Planning and control system, Knowledge repository, Mathematical model, Functionality

Résumé

La gestion efficace des projets de construction est essentielle en raison de leur complexité inhérente et des implications financières substantielles. À cet égard, la planification et le contrôle des projets jouent un rôle crucial dans la réussite de l'exécution des projets, nécessitant des décisions basées sur les données et les connaissances pour naviguer dans ces complexités et garantir des résultats positifs. Malgré la présence de divers systèmes de planification et de contrôle, une planification et un contrôle inefficaces restent des causes majeures de faible productivité, de dépassements de budget et de retards dans les projets de construction. L'intégration des systèmes de planification et de contrôle existants peut remédier à ces problèmes en agrégant les avantages de chacun. Cependant, un écart significatif subsiste en raison de l'absence d'un cadre intégré et multi-niveaux combinant différentes méthodes de planification et métriques de contrôle à travers divers niveaux d'échéancier, tirant parti des forces de chacun pour offrir une solution plus efficace. De plus, il existe une insuffisance de systèmes basés sur les données et les connaissances qui répondent aux besoins spécifiques et aux applications des équipes de projet en matière de planification et de contrôle, proposant des solutions multi-niveaux optimisées. Cette étude vise à combler cette lacune en développant d'abord un cadre intégré et multi-niveaux pour la planification et le contrôle des projets. Ensuite, elle développe et met en œuvre un système d'aide à la décision (SAD) basé sur les données et les connaissances, qui exploite une base de connaissances construite à partir des expériences des experts. Ce système propose des solutions multi-niveaux et intégrées pour la planification et le contrôle des projets de construction, améliorant à la fois les cadres théoriques et les applications pratiques. Le SAD développé simplifie le processus de prise de décision en posant des questions simples et pertinentes adaptées aux besoins de l'équipe de projet, suggérant ainsi les approches les plus appropriées pour la planification et le contrôle des projets. Le cadre et le système d'aide à la décision développés ont été validés en les appliquant à une étude de cas de rénovation et en recevant des retours positifs de la part des experts.

Enfin, une directive méthodologique détaillée a été élaborée pour faciliter la mise en œuvre du système de planification et de contrôle multi-niveaux recommandé par le SAD pour les projets de rénovation. Cette directive offre des instructions claires et étape par étape pour assurer une adoption simple et une intégration efficace dans les pratiques de gestion de projet. Cet outil polyvalent peut être appliqué à divers types de projets durant la phase de préconstruction, déterminant les stratégies de planification et de contrôle les plus efficaces en fonction des exigences fonctionnelles de l'équipe de projet.

Mots-clés : Cadre multi-niveaux, Système d'aide à la décision, Système de planification et de contrôle, Référentiel de connaissances, Modèle mathématique, Fonctionnalité

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ABBREVIATIONS

4DBIM	Four-Dimensional Building Information Modelling
4D-DT	4D-Digital Twins
4D-VR	4D-Virtual Reality
AACE	Association for the Advancement of Cost Engineering
ABM	Agent-based Modeling
AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
AR	Augmented Reality
AWP	Advanced Work Packaging
BEP	BIM Execution Plan
BERT	Bidirectional Encoder Representations from Transformers
BIM	Building Information Modelling
BPMN	Business Process Modeling Notation
CCPM	Critical Chain Project Management
CII	Construction Industry Institute
CL	Commitment Level
CLR	Capacity to Load Ratio
CMAA	Construction Management Association of America
CMF	Control Metrics' Functionalities
CPI	Collaborative Planning Index
CPI	Cost Performance Index
CPM	Critical Path Method
CPT	Constraint Processing Time
CRAN	Nancy Automation Research Center
CS	Collaborative Scheduling
CU	Completed Uncommitted
DB	Design-Build
DC	Degree Centrality
DES	Discrete Event Simulation
DSR	Design Science Research
DSS	Decision Support System
DT	Digital Twin
EP	Efficiency Parametric
EVM	Earned Value Management
FMEA	Failure Mode and Effects Analysis
GA	Genetic Algorithms
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
IoT	Internet of Things
IPD	Integrated Project Delivery
IQR	Interquartile Range
IVR	Immersive Virtual Reality
JIT	Just in Time

LBMS	Location Based Management System
LBP	Location Based Planning
LHS	Left Hand Side
LOB	Line of Balance
LOD	Level of Development
LPS	Last Planner System
LRI	Location Risk Index
LSM	Linear Scheduling Methods
MIPRI	Multi-level and Integrated Method-Process-Responsible role-Information
MPCS-DSS	Multi-level Planning and Control System Decision Support System
MV	Milestone Variance
NLP	Natural Language Processing
PCN	Percent Complete New
PDCA	Plan-Do-Check-Act
PPC	Percent Planned Complete
PRCO	Percent Required Complete and Ongoing
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSO	Particle Swarm Optimization
RCR	Required Capacity Ratio
RFID	Radio-Frequency Identification
RFP	Realized Flow Potential
RHS	Right Hand Side
RL	Required Level
RPN	Risk Priority Number
RST	Rough Set Theory
SA	Simulated Annealing
SBERT	Sentence-Bidirectional Encoder Representations from Transformers
SD	System Dynamic
Simplified Analysis	SA
SM	Simulation-based Methods
SMEs	Small and Medium-sized Enterprises
SMOTE	Synthetic Minority Oversampling Technique
SNA	Social Network Analysis
SP	Stability Parametric
SPI	Schedule Performance Index
STS	Semantic Textual Similarity
TA	Task Anticipated
TCM	Tri-Constraint Method
TMR	Tasks Made Ready
TTP	Takt Time Planning
UAV	Unmanned Aerial Vehicles
VDC	Virtual Design and Construction
VP	Value Parametric
VR	Virtual Reality

WAM	Weighted Adjacency Matrix
WFP	Workforce Planning
WoS	Web of Science
WWP	Weekly Work Plan

GLOSSARY

Collaborative planning	Collaborative Planning is a comprehensive process in which all key stakeholders actively participate, working together to develop a unified project schedule. It emphasizes open communication, mutual understanding, and collective decision-making, ensuring that each party's insights and expertise contribute to a realistic and achievable plan. By fostering collaboration, this approach leads to improved project outcomes through better coordination, alignment of goals, and shared ownership of the project's success .
Integrated planning and control	Integrated planning and scheduling is an approach that combines various planning and scheduling methods to overcome their individual limitations. This integration aims to create a more efficient and cohesive planning and scheduling system for effective construction site management.
Lean-based planning and control	Lean-based planning and control is an approach that aims to minimize waste and maximize value by enhancing efficiency, collaboration, and flow throughout the construction process. This methodology utilizes systems such as the Last Planner System (LPS), Takt time planning and control, and Location-based Management Systems (LBMS) to optimize resource allocation and scheduling. By focusing on continuous improvement and real-time project conditions, lean planning and control ensure that each activity adds value while reducing delays and non-essential tasks, ultimately enhancing overall project performance.
Multi-level planning and control	Multi-level planning and control refers to a hierarchical approach where planning methods and control metrics are aligned across different levels of the project schedule. This structured framework ensures that higher-level strategic plans seamlessly integrate with detailed, operational schedules. By aligning planning and control across these levels, it enables more effective decision-making, improves coordination, and enhances project performance through better visibility of progress and risks at various stages.
Single planning methods	Single planning methods refer to widely used techniques in the construction industry, such as CPM (Critical Path Method), CCPM (Critical Chain Project Management), LSM (Linear Scheduling Method) , LOB (Line of Balance), AWP (Advanced Work Packaging), LPS (Last Planner System), LBMS (Location-Based Management System), and TTP (Takt Time Planning). Each method has its advantages and disadvantages, and there is no one-size-fits-all solution for all scheduling levels. Each method can offer valuable contributions to the planning process, depending on the specific context and requirements of the project.

Résumé de la thèse

Le secteur de la construction est en proie à des inefficacités chroniques, telles qu'une faible productivité, un gaspillage important, des dépassements de coûts et des retards dans les délais. L'un des principaux facteurs à l'origine de ces problèmes est la fragmentation et l'inefficacité des méthodes de planification et de contrôle. De plus, la gestion efficace des projets de construction est cruciale en raison de leur complexité et de leurs implications financières importantes. Dans ce contexte, le domaine de la planification et du contrôle des projets joue un rôle essentiel dans l'exécution réussie des projets, nécessitant des décisions fondées sur des données et des connaissances pour naviguer dans ces complexités et garantir des résultats favorables. Une analyse de la littérature et du retour d'information des experts révèle une lacune importante due à un manque de compréhension des différentes méthodologies de planification et de contrôle par les parties prenantes du projet. En outre, malgré la mise en œuvre de divers systèmes de planification et de contrôle, il subsiste une lacune importante due à l'absence d'un système fondé sur les données et les connaissances qui prenne en compte les besoins et les applications spécifiques de l'équipe du projet, suggérant ainsi une solution optimisée. Pour relever ces défis, cette thèse explore le développement d'un système intégré de planification et de contrôle à plusieurs niveaux pour les chantiers de construction, en utilisant la modélisation des données du bâtiment (BIM) et les principes de la construction allégée. Utilisant une méthodologie de recherche en science de la conception comme cadre général, cette étude adopte une approche mixte, incorporant des analyses documentaires systématiques, l'analyse de documents, l'analyse de contenu, l'analyse de réseaux sociaux (ou Social Network Analysis - SNA en anglais), la similarité textuelle sémantique, l'analyse de regroupement, des entretiens avec des experts, la théorie des ensembles rugueux et la modélisation mathématique pour atteindre ses objectifs.

Tout d'abord, une analyse documentaire approfondie combinée à une analyse quantitative des réseaux sociaux a été menée pour définir les systèmes de planification et de contrôle existants, en clarifiant leurs concepts fondamentaux. Cela a permis de mieux comprendre les objectifs et les fonctionnalités essentiels pour les équipes de projet. Cette phase a abouti à l'identification et à l'analyse de 26 méthodes de planification intégrée, 82 mesures de contrôle et 10 techniques de planification collaborative basées sur les processus et la technologie, ainsi que 148 objectifs associés appelés fonctionnalités des systèmes de planification et de contrôle dans cette étude. Compte tenu de l'ampleur des 148 fonctionnalités identifiées, une réduction était nécessaire pour distiller les concepts fonctionnels essentiels des systèmes de planification et de contrôle. À cette fin, le traitement du langage naturel - en particulier la similarité sémantique textuelle associée au regroupement hiérarchique - a été déployé comme méthode optimale pour identifier les principaux concepts de fonctionnalité et les organiser en une taxonomie à travers différents niveaux de planification. Cet effort a abouti à

l'identification et à la catégorisation de 20 concepts de fonctionnalité clés au sein d'une taxonomie des fonctionnalités des systèmes de planification et de contrôle des projets. Au cours de la phase suivante de la recherche, un concept de fonctionnalité générale - la prise de décision guidée par l'information - a été exclu afin d'affiner davantage la focalisation, laissant 19 groupes de fonctionnalités comme objectifs principaux des systèmes de planification et de contrôle. En suivant les étapes clés de la méthode de recherche en science de la conception - identification du problème, conception de l'artefact, développement et validation - des entretiens semi-structurés ont été menés pendant six mois, recueillant les commentaires de dix experts du monde universitaire et de l'industrie dans les domaines de la planification et du contrôle de projets. Ce processus complet a conduit à l'élaboration d'un cadre intégré de planification et de contrôle à plusieurs niveaux, marquant ainsi une avancée significative dans ce domaine.

Sur la base du cadre proposé et des fonctionnalités identifiées, un système d'aide à la décision (DSS) a été conçu, développé et mis en œuvre. Pour ce faire, un diagramme relationnel des principaux composants du cadre multi-niveaux a été créé, servant de base à la conception d'une enquête pour la collecte de données. Grâce à un échantillonnage raisonné, 23 experts ont participé à des entretiens semi-structurés pour la collecte des données. Après environ 23 heures de collecte de données, des techniques de prétraitement, y compris le traitement des valeurs aberrantes à l'aide de la méthode de l'intervalle interquartile (IQR) et le traitement des ensembles de données déséquilibrés à l'aide de la technique de suréchantillonnage synthétique des minorités (SMOTE), ont été appliquées afin d'améliorer la qualité des données pour les analyses ultérieures.

La théorie des ensembles approximatifs (RST), une méthode qui traite les incertitudes dans les données d'entrée, a été sélectionnée pour la génération de règles et la construction d'un référentiel de connaissances pour le DSS. Cette étude a utilisé le paquet R.ROSETTA dans le langage de programmation R pour mettre en œuvre la RST et les processus de découverte de connaissances. À la suite du processus de génération et de validation des règles à l'aide de la méthodologie RST, un ensemble de 2 280 règles a été formulé. Ces règles ont été exprimées sous forme d'énoncés individuels ou de combinaisons d'énoncés liés par des conditions « ET » ou « OU » et ont été classées en trois catégories distinctes : les méthodes de planification, les mesures de contrôle et les niveaux de calendrier. La base de données résultante a servi de référentiel de connaissances pour les systèmes de planification et de contrôle des projets.

Pour mettre en œuvre le moteur d'inférence et l'activation des règles, une approche de chaînage avant a été employée en utilisant le moteur de connaissances Pyke en Python. En outre, une interface utilisateur a été conçue pour recueillir les exigences de l'équipe de projet et afficher les résultats, formant ainsi un système de planification et de contrôle à plusieurs niveaux. En outre, un modèle mathématique multi-objectif a été développé pour optimiser les résultats du DSS et proposer un système intégré et multi-niveaux de planification et de contrôle des projets de construction. L'objectif était de minimiser le nombre de méthodes de planification et de mesures de contrôle à chaque niveau du calendrier pour une mise en œuvre pratique tout en répondant aux exigences maximales de l'équipe de projet.

Pour évaluer la validité, l'utilité et la praticité de la solution, deux approches ont été adoptées. Tout d'abord, une étude de cas a été menée dans le cadre du projet IsoBIM afin de démontrer la praticité du DSS et du modèle mathématique en proposant un système de planification et de contrôle à plusieurs niveaux pour un projet de rénovation. Deuxièmement, des mesures

quantitatives de performance provenant d'enquêtes de satisfaction ont été utilisées pour une évaluation générale.

La mise en œuvre du DSS pour l'étude de cas sur la rénovation a permis d'activer et de déclencher 59 des 2 280 règles stockées dans la base de données de connaissances. Sur la base des règles activées, 4DBIM, la planification du temps de cycle et le dernier système de planification ont été suggérés comme méthodes de planification pour les trois niveaux de calendrier. En outre, MV, PPC, RL et CLR ont été proposés comme mesures de contrôle conformes aux exigences de contrôle du projet. Cette activation a mis en évidence la capacité dynamique du moteur d'inférence à appliquer sélectivement les règles pertinentes en fonction des exigences contextuelles de l'équipe de projet.

Après l'activation des règles, le modèle mathématique a été utilisé pour proposer des solutions optimisées à différents niveaux de programmation, guidées par les résultats du DSS. Les résultats du modèle mathématique ont été illustrés par des diagrammes de Pareto, ce qui a permis à l'équipe du projet de sélectionner les solutions les mieux adaptées aux exigences spécifiques posées par les différentes conditions du projet. Pour le système optimisé de planification et de contrôle à plusieurs niveaux de l'étude de cas, au niveau à long terme, deux méthodes de planification - 4DBIM et planification du temps takt - ainsi qu'une mesure de contrôle - variance de jalon (MV) - ont été choisies. Au niveau du calendrier à moyen terme, la planification en temps réel et le dernier système de planification ont été choisis comme méthodes de planification, tandis que l'indice de risque de localisation (LRI) et la tâche rendue prête (TMR) ont été considérés comme des mesures de contrôle basées sur les circonstances du projet. Dans la planification à court terme, la planification du temps de cycle et le système du dernier planificateur ont à nouveau été sélectionnés comme méthodes de planification, complétés par le pourcentage d'achèvement prévu (PPC) et le rapport capacité/charge (CLR) comme mesures de contrôle. Cette intégration de diverses méthodes de planification et de mesures de contrôle proposées sur trois niveaux d'ordonnement fonctionne comme un système intégré à plusieurs niveaux pour la planification et le contrôle des projets. L'évaluation générale du système indique que cette approche améliore considérablement l'efficacité de la réalisation des objectifs du projet.

En conclusion, cette étude a adopté une approche fondée sur les données et les connaissances par le biais d'un processus complet et intégré qui s'appuie sur une méthodologie mixte pour extraire et utiliser l'expertise des professionnels de la construction. En combinant les observations qualitatives des experts du secteur et l'analyse des données quantitatives, la recherche a permis de mettre au point un solide système d'information de gestion. Cette approche a permis de s'assurer que les expériences pratiques et les connaissances des ingénieurs étaient systématiquement saisies et appliquées, ce qui a conduit à des solutions de gestion de projet plus précises, plus fiables et plus adaptables. Afin de mettre en œuvre avec succès la solution proposée pour l'étude de cas, une ligne directrice méthodologique a été élaborée, présentant les détails requis, y compris les processus et les flux de travail, les rôles et les responsabilités, et les informations pour la mise en œuvre de la solution DSS. Cette recherche représente une avancée significative dans l'application des systèmes d'aide à la décision dans la gestion de la construction. Elle fournit un cadre solide pour améliorer les résultats des projets grâce à des systèmes de planification et de contrôle intégrés et à plusieurs niveaux. Les implications de cette recherche sont profondes et sont prêtes à avoir un impact sur les pratiques actuelles et les innovations futures dans l'industrie de la construction.

La principale contribution de cette recherche réside dans l'intégration d'approches basées sur les données et les connaissances afin de développer une approche robuste basée sur des modèles pour remédier à l'inefficacité des systèmes de planification et de contrôle. Cette stratégie multidisciplinaire combine diverses méthodes et techniques pour créer un système avancé d'aide à la décision pour la planification et le contrôle des projets de construction. En combinant ces diverses approches, la recherche contribue à l'élaboration d'un cadre global qui exploite à la fois des données quantitatives et qualitatives. Cette approche holistique représente une avancée significative dans le domaine, offrant une nouvelle méthodologie qui comble le fossé entre les idées basées sur les données et les connaissances des experts. En outre, cette recherche fait progresser de manière significative les connaissances théoriques et les applications pratiques dans le domaine de la planification et du contrôle des projets et de la production dans le secteur de la construction, grâce aux contributions clés suivantes :

1. Identification et analyse des méthodes de planification et des mesures de contrôle et de leurs objectifs

- Contribution à la connaissance : L'identification et l'analyse systématiques des méthodes de planification simples, intégrées et collaboratives, ainsi que de diverses mesures de contrôle, enrichissent la littérature existante en fournissant une compréhension complète de leurs applications, de leurs principaux objectifs (fonctionnalités) et de leurs interrelations.
- Contribution à la pratique : Les gestionnaires de construction peuvent tirer parti de ces connaissances pour mieux comprendre et mettre en œuvre des systèmes de planification et de contrôle plus robustes et intégrés, adaptés aux besoins spécifiques de leurs projets.

2. Conceptualisation et développement d'une taxonomie des concepts sous-jacents des systèmes de planification et de contrôle

- Contribution à la connaissance : Cette recherche présente une nouvelle méthodologie qui combine la similarité textuelle sémantique et l'analyse de regroupement avec les opinions des experts du domaine pour développer une taxonomie des concepts de planification et de contrôle. Cette approche innovante permet non seulement d'améliorer la compréhension de ces concepts, mais aussi de jeter des bases solides pour de futures recherches universitaires. En catégorisant systématiquement les concepts sous-jacents, cette taxonomie facilite l'utilisation plus efficace des méthodes de planification à plusieurs niveaux par les parties prenantes du projet et sert de référence précieuse pour les chercheurs qui explorent des domaines similaires.
- Contribution à la pratique : Les acteurs du projet peuvent utiliser cette taxonomie pour mieux comprendre et appliquer efficacement diverses méthodes de planification à plusieurs niveaux, améliorant ainsi la gestion et l'exécution globales du projet.

3. Développement d'un cadre intégré de planification et de contrôle à plusieurs niveaux

- Contribution à la connaissance : Le cadre intégré à plusieurs niveaux développé dans cette étude offre des avancées théoriques significatives pour les pratiques

de gestion de la construction. En harmonisant diverses méthodes de planification et mesures de contrôle à différents niveaux du calendrier, ce cadre répond aux défis pressants de l'industrie tels que l'inefficacité des systèmes de planification et de contrôle et l'alignement insuffisant sur les besoins fonctionnels des équipes de projet. En outre, l'incorporation innovante de caractéristiques internes et externes, ainsi que l'utilisation d'un modèle mathématique multi-objectif pour l'optimisation, représentent une contribution substantielle au corpus de connaissances. Cette méthodologie permet non seulement de mieux comprendre la planification et le contrôle à plusieurs niveaux, mais aussi de jeter des bases solides pour les recherches futures dans ce domaine.

- Contribution à la pratique : L'application pratique de ce cadre, validée par une étude de cas de rénovation, démontre sa valeur stratégique et son efficacité dans des scénarios réels. En outre, le cadre développé peut servir de base à un outil de système d'aide à la décision qui suggère un système de planification et de contrôle des projets de construction adapté aux besoins spécifiques des équipes de projet. L'adoption de ce cadre peut conduire à une amélioration de la prise de décision et à une approche plus systématique, transparente et proactive de la gestion des projets de construction.

4. Conception, développement et mise en œuvre d'un système d'aide à la décision

- Contribution à la connaissance : L'adoption d'une méthodologie précise et complète pour la gestion des connaissances, le développement d'un système d'aide à la décision et l'optimisation des résultats représente une avancée théorique significative. Cette approche comprend l'application de la théorie des ensembles rugueux pour gérer l'incertitude dans la formulation des données et des connaissances, la mise en œuvre d'un moteur d'inférence pour améliorer les processus décisionnels et le développement d'un modèle mathématique multi-objectif pour l'optimisation. L'ensemble de ces éléments jette les bases d'études ultérieures en fournissant un cadre robuste qui peut être adapté et étendu à divers contextes dans le domaine de la gestion de la construction et au-delà.
- Contribution à la pratique : Le système d'aide à la décision aide les gestionnaires de projet à sélectionner les approches de planification et de contrôle les plus appropriées en fonction des besoins spécifiques du projet, améliorant ainsi les processus de prise de décision et les résultats du projet.

5. Guide méthodologique pour les projets de rénovation

- Contribution à la connaissance : Grâce à l'analyse de diverses lignes directrices en matière de planification et de contrôle de projets, combinée au retour d'information d'experts dans ce domaine, cette étude a permis d'identifier et d'extraire les éléments essentiels nécessaires à une ligne directrice méthodologique solide. Une procédure rigoureuse comprenant plusieurs étapes clés a été adoptée pour établir cette ligne directrice, qui vise à aider l'industrie à mettre en œuvre un système de planification et de contrôle de projet intégré et à plusieurs niveaux. Les processus détaillés, les étapes, les activités, les informations requises et les rôles des parties prenantes inclus dans la ligne directrice clarifient sa mise en œuvre, garantissant qu'elle est à la fois complète

et pratique. Cette avancée méthodologique contribue de manière significative au corpus de connaissances en offrant une approche structurée qui peut être utilisée et développée par les universitaires et les praticiens.

- Contribution à la pratique : Les praticiens impliqués dans des projets de rénovation peuvent suivre ce guide pour mettre en œuvre des stratégies de planification et de contrôle efficaces, garantissant ainsi une meilleure gestion et l'achèvement réussi du projet.

Chapter 1. Introduction

1.1. Background and Motivation

The construction industry is a significant contributor to enhancing quality of life and serves as a crucial pillar in both global and national economies. The industry represents 13% of the global gross domestic product (GDP) and is projected to increase to 13.5% by 2030 (Oxford Economics 2021). In 2021, the construction market was valued at \$7.28 trillion, with the capacity to employ over 180 million people worldwide (Business Wire 2022; Chui and Mischke 2019).

Despite its critical importance, the construction industry faces substantial challenges. According to McKinsey's study (Changali et al. 2015), 98% of construction projects exceed their budgets by more than 30%, and 77% are at least 40% behind schedule. Furthermore, within the national context, France has also faced these challenges. In 2018, 29% of home buyers in France experienced an average delay of 5.4 months in the delivery of their homes, and 47% were dissatisfied with the quality of the workmanship. Additionally, the French construction sector is responsible for 20-25% of the country's total greenhouse gas emissions (GHG) (Michel and Rivaton 2021).

Low productivity, predictability, and profitability, insufficient knowledge management and learning, resistance to change (Sawhney et al. 2020a), inefficient stakeholder collaboration, and ineffective planning, scheduling, and control (AlNasseri and Aulin 2015) are among the key factors aggravating these challenges. These issues collectively contribute to the significant increases in project costs and time. Over the past decades, a wide variety of planning and control methods and tools have been developed and implemented to address these challenges. The critical path method (CPM) represents one of the earliest techniques conceived for project planning, scheduling, and control (Kelley Jr and Walker 1959). Despite its widespread adoption and the fact that it remains a standard requirement in many countries—often mandated by project owners for scheduling purposes (Olivieri et al. 2016)—several concerns have been raised about its limitations. These concerns include a limited focus on schedule workflow, an emphasis on project control over production control, insufficient 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). To address these challenges, various systems such as advanced work packaging (AWP) and workforce planning (WFP) (Hamdi 2013), scrum and kanban (Sakikhales 2021), critical chain project management (CCPM) (Raz et al. 2003), location-based planning (LBP) (Arditi and Albulak 1986), last planner system (LPS) (Ballard and Tommelein 2021), takt time planning (TTP) (Frandsen and Tommelein 2014), location-based management system

(LBMS) (Seppänen et al. 2014), and four-dimensional building information modelling (4DBIM) (Sheikhhoshkar et al. 2024b) have been developed. These systems contribute to the body of project and production planning and control knowledge by enhancing communication and collaboration, standardizing workflows, improving resource utilization, optimizing scheduling and logistics, and facilitating continuous improvement, among other benefits. Furthermore, these systems have been integrated with each other and with additional methods to enhance their effectiveness and address the inherent shortcomings of each, resulting in hybrid systems such as BIM-LPS-Kanban (Sacks et al. 2010; Schimanski et al. 2021b), CCPM-LPS-LSM (Salama et al. 2021), LBMS-LPS-CPM (Olivieri et al. 2016), 4DBIM-LPS-LBMS (Silveira and Costa 2023), LPS-LBMS (Dave et al. 2016), and 4DBIM-LPS (Lin and Golparvar-Fard 2021), among others.

Moreover, recent technological advancements, particularly within the framework of Industry 4.0, have spurred numerous studies aimed at enhancing planning and control systems. Notably, virtual reality (VR) (Boton 2018; Rashidi et al. 2023), digital twins created and continuously updated through the integration of artificial intelligence (AI), the internet of things (IoT), machine learning, and cognitive computing (Alizadehsalehi and Yitmen 2023), multi-user VR (Truong et al. 2021), touch table and touch wall screens (Boje et al. 2022), and web-based platforms (Lin and Golparvar-Fard 2016) have emerged and contributed as key technologies integrated with planning methods. These technologies achieve a variety of goals, such as identifying sequencing and planning issues, improving project and process understanding, performing constructability analysis, enhancing safety and disaster management, optimizing resource allocation, decentralizing work tracking and information sharing on construction sites, enabling collaborative interactions among team members and stakeholders in a unified environment, adopting a user-centric approach, and collaborative planning.

These advancements extend beyond merely enhancing planning methods. Efforts have also been directed towards the establishment and utilization of control systems such as earned value management (EVM) (Sheikhhoshkar et al. 2024c), buffer control (Zhang et al. 2018), and lean-driven control frameworks (Hamzeh et al. 2019b). These systems are essential for the continuous monitoring and analysis of project performance, efficiency, and other dynamic factors, including resource allocation efficiency, construction flow quality, constraint removal, labor productivity, and commitment quality.

Despite the development of numerous individual and integrated planning and control systems, project teams continue to face challenges in achieving a fit-for-purpose solution. The primary causes of this issue are cited as insufficient understanding, familiarity, and information about the applicability and efficiency of these systems among on-the-ground project teams (AlNasser and Aulin 2015), as well as the lack of utilization of varied experiences from practical applications of these systems.

To effectively implement a practical system for construction site management, three essential steps must be followed. First, identify appropriate mechanisms to gain a deeper understanding of the underlying theories and concepts of various planning and control systems. Second, adopt a suitable system for project planning and control that meets the diverse functional needs of project teams and applies to a wide range of project types. Third, develop a system that leverages expert knowledge and practical experiences to propose a solution that is fit for purpose and requirements.

1.2. Problem Statement and Research Gaps

The formulation of well-grounded research questions and objectives is fundamental to all scholarly research. Various factors influence the development of these questions and objectives, including research funding, existing literature, and fieldwork experience. Sandberg and Alvesson (2011) proposed that the most prevalent method for generating research questions and objectives involves identifying gaps using a structured approach. To do so, they delineated three primary modes of gap-spotting: confusion, neglect, and application, which are employed in this research.

1. **Confusion:** This approach aims to reveal confusion in previous research. The issue may have already been investigated in the literature, but the results conflict with available evidence. The goal is to clarify and resolve these conflicting explanations.
2. **Neglect:** Highlighting neglected areas within the literature is one of the most common strategies for constructing research questions. This mode of gap analysis involves identifying and investigating overlooked or under-researched areas. Neglect spotting can be further subdivided into three categories: identifying an overlooked area, an under-researched area, and a lack of empirical support.
3. **Application:** This mode entails recognizing a new application within the existing body of knowledge. It allows researchers to formulate research questions based on the inadequacies of current theories or perspectives within a particular research area. Identifying research with insufficient coverage of existing knowledge and without innovative perspectives is the primary objective.

Through an extensive review of the literature and consultations with industry experts and companies, it has become evident that the presence of numerous single and integrated planning methods and control metrics (Dallasega et al. 2021), coupled with a lack of comprehensive understanding and knowledge of these systems among project stakeholders (AlNasseri and Aulin 2015; Salling et al. 2023), has led to significant confusion in the literature regarding the application of developed methods, systems, and tools for project planning and control considering the functional requirements of the project teams. This confusion is further reflected in practice, where selecting the most appropriate approach for specific projects remains a challenge.

Furthermore, in addressing the neglect gaps, it was discovered that a comprehensive multi-level project planning and control framework and a data-driven and knowledge-based decision support system to suggest the fit-for-purpose planning and control system in the pre-construction phase of the projects are lacking (Dallasega et al. 2021). Additionally, the low maturity level of companies, particularly small and medium-sized enterprises (SMEs), in project planning and control, lean construction, and building information modelling is often overlooked when selecting a planning and control system for a project. Moreover, the involvement of project stakeholders in the planning process is insufficiently addressed, both in practical applications and academic research.

Additionally, From the literature analysis and industry observations, several application gaps were identified. An analysis of collaborative planning and control methodologies reveals a lack of attention to the people and process-oriented approach in construction planning and control systems compared with the manufacturing applications (Shelbourn et al. 2007).

Therefore, the construction industry practices may benefit from integrating more holistic strategies that prioritize both human factors and process efficiency, aligning more closely with the proven methodologies employed in manufacturing. Moreover, there is a lack of a structured approach for knowledge extraction and repository development in this domain, as well as the absence of a methodological guideline for planning and control of renovation projects.

1.3. Research Scope

This thesis is part of the IsoBIM project, which outlines a collaborative approach for renovating buildings with external insulation, grounded in 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, thereby enhancing their efficiency and productivity. The IsoBIM framework, as depicted in Fig. 1.1, encompasses the entire renovation process, beginning with the identification of optimal renovation solutions, advancing through the formulation of configuration and layout models, dynamic data management, and culminating in the development of a multi-level and collaborative planning and control framework and guideline for construction sites, which constitutes the focus of this research.

Moreover, considering the project lifecycle, the outcomes of this research assist project teams during the pre-construction phase in selecting the most suitable planning and control system for their projects, tailored to their functional requirements. Additionally, by addressing project control aspects and suggesting control metrics for monitoring various facets of the project, this study contributes significantly to the construction phase as well.

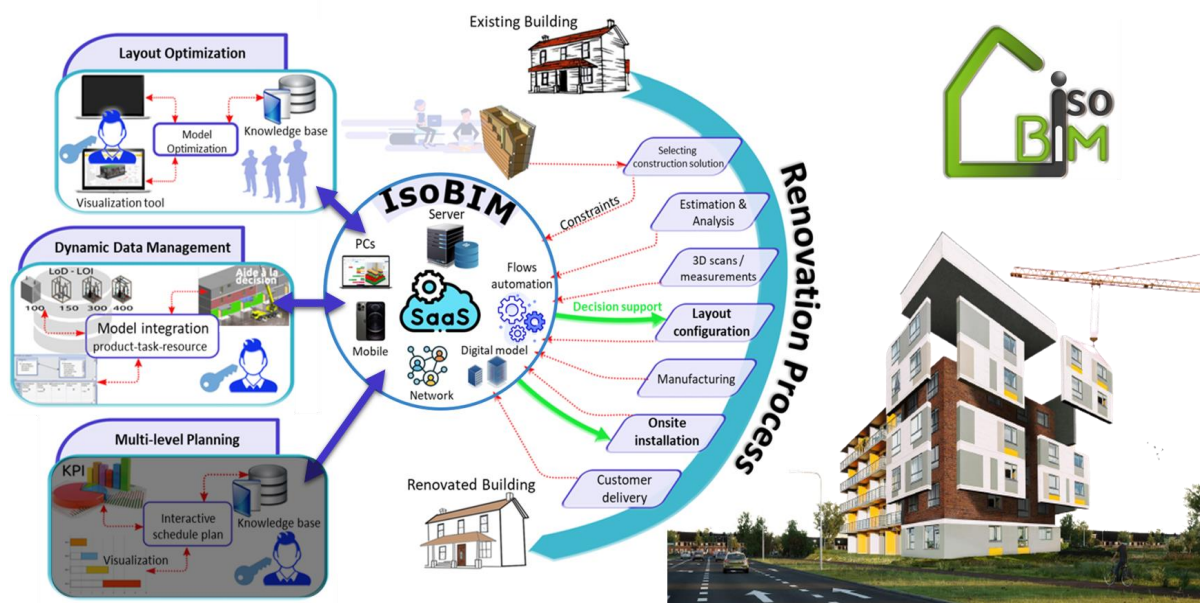


Fig. 1.1. IsoBIM project outline

1.4. Research Objectives and Methodologies

The primary goal of this research is to develop multi-level and collaborative planning and control approaches for construction site management by leveraging BIM and Lean principles. To address the identified research gaps and achieve the primary goal, this research aims to

fulfil five specific objectives, as follows:

1. To identify single, integrated, and collaborative planning methods as well as various control metrics and their functionalities
2. To conceptualize and develop a taxonomy of planning and control underlying concepts (functionalities) to better understand and more efficiently utilize planning methods at multi-level by project stakeholders
3. To propose a comprehensive methodological multi-level and collaborative planning and control framework for IsoBIM's target projects
4. To design a decision support system (DSS) for implementing the developed multi-level and collaborative planning and control framework and suggesting the best approach based on the project team needs
5. To propose a methodological guideline for implementing the suggested approach by DSS for renovation projects

The research objectives, methodologies, and outcomes are presented in Fig. 1.2. It should be noted that this thesis adopts design science research (DSR) as a guiding methodological framework. DSR is a systematic approach aimed at creating and evaluating artifacts designed to solve identified problems and contributes to theory building in a given field (Agrawal et al. 2022). Within the framework of DSR, a mixed research method was employed, encompassing a comprehensive literature review, document analysis, site observation, semi-structured interviews with domain experts, surveys, case studies, natural language processing (NLP), social network analysis (SNA), clustering analysis, knowledge management, mathematical modelling, and optimization. Each of these methods was selected and applied according to their specific objectives at various stages of the research process. This multi-methodological approach ensures a rigorous and comprehensive investigation, as illustrated in Fig. 1.2.

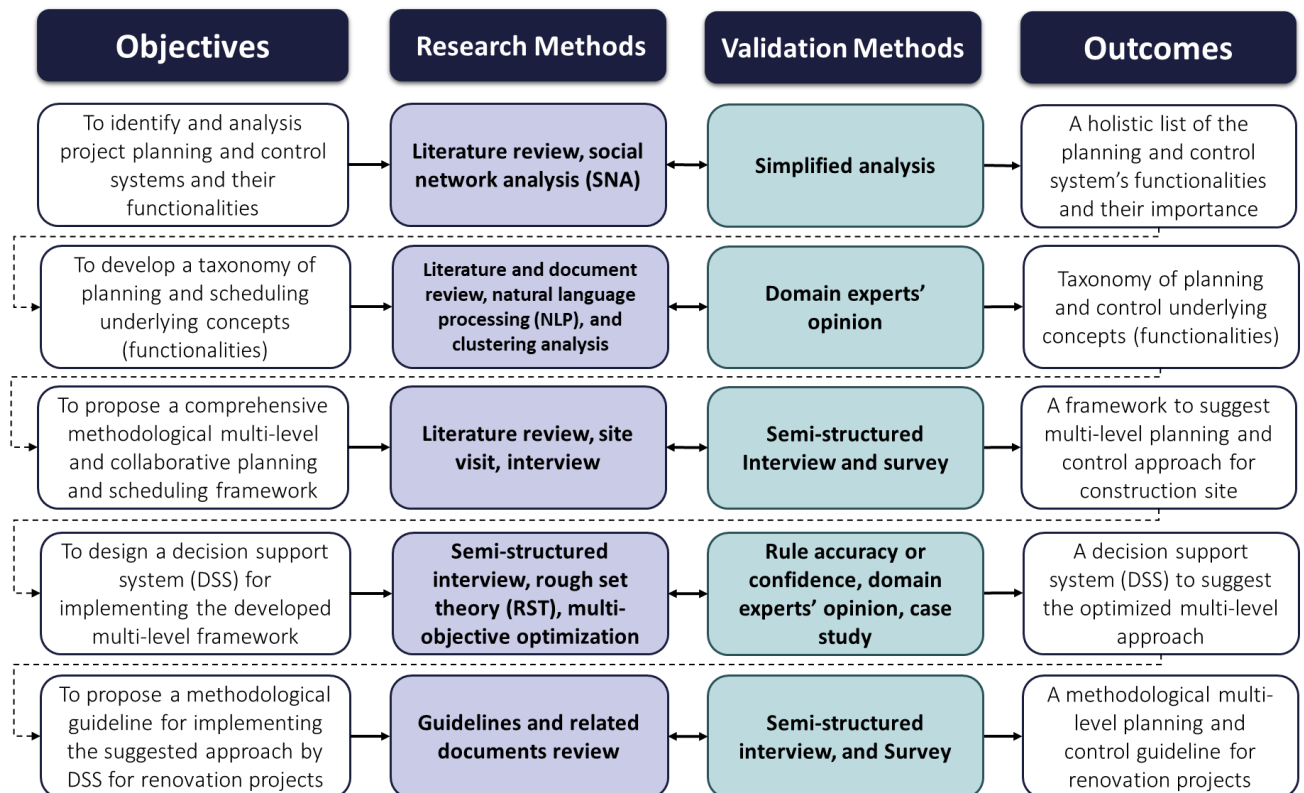


Fig. 1.2. Research objectives, methodologies, and outcomes

1.5. Research Questions

Based on the stated objectives, this thesis aims to answer the following research questions:

Questions to be answered for objective 1:

- What are the existing single, integrated, and collaborative planning methods currently used in construction site management?
- What are the metrics used to control construction projects?
- What are the underlying principles and objectives of existing planning and control systems?

Questions to be answered for objective 2:

- What are the key underlying concepts of the planning and control systems' functionalities in construction projects?
- How can these concepts be categorized into a comprehensive taxonomy to facilitate better understanding and utilization by project stakeholders?

Questions to be answered for objective 3:

- What are the essential components of a multi-level and collaborative planning and control framework?
- How can the components of the multi-level and collaborative planning and control framework be integrated?

Questions to be answered for objective 4:

- How can the DSS be tailored to implement the proposed multi-level and collaborative planning and control framework?
- How can the experts' knowledge be formalized to build a knowledge repository for a DSS?
- How can the developed knowledge repository be used to infer the most suitable planning and control system based on the project team's functional requirements?
- How can the suggestions provided by the DSS be optimized?

Questions to be answered for objective 5:

- What are the key components of a practical guideline?
- How can implement the DSS-recommended approach for a renovation project step-by-step?

1.6. Research Contribution

The primary contribution of this research lies in integrating data-driven and knowledge-based approaches to develop a robust model-driven approach for addressing inefficiency in planning and control systems, as shown in Fig. 1.3. This multidisciplinary strategy combines various methods and techniques to create an advanced decision support system for construction project planning and control. By combining these diverse approaches, the research contributes to developing a comprehensive framework that leverages both quantitative and qualitative data. This holistic approach represents a significant advancement in the field, offering a novel methodology that bridges the gap between data-driven insights and expert knowledge. Fig. 1.4 provides a more detailed view of the process flow from data-driven and knowledge-based approaches to the model-driven approach, highlighting the transformation of data and knowledge into actionable decision support and optimization. In addition, this research significantly advances both theoretical knowledge and practical applications in the project and production planning and control field in construction through the following key contributions:

1. Identifying and analyzing the planning methods and control metrics and their objectives

- *Contribution to knowledge:* The systematic identification and analysis of single, integrated, and collaborative planning methods, along with various control metrics, enrich the existing literature by providing a comprehensive understanding of their applications, main objectives (functionalities) and interrelations.
- *Contribution to practice:* Construction managers can leverage these insights to better understand and implement more robust and integrated planning and control systems, tailored to the specific needs of their projects.

2. Conceptualization and development of a taxonomy of planning and control systems' underlying concepts

- *Contribution to knowledge:* This research presents a novel methodology that combines semantic textual similarity and clustering analysis with domain experts' opinions to develop a taxonomy of planning and control concepts. This innovative approach not only enhances the understanding of these concepts and but also lays a robust foundation for future academic research. By systematically categorizing the underlying concepts, this taxonomy facilitates more efficient utilization of planning methods at multiple levels by project stakeholders and serves as a valuable reference for scholars exploring similar domains.
- *Contribution to practice:* Project stakeholders can utilize this taxonomy to better understand and efficiently apply various planning methods at multiple levels, improving overall project management and execution.

3. Development of an integrated multi-level planning and control framework

- *Contribution to knowledge:* The integrated multi-level framework developed in this study offers significant theoretical advancements for construction management practices. By harmonizing various planning methods and control metrics across different schedule levels, this framework addresses pressing industry challenges such as ineffective planning and control systems and insufficient alignment with project teams' functional needs. Furthermore, the innovative incorporation of internal and external characteristics, along with the utilization of a multi-objective mathematical model for optimization, represents a substantial contribution to the body of knowledge. This methodology not only enhances the understanding of multi-level planning and control but also lays a robust foundation for future research in this domain.
- *Contribution to practice:* The practical application of this framework, validated through a renovation case study, demonstrates its strategic value and effectiveness in real-world scenarios. Furthermore, the developed framework can serve as a foundation for a decision support system tool that suggests a fit-to-purpose planning and control system for construction projects, tailored to the specific requirements of project teams. Adoption of this framework can lead to improved decision-making and a more systematic, transparent, and proactive approach in managing construction projects.

4. Design, development and implementation of a decision support system

- *Contribution to knowledge:* Adopting a precise and comprehensive methodology for knowledge management, DSS development, and results optimization represents a significant theoretical advancement. This approach includes applying rough set theory to handle uncertainty in data and knowledge formulization, implementing an inference engine to enhance decision-making processes, and developing a multi-objective mathematical model for optimization. These components collectively pave the foundation for further studies by providing a robust framework that can be adapted and expanded in various contexts within construction management and beyond.

- *Contribution to practice:* The DSS aids project managers in selecting the most appropriate planning and control approaches based on specific project needs, thereby enhancing decision-making processes and project outcomes.

5. Methodological guideline for renovation projects

- *Contribution to knowledge:* Through the analysis of various guidelines in project planning and control, combined with feedback from experts in the field, this study identified and extracted the essential components necessary for a robust methodological guideline. A rigorous procedure involving multiple key steps was adopted to establish this guideline, aimed at helping the industry implement a multi-level and integrated project planning and control system. The detailed processes, steps, activities, required information, and stakeholder roles included in the guideline provide clarity for its implementation, ensuring that it is both comprehensive and practical. This methodological advancement contributes significantly to the body of knowledge by offering a structured approach that can be utilized and further developed by academics and practitioners alike.
- *Contribution to practice:* Practitioners involved in renovation projects can follow this guideline to implement effective planning and control strategies, ensuring better management and successful project completion.

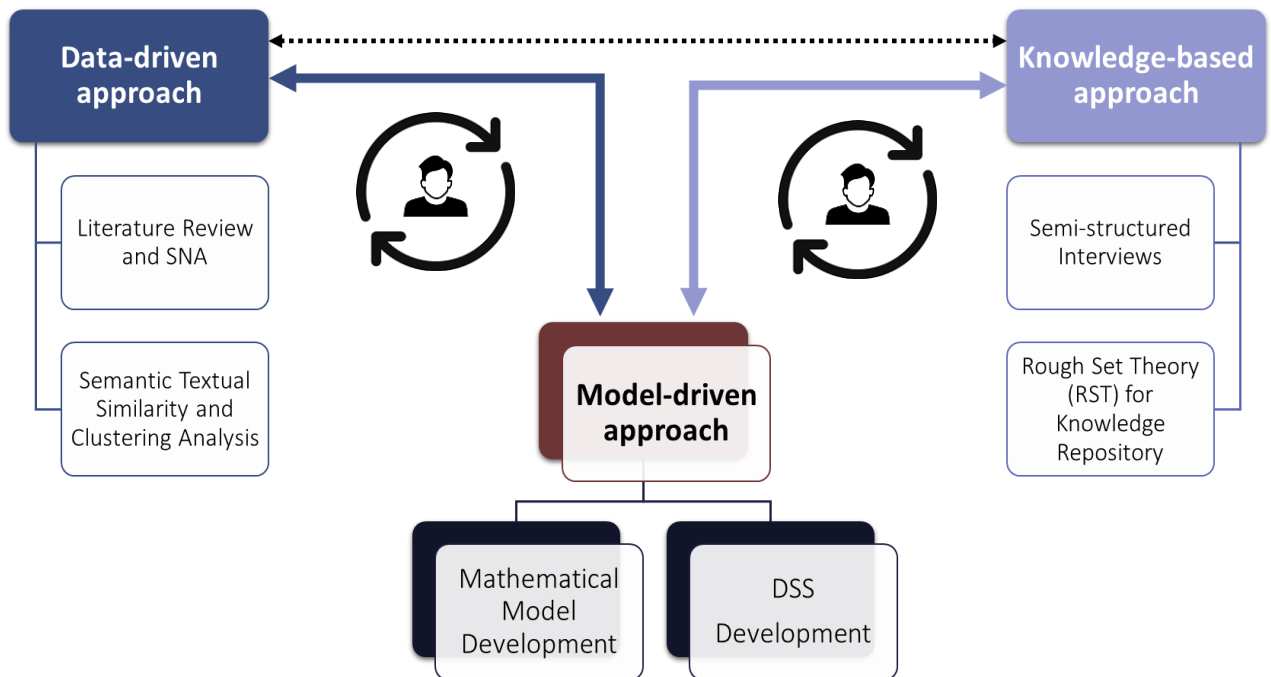


Fig. 1.3. Key components of the applied methodology's contribution

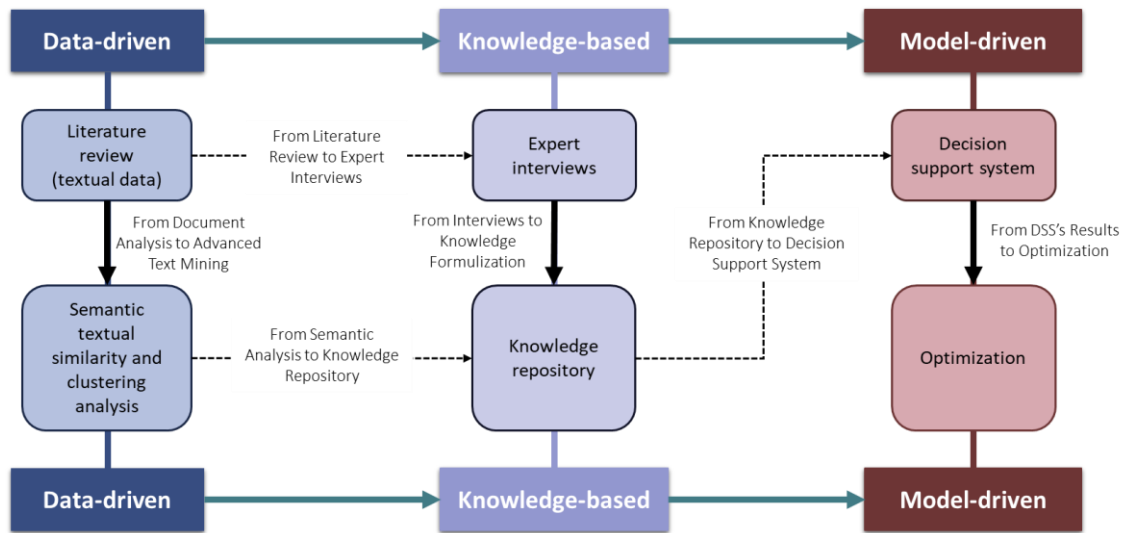


Fig. 1.4. Detailed view of the transformation process from data-driven and knowledge-based approaches to model-driven DSS

1.7. Dissertation Outline

This thesis is structured as a paper-based thesis, comprising seven chapters. The first chapter provides an introduction to the overall research. Chapter 2 includes three papers. Chapters 3, 4, and 5 are presented as standalone papers. Chapter 6 serves as a comprehensive guideline for the industry. Each chapter addresses a specific aspect of the research objectives, contributing to the overall goal of the study. Every chapter includes its own introduction, methodology, and conclusions sections. The final chapter provides a summary of the overall findings, contributions, limitations, and future work directions, serving as the general conclusion of the research. Additionally, the references for each chapter are listed at the end of the respective chapters, ensuring clarity and organization. Table 1.1 illustrates the structure of the dissertation. The organization of the dissertation is as follows:

Chapter 1 presents the background and motivation for this research, leading to the establishment of specific research objectives and questions designed to address the identified gaps in existing literature and practice. Additionally, this chapter outlines the contributions of the research to both knowledge and practice and provides an overview of the thesis structure.

Chapter 2 examines single and integrated planning methods, control metrics, and collaborative planning methods, focusing on their goals and objectives, which are referred to as their functionalities in this research. To achieve this, a systematic literature review and content analysis were conducted to explore various planning and control systems and identify their associated functionalities. Subsequently, SNA was employed to quantify the significance of each identified functionality, providing a comprehensive understanding of their relative importance within the context of planning methods.

Chapter 3 discusses the application of advanced text-mining techniques and hierarchical clustering to identify and classify the functionality concepts of project planning and control systems explored in Chapter 2. Furthermore, a taxonomy of these functionalities was developed through a meticulous analysis of the findings, supplemented by insights from domain experts.

Table 1.1. Dissertation structure

Chapter 1		Chapter 2			Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
		Section 1	Section 2	Section 3					
Title	Introduction	Functionality as a Key Concept for Integrated Project Planning and Scheduling Methods	An advanced exploration of functionalities as the underlying principles of construction control metrics	From process-based to technology-driven: a study on functionalities as key elements of collaborative planning methods for construction projects	From NLP to Taxonomy: Identifying and Classifying Key Functionality Concepts of Multi-level Project Planning and Control Systems	An Innovative Integrated Framework for Multi-level Production Planning and Control Systems in Construction	Data-driven and Knowledge-based Decision Support System for Construction Planning and Control	Methodological Guideline	Conclusion
Related objective	-	<i>Objective 1</i>			<i>Objective 2</i>	<i>Objective 3</i>	<i>Objective 4</i>	<i>Objective 5</i>	-
Journal	-	Journal of Construction Engineering and Management Q1, IF = 5.1	Smart and Sustainable Built Environment Q1, IF = 3.5	Production Planning & Control Q1, IF = 8.3	Journal of Information Technology in Construction (ITcon) Q1, IF = 4.3	Developments in the Built Environment Q1, IF = 6.2	Automation in Construction Q1, IF = 9.6	-	-
Status	-	Published	Published	Published	<i>Accepted/In-press</i>	Published	<i>Revised (second round)</i>	-	-

Chapter 4 focuses on developing an innovative integrated multi-level framework for production planning and control. This framework harmonizes various planning methods and control metrics across different schedule levels, building on the functionality concepts and taxonomy identified in Chapter 5. Utilizing the DSR methodology, this study systematically designs, develops, and evaluates the comprehensive framework. Two approaches were employed to validate its practicality and effectiveness: a case study and feedback from industry and academic experts. Additionally, a multi-objective mathematical model is incorporated to clarify the framework's components, demonstrating its practicality and optimizing the selection and integration process of planning methods and control metrics at different schedule levels.

Chapter 5 addresses the lack of a data-driven and knowledge-based system to consider the specific project team's needs and applications to suggest an optimized planning and control system. This chapter outlines a rigorous mixed-methodology approach, beginning with the collection of domain experts' knowledge. This knowledge is then formalized through the application of rough set theory. Subsequently, a knowledge- and data-driven decision support system is developed, leveraging the constructed knowledge database to recommend multi-level and integrated planning and control systems for construction projects. The chapter concludes with the incorporation of a multi-objective mathematical model to optimize the approaches suggested by the DSS as well as validating the results through a case study and domain experts' opinions.

Chapter 6 presents a rigorous procedure comprising multiple key steps to establish a methodological guideline for the industry to implement a multi-level and integrated project planning and control system. This chapter systematically develops and delineates the detailed processes, requisite information, stakeholder roles, and necessary activities and steps. The proposed guideline is designed to facilitate the effective implementation of the multi-level and integrated project planning and control system recommended by the DSS within the context of a renovation case study.

Chapter 7 presents the overall conclusions of the thesis, along with the limitations, future directions, and the research contributions.

1.8. Publications

Throughout this thesis's efforts, the author has collaboratively authored seven papers with the supervisory team. The outcomes of these publications are as follows:

- **Sheikhhoshkar, M.**, Bril El-Haouzi, H., Aubry, A., and Hamzeh, F. (2023). "Functionality as a key concept for integrated project planning and scheduling methods." *Journal of Construction Engineering and Management*, 149(7), 04023053. <https://doi.org/10.1061/JCEMD4.COENG-13427>.
- **Sheikhhoshkar, M.**, Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Rahimian, F. (2024). "From process-based to technology-driven: a study on functionalities as key elements of collaborative planning methods for construction projects." *Production Planning & Control*, 1-22, <https://doi.org/10.1080/09537287.2024.2360581>.
- **Sheikhhoshkar, M.**, Bril El Haouzi, H., Aubry, A., and Hamzeh, F. (2024). "An advanced exploration of functionalities as the underlying principles of construction control metrics." *Smart and Sustainable Built Environment*, 13(3), 644-676. <https://doi.org/10.1108/SASBE-12-2023-0379>.

- **Sheikhhoshkar, M.**, H. B. El-Haouzi, A. Aubry, F. Hamzeh, and M. Poshdar. (2023). "Analyzing the Lean Principles in Integrated Planning and Scheduling Methods." Proc. 31st Annual Conference of the International Group for Lean Construction, IGLC31, 1196–1207, <https://doi.org/10.24928/2023/0159>.
- **Sheikhhoshkar, M.**, Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Rahimian, F. (2024). " From NLP to Taxonomy: Identifying and Classifying Key Functionality Concepts of Multi-level Project Planning and Control Systems." Journal of Information Technology in Construction, (Accepted/In press), <https://hal.univ-lorraine.fr/hal-04701660v1>.
- **Sheikhhoshkar, M.**, Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Sakikholes, M. (2024). "An Innovative Integrated Framework for Multi-level Production Planning and Control Systems in Construction." Developments in the Built Environment, 19, 100524, <https://doi.org/10.1016/j.dibe.2024.100524>.
- **Sheikhhoshkar, M.**, Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Rahimian, F. (2024). " A Data-driven and Knowledge-based Decision Support System for Construction Planning and Control." Automation in Construction, *Under Review (second round)*.

Chapter 2. Review and Analysis of Planning and Control Systems in Construction

This chapter includes three papers, each containing a copy of the following published papers that collectively address the key aspects of a comprehensive analysis of single and integrated planning and scheduling methods, control metrics, collaborative planning approaches, and their functionalities in the construction industry.

- **Section 2.1: Sheikhhoshkar, M., Bril El-Haouzi, H., Aubry, A., and Hamzeh, F.** (2023). "Functionality as a key concept for integrated project planning and scheduling methods." *Journal of Construction Engineering and Management*, 149(7), 04023053
<https://doi.org/10.1061/JCEMD4.COENG-13427>.
- **Section 2.2: Sheikhhoshkar, M., Bril El Haouzi, H., Aubry, A., and Hamzeh, F.** (2024). "An advanced exploration of functionalities as the underlying principles of construction control metrics." *Smart and Sustainable Built Environment*, 13(3), 644-676.
<https://doi.org/10.1108/SASBE-12-2023-0379>.
- **Section 2.3: Sheikhhoshkar, M., Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Rahimian, F.** (2024). "From process-based to technology-driven: a study on functionalities as key elements of collaborative planning methods for construction projects." *Production Planning & Control*, 1-22,
<https://doi.org/10.1080/09537287.2024.2360581>.

2.1. Section 1: Functionality as a Key Concept for Integrated Project Planning and Scheduling Methods

This section is part of the review and analysis of literature on planning and control systems, aligned with the first objective of this thesis. The aim is to present and analyze a holistic list of integrated planning and scheduling methods and their functionalities in the construction sector. To do so, a multi-step methodology is adopted. First, the authors identified integrated planning and scheduling methods and their functionalities through a systematic literature review. Second, social network analysis (SNA) and Pareto analysis are used to assess and analyze the significance of the identified functionalities in the integrated planning and scheduling methods. The findings indicated that the last planner system, building information modeling, simulation methods and location-based management system are mainly used common planning methods in the integrated planning and scheduling methods. Also, 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 planning and scheduling methods. This section will aid project stakeholders in better understanding and sensemaking of integrated

planning and scheduling methods by identifying and highlighting their underlying concepts and objectives.

2.1.1. 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 methods (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 planning and 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. 2021a). Moreover, some researchers focused on integrating LBMS, LPS, and CPM to address some gaps in conventional planning and 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 planning and scheduling method followed the principle of takt time (TT) and just in time (JIT). Integration of 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. 2021b), 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 planning and scheduling methods that have been performed in previous studies. In this study, these mixed methods are considered as integrated planning and scheduling methods. Over time, the number of integrated planning and scheduling methods contributing to project performance and success has expanded. Although several integrated planning and 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 planning and 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 planning and 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 planning and 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 planning and 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 planning and 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.

2.1.2. Research Methodology

To achieve this study's objectives, the authors proceeded with a process composed of several interdependent steps, as shown in Fig. 2.1

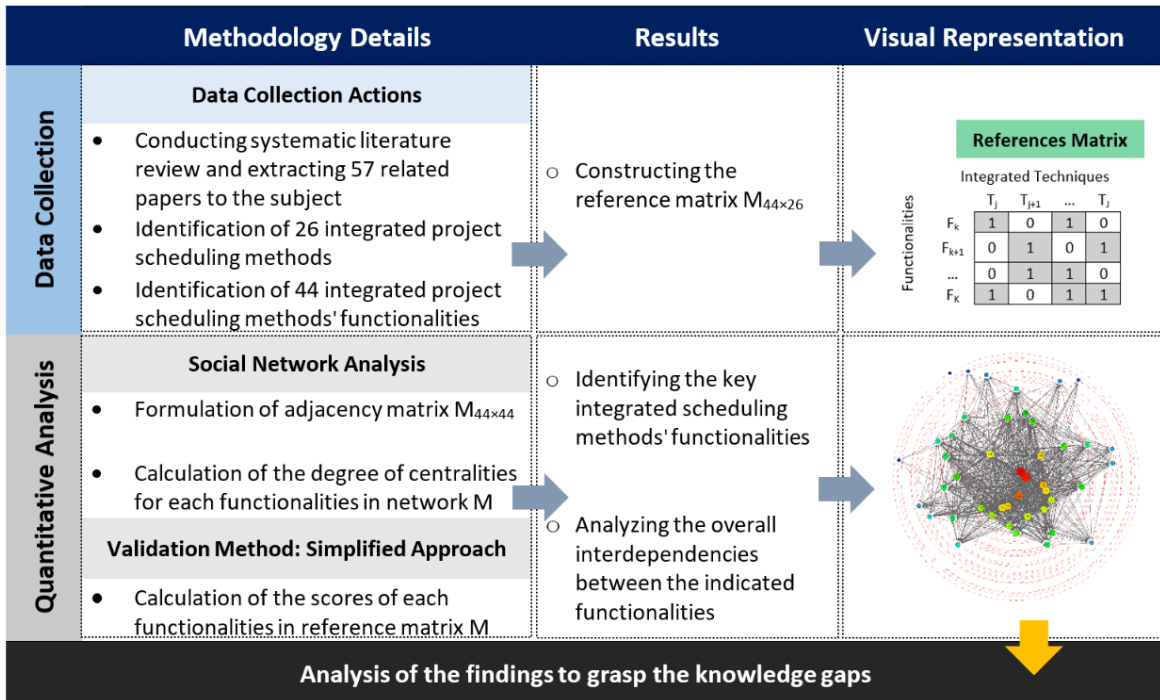


Fig. 2.1. Summary of the adopted research methodology

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 planning and scheduling methods and defined them as integrated planning and 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 planning and 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.

2.1.2.1. Conducting a Systematic Literature Review

The authors conducted a systematic literature review and analysis addressing the integrated planning and 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. 2.2 and detailed in the following subsections.

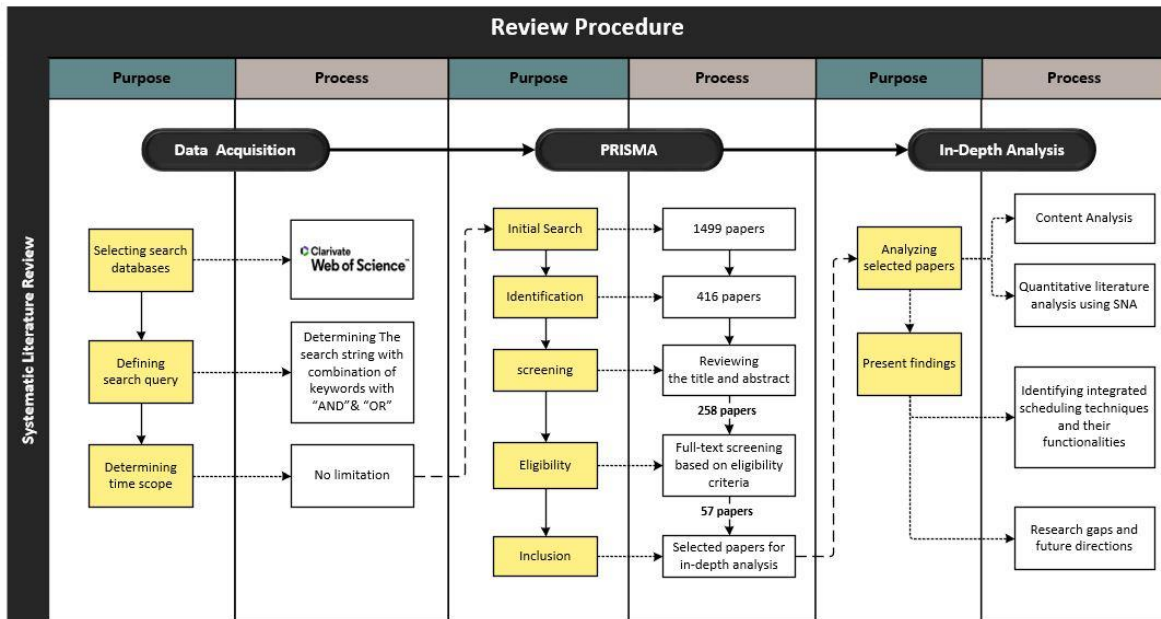


Fig. 2.2. Adopted systematic review procedure

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 2.1. The Web of Science (WoS) database was selected as the search engine, and the search string was determined using the combination of planning and scheduling methods with "AND" & "OR", as shown in Table 2.2. 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 2.1. 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)	

Table 2.2. 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")

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 planning and scheduling methods. The criteria for this aim are provided in Table 2.3. Using these criteria, the sample size was decreased to 57 publications.

Table 2.3. Inclusion and exclusion criteria for screening

Inclusion	Exclusion
<ul style="list-style-type: none"> • Written in English • Peer-reviewed articles that have been published in reputable scholarly construction and manufacturing journals and conferences • Act toward at least one combination of planning and scheduling methods (LPS-4D) • Inside the scope of the construction industry 	<ul style="list-style-type: none"> • Written in a different language than English • Not peer-reviewed; book, book chapter, technical reports • Deals only one planning and scheduling method (LOB OR LPS) • Outside the scope of the construction industry

Content Analysis

After the screening phase, 57 retrieved publications were subjected to content analysis to determine the goals, objectives, and outcomes of integrated planning and scheduling methods. In this regard, First, 26 integrated planning and scheduling methods were found relevant and valuable for this paper's purpose. Second, the retrieved articles based on 26

identified integrated planning and 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 planning and scheduling methods: 1) aims and objectives, 2) research questions, and 3) the benefits of each integrated planning and scheduling method. In the first step, 82 objectives for integrating common planning and 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 planning and scheduling methods' functionalities for further analysis. The following subsections describe the procedure for analyzing the integrated planning and scheduling methods and their functionalities in detail.

2.1.2.2. Literature Quantitative Analysis

After collecting the publications and conducting a content analysis, the authors identified the functionality of integrated planning and 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 planning and 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. 2.3 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 planning and scheduling method. As seen in Fig. 2.3, functionality F_k is described in integrated planning and 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 planning and 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.

		Integrated Techniques			
		T_j	T_{j+1}	...	T_j
Functionalities	F_k	1	0	1	0
	F_{k+1}	0	1	0	1
	...	0	1	1	0
	F_k	1	0	1	1

Fig. 2.3. An example of a reference matrix

2.1.2.3. 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 (sheikhHosseini et al. 2018b). A current example of SNA applications in the quantitative literature analysis in the construction management field is the research of (Elsayegh and El-adaway 2021b), 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. 2018b), 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 2021b), (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 planning and scheduling methods by analyzing their interdependence. The authors ultimately selected SNA as the best approach to find the most prevalent functionalities leading to integrated planning and 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 planning and scheduling methods. To do this, The authors sought a metric that can quantify the importance of integrated planning and 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 planning and 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 (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 planning and 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 Eq. (2.1)

$$WAM_{f \times f} = \begin{cases} M_{f \times t} \times M_{f \times t}^T & \text{for } k \neq j \\ 0 & \text{for } k = j \end{cases} \quad (2.1)$$

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 planning and scheduling methods (i.e., 26). Fig. 2.4 and Fig. 2.5 show an example of creating and visualizing a WAM for a reference matrix with four integrated methods and four functionalities. Fig. 2.4 illustrates how the adjacency matrix is developed, while Fig. 2.5 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.

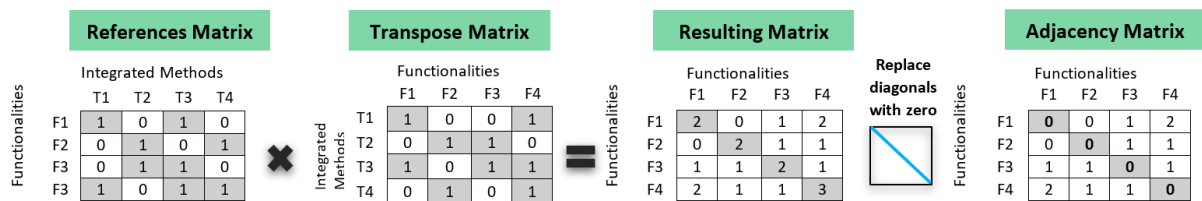


Fig. 2.4. An illustration of an adjacency matrix

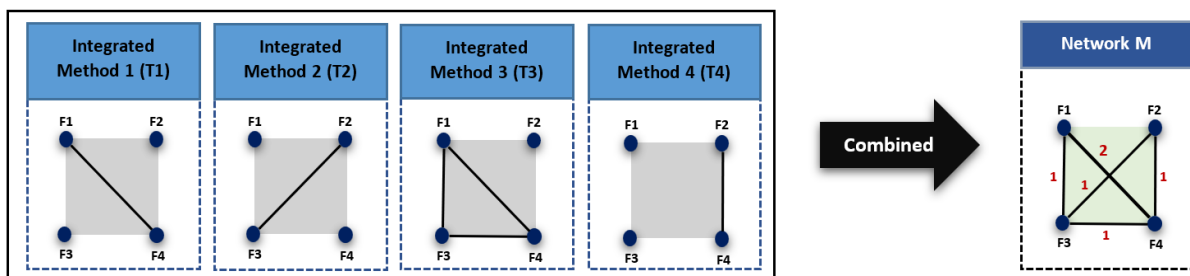


Fig. 2.5. Visual representation of reference and adjacency matrix

After developing the WAM, The DC for each functionality of integrated planning and scheduling methods is calculated based on Eq. (2.2).

$$DC_k = \sum_{j; j \neq k} M_{k,j} \quad (2.2)$$

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 Eq. (2.3), the normalized DC of a functionality k in a network is simply the DC of the evaluated functionality divided by the highest DC in the studied network.

$$\overline{DC}_k = \frac{DC_k}{\max \{DC_k\}} \quad (2.3)$$

Thus, the normalized \overline{DC}_k range from 0 to 1 for all functionalities.

2.1.2.4. Validation Method: Simplified Analysis

The simplified analysis was considered in the research of Elsayegh and El-adaway (2021b) for validation of SNA results. In this research, the same approach was carried out to verify the SNA and assess whether or not it is working as expected. In this method, a score for each identified functionality is calculated by summing up all the cells in the row that belong to that functionality using Eq. (2.4). For instance, a score of 11 for a functionality F15 in matrix \mathbf{M} indicates that this functionality is addressed in 15 integrated planning and scheduling methods.

$$Score_k = \sum_{z=1}^{26} M_{k,z} \quad (2.4)$$

where $Score_k$ is the frequency of referencing functionality k , $M_{k,z}$ is the cell's value in the reference matrix (either 0 or 1) that corresponds to functionality k and the integrated planning and scheduling method z . Similar to SNA normalization according to Eq. (2.5), functionalities are assigned a normalized score in the simplified analysis method. Therefore, the normalized score varies from 0 to 1 for each functionality in the reference matrix.

$$\overline{Score}_k = \frac{Score_k}{\max \{Score_k\}} \quad (2.5)$$

2.1.2.5. Pareto Chart Analysis

After analyzing the functionality of integrated planning and 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 planning and 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 planning and scheduling methods.

2.1.3. Results and Analysis

2.1.3.1. 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 planning and scheduling methods in the construction industry. This meta-analysis search and screening efforts retrieved 57 journal and conference articles are shown in Table 2.4 and were approved for further analysis. Table 2.4 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 planning and scheduling methods. The shortcomings of planning and 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 planning and scheduling methods (POLIANI 2020).

Table 2.4. 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. 2021a), (Schimanski et al. 2021b), (Silveira and Costa 2023)	40

Fig. 2.6 more clearly depicts the distribution of the papers across the years of the research period. The number of papers addressing integrated planning and scheduling methods in the construction industry has been on a trend since 2014 and reached its peak in 2021.

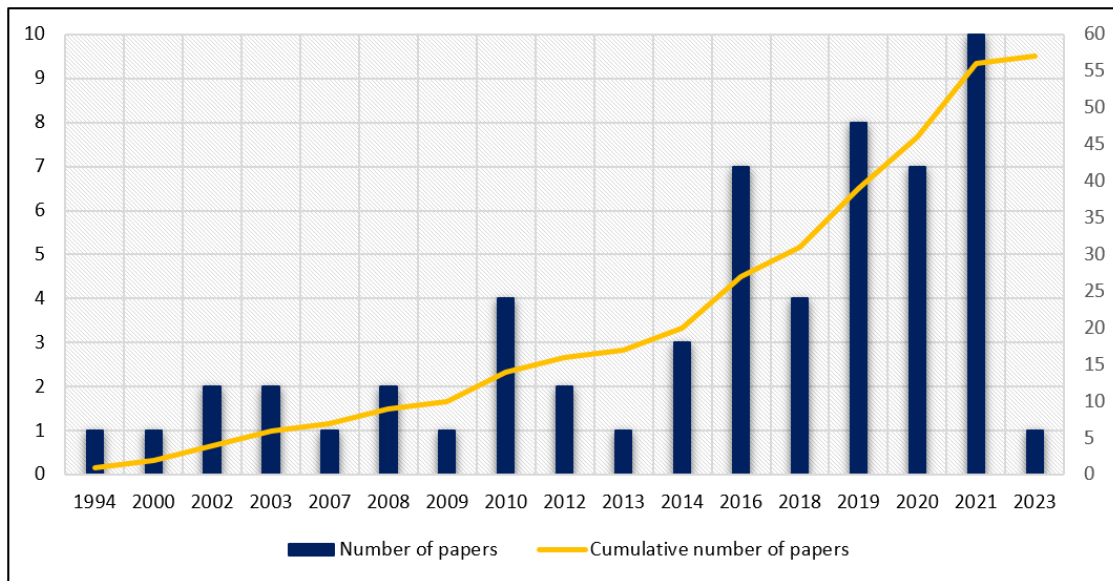


Fig. 2.6. Distribution of the papers across the years

2.1.3.2. Integrated Planning and scheduling Methods and their Functionalities in the Construction Industry

By analyzing the content of the publications in Table 2.4, the authors identified 26 integrated planning and scheduling methods and 44 planning and scheduling methods' functionalities listed in Table 2.5 and

Table 2.6. The 26 identified integrated planning and scheduling methods were developed by combining 14 common planning and scheduling methods and lean principles illustrated in a Sankey diagram in Fig. 2.7. Also, Fig. 2.8 clearly indicates the distribution of utilized common planning and scheduling methods in integrated planning and 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 planning and 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 planning and scheduling.

Table 2.5. Identified integrated planning and planning and scheduling methods

ID	Integrated planning and scheduling methods	Abbreviations	References
1	4D BIM-Last Planner System	<i>4D-LPS</i>	(Igwe et al. 2019; Igwe 2021; Lin and Golparvar-Fard 2021; Ortenburger and Hartmann 2021)
2	4D BIM-Linear Scheduling Method	<i>4D-LSM</i>	(Russell et al. 2009; Staub-French et al. 2008)
3	BIM-Just In Time	<i>BIM-JIT</i>	(Abbasi et al. 2020; Jeong et al. 2016)
4	BIM-Location-Based Management System	<i>BIM-LBMS</i>	(Jongeling and Olofsson 2007; Ratajczak et al. 2019)
5	BIM-Last Planner System	<i>BIM-LPS</i>	(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. 2021a; Schimanski et al. 2021b; Sriprasert and Dawood 2002; Sriprasert and Dawood 2003; Toledo et al.

			2016)
6	BIM-Last Planner System-Kanban	<i>BIM-LPS-Kanban</i>	(Sacks et al. 2010; Schimanski et al. 2021a)
7	BIM-Simulation Modeling	<i>BIM-SM</i>	(Abbasi et al. 2020; Jeong et al. 2016; König et al. 2012; Lu and Olofsson 2014)
8	BIM-Takt Time Planning	<i>BIM-TTP</i>	(Abbasi et al. 2020; Frandson 2019; Melzner 2019)
9	BIM-Takt Time Planning- Simulation Modeling	<i>BIM-TTP-SM</i>	(Abbasi et al. 2020; Aslam et al. 2020; Frandson 2019)
10	Critical Chain Project Management- Last Planner System	<i>CCPM-LPS</i>	(Shen and Chua 2008)
11	Critical Chain Project Management- Last Planner System- Linear Scheduling Method	<i>CCPM-LPS-LSM</i>	(Salama et al. 2021)
12	Critical Path Method- Location-Based Management System	<i>CPM-LBMS</i>	(Olivieri et al. 2018; POLIANI 2020)
13	Critical Path Method- Last Planner System	<i>CPM-LPS</i>	(Huber and Reiser 2003; POLIANI 2020)
14	Earn Value Management- Last Planner System	<i>EVM-LPS</i>	(Kim and Ballard 2010; Novinsky et al. 2018)
15	Location-Based Management System- Critical Chain Project Management	<i>LBMS-CCPM</i>	(Büchmann-Slorup 2014)
16	Location-Based Management System- Last Planner System- Critical Path Method	<i>LBMS-LPS-CPM</i>	(Olivieri et al. 2016; POLIANI 2020)
17	Line of Balance - Critical Path Method	<i>LOB-CPM</i>	(Ammar 2013; Suhail and Neale 1994)
18	Line of Balance- Monte Carlo Simulation	<i>LOB-Monte Carlo</i>	(Tokdemir et al. 2019)
19	Last Planner System-BIM-Simulation Modeling	<i>LPS-BIM-SM</i>	(Wickramasekara et al. 2020)
20	Last Planner System- Location-Based Management System	<i>LPS-LBMS</i>	(Dave et al. 2016; Salama et al. 2021; Seppänen et al. 2010)
21	Last Planner System- Line of Balance- Simulation Modeling	<i>LPS-LOB-SM</i>	(Ajweh 2014; Salama et al. 2021)
22	Last Planner System- Six Sigma	<i>LPS-SS</i>	(Aslam et al. 2020)
23	Linear Scheduling Method- Critical Chain Project Management	<i>LSM-CCPM</i>	(Salama et al. 2018; Salama et al. 2021)
24	Last Planner System- Simulation Modeling	<i>LPS-SM</i>	(Abdelmegid et al. 2019; Abdelmegid et al. 2021; Hamzeh et al. 2015a; Hamzeh et al. 2015b; Mota et al. 2010)
25	Critical Path Method- Simulation Modeling	<i>CPM-SM</i>	(Simmons 2002; Tokdemir et al. 2019)
26	Linear Scheduling Method- Critical Chain Project Management- BIM	<i>LSM-CCPM-BIM</i>	(Salama et al. 2016)

Table 2.6. Planning and 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

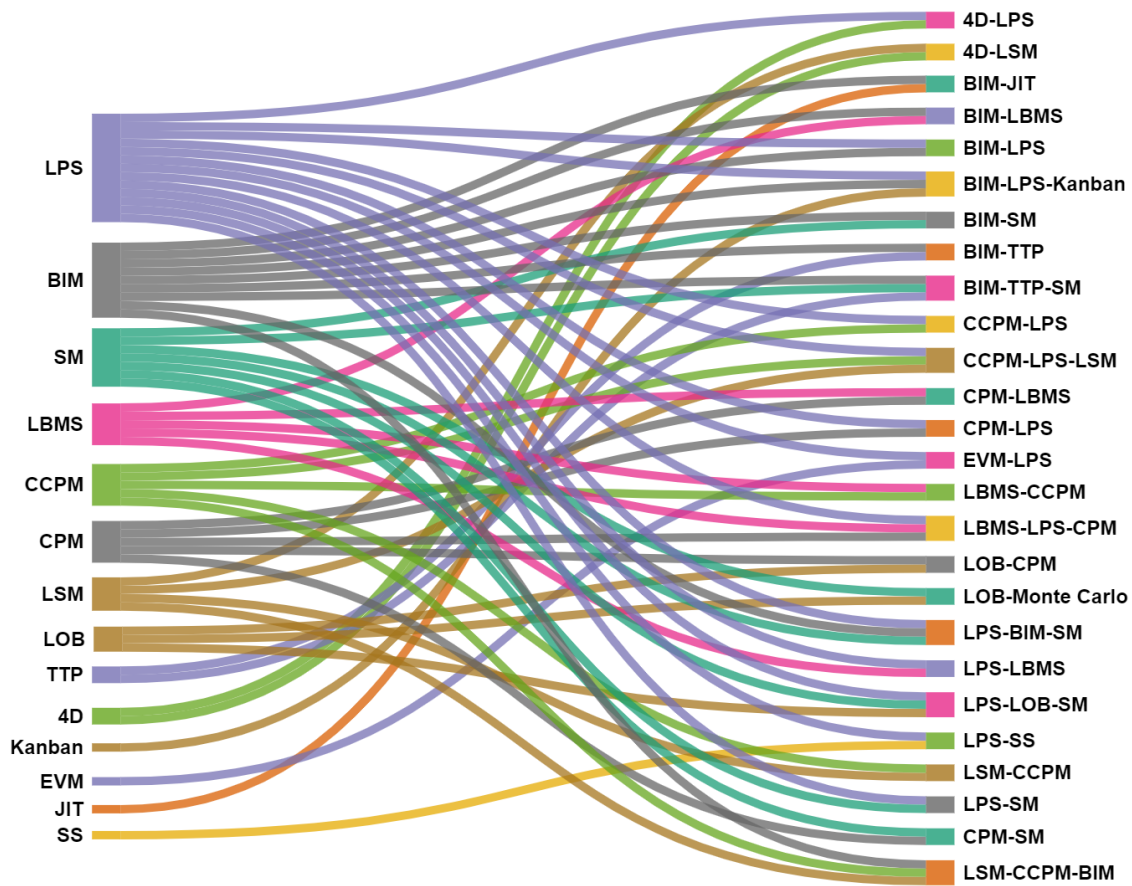


Fig. 2.7. Sankey diagram of integrated planning and scheduling methods

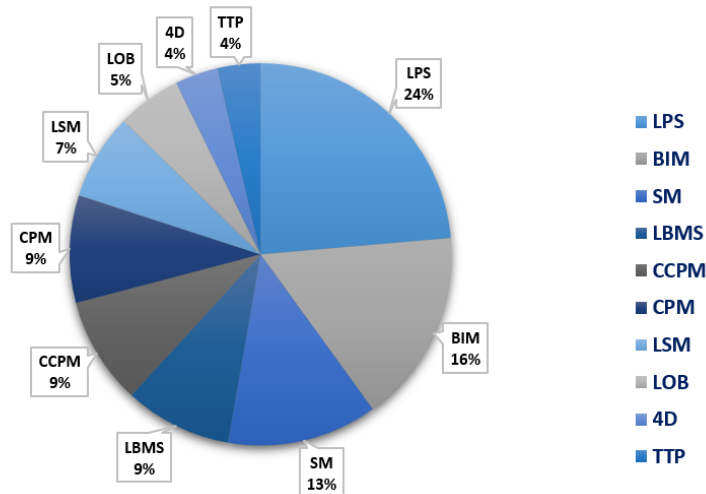


Fig. 2.8. Distribution of utilized common planning methods in integrated planning and scheduling methods

Moreover, Fig. 2.9, matrix M , represents the mapping between the identified project planning and scheduling methods' functionalities and the analyzed integrated planning and scheduling methods based on the literature. A red-colored cell indicates that the respective integrated planning and scheduling methods have addressed the functionalities. As can be seen, the integrated planning and 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 planning and scheduling methods.



Fig. 2.9. Mapping between the identified functionalities and analyzed integrated planning and 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 for practical deployment in the construction industry. Analyzing the various abstraction levels of common planning and 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 planning and scheduling. 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 planning and 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 planning and scheduling method in integrated methods was used to calculate the normalized score for each common planning and scheduling method within each class. Fig. 2.10 displays the findings of the analysis's common planning and 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. 2.10 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 planning and scheduling methods.

In contrast, a negative score indicates that the planning and 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 planning and 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 planning and scheduling methods have paid less attention to BIM and SM and given more emphasis to conventional methods such as CCPM, LSM, and CPM.

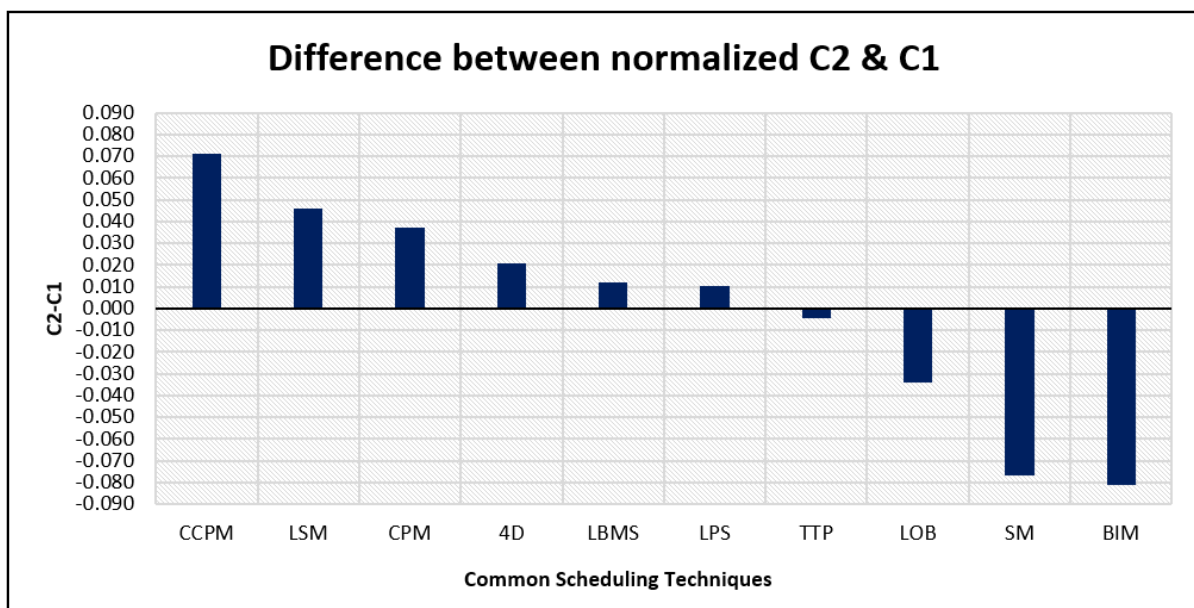


Fig. 2.10. Derived differences in the scores of C1 and C2 studies for common planning methods

2.1.3.3. Quantitative Analysis of the Integrated Planning and scheduling Methods' Functionalities

After reviewing the publications listed in Table 2.4 and finding the integrated planning and scheduling methods' functionalities, the authors developed a reference matrix M based on the identified functionalities and integrated planning and 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 planning and 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 $M_{44 \times 26}$, the authors produced the weighted adjacency matrix $WAM_{44 \times 44}$ 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 planning and scheduling methods. The functionalities network shown in Fig. 2.11 consists of 44 nodes (representing 44 integrated planning and 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. Clearly, the network has a significant number of nodes and connections. As a result, a color-coded matrix was provided in

Fig. 2.12 to illustrate the degree of connectivity between nodes. Both rows and columns of the matrix represent the functionality of integrated planning methods. The matrix is color-coded according to the intensity of the link between any two functionalities. As shown in

Fig. 2.12, the white-colored cells for a pair of functionalities imply that they have never co-occurred in any of the studied integrated planning and scheduling methods. On the other hand, some pairs of functionalities contain dark purple cells, suggesting high weights and, thereby, a high frequency of co-occurrence in the integrated planning and scheduling methods. An example of the former would be F3 (considering the continuous flow of work) and F44 (applying creativity techniques to planning and scheduling). The latter is represented in the weights of edges between F1 (improving the reliability of the planning) and F39 (increasing transparency).

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

Concerning the first perspective, Fig. 2.11 shows 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 planning and scheduling methods in combination with other functionalities in

construction projects. As also seen in Fig. 2.9, F15 (improving managerial practices) and F19 (managing uncertainties) have been among the top four used functionalities in integrated planning and scheduling methods. Nevertheless, according to SNA 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 multi-functional nature of integrated planning and 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 planning and scheduling methods is to combine the functionalities of conventional planning and scheduling methods to compensate for their deficiencies, assessing the combination of functionalities employed in integrated planning and scheduling methods conducted in this research is necessary. Regarding the combination analysis of functionalities, according to

Fig. 2.12, 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 planning and scheduling methods.

Following the second perspective, Fig. 2.11 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 planning and scheduling methods.

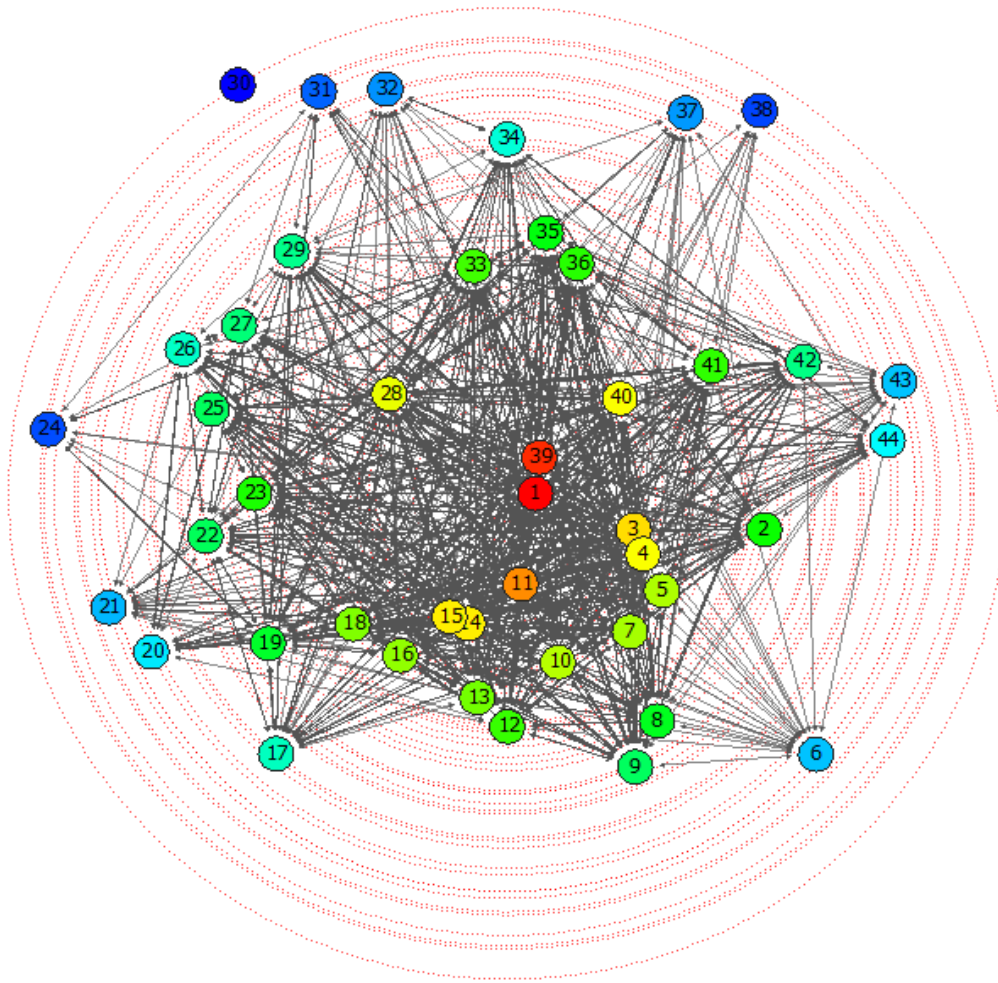


Fig. 2.11. Functionalities network

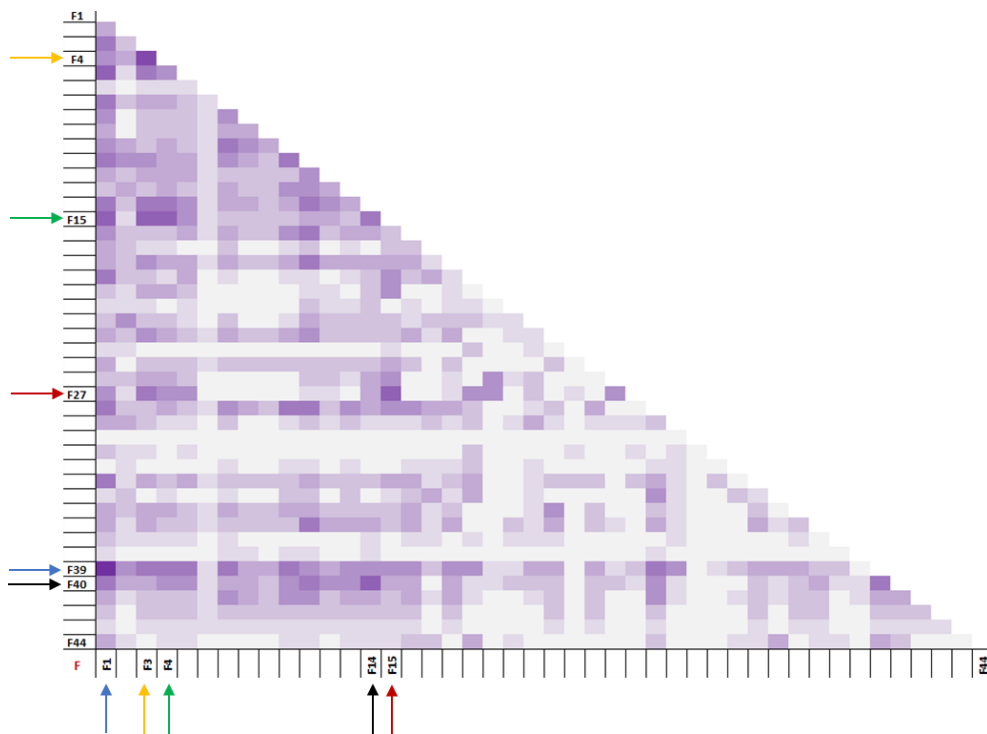


Fig. 2.12. Color-coded matrix of functionalities

2.1.3.4. 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 planning and scheduling methods, as illustrated by the Pareto chart in Fig. 2.13. As shown in Fig. 2.9, integrated planning and scheduling methods and even conventional planning and 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 planning and scheduling methods.

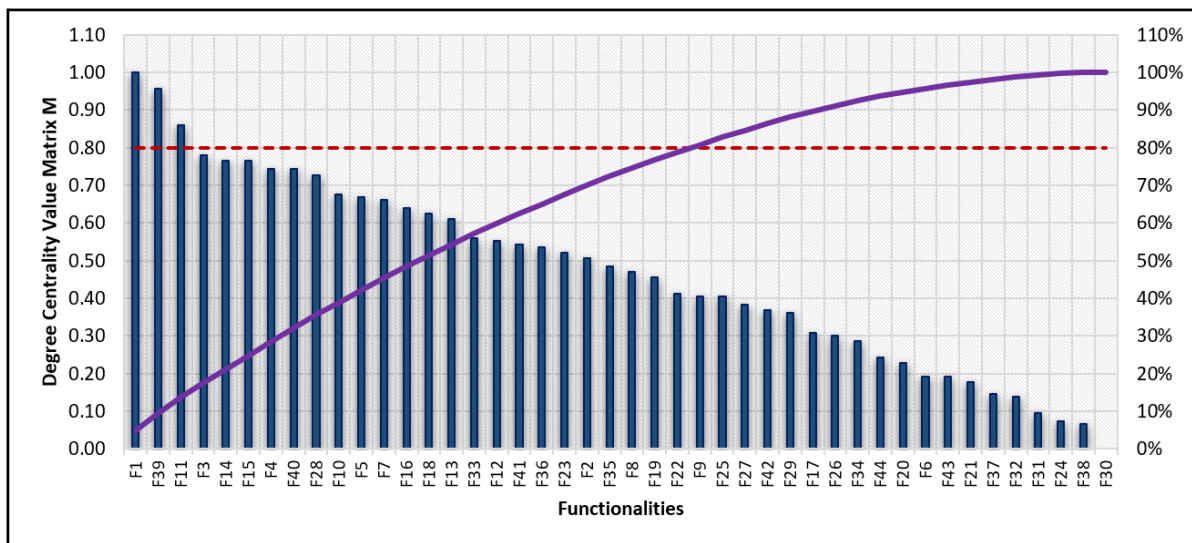


Fig. 2.13. Pareto Analysis of Functionalities

2.1.4. 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. 2.14. 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 2021b). On the contrary, the simplified analysis is calculated mainly on the simple frequency of the co-occurrence of functionalities in the analyzed integrated planning and scheduling methods. In Table 2.7, 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 2.7 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 2.7. Statistical test results on the simplified analysis and SNA

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

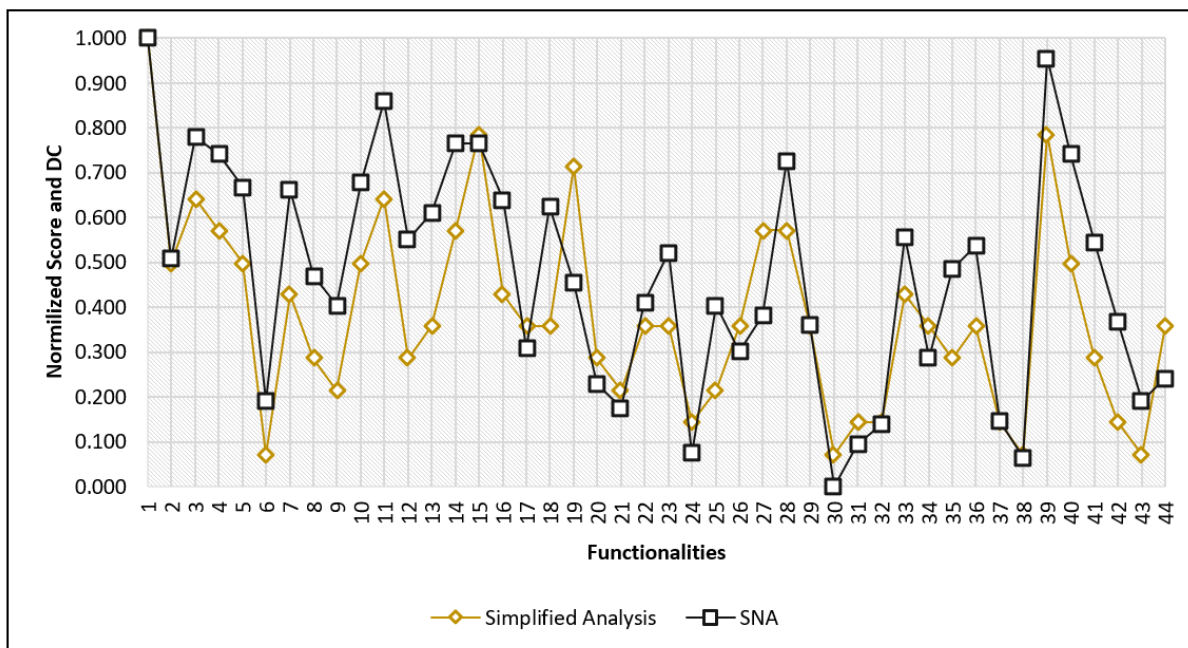


Fig. 2.14. Comparison results between simplified analysis and SNA

2.1.5. Discussions of the Research Findings

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

This study identified and analyzed the integrated planning and scheduling methods' functionalities to the project team can choose the project planning and scheduling method according to the needs and characteristics of the project with a better understanding.

Functionalities were considered due to the insufficient understanding and awareness of project planning and scheduling theories and methods on behalf of project stakeholders and participants (AlNasseri and Aulin 2015). This implies that these methods address a broader range of project planning, scheduling, and control issues. Between identified integrated planning and scheduling methods, BIM-LPS, BIM-LPS-Kanban, LBMS-LPS-CPM and BIM-LPS-SM have utilized the most combination of functionalities. The combination of common planning and scheduling methods with BIM demonstrates the attention of researchers and the industry to the use of semantic information of BIM models as well as its visualization capability in the form of 4D modeling to improve communication between stakeholders in the project. Furthermore, the last planner system is employed more often, according to the distribution of common planning and scheduling methods in integrated planning and scheduling methods.

Although simulation methods are not practical project planning and scheduling methods, different types of it (such as System Dynamic (SD), Discrete Event Simulation (DES), Agent-based Modeling (ABM) and Monte Carlo) have contributed several functions to common planning and 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 planning and 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 planning and 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 planning and 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 planning and scheduling methods by using integrated planning and 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).

Regarding the combination analysis of integrated planning and scheduling methods' functionalities, 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 considered the most in integrated planning and scheduling methods. These analyses demonstrate that integrated planning and scheduling methods are developed to address the aforementioned concerns regarding low productivity caused by inefficient construction planning and scheduling. In addition, they will be able to

manage the whole planning and scheduling process, including long-term, medium-term, and short-term planning.

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

Following the results in Fig. 2.7 and Fig. 2.8, the last planner system has gained the most attention among integrated planning and scheduling methods. Several integrated planning and scheduling technologies, such as LPS-BIM and LPS-CPM-LBMS, have attempted to account for the shortcomings of the last planner 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 planning and 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. 2.11, which demonstrates that F30 (eliminating the root causes of variability) had the lowest DC between integrated planning and scheduling methods' functionalities. This functionality is only considered in LPS-SS integrated methods. Consequently, there is a need for further study in this area.

2.1.6. Conclusion, Limitations, and Future Directions

Understanding the functionality of integrated planning and 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 planning and scheduling methods and 44 associated functionalities using SNA. Accordingly, 14 common planning and scheduling methods and lean principles were included to create 26 identified integrated planning and scheduling methods. The Last Planner System (LPS), Building Information Modeling (BIM), Simulation Modeling (SM) and Location-based Management System (LBMS) are utilized, as common planning and scheduling methods, more often in integrated planning and scheduling methods. Moreover, It has been demonstrated, as well, that studies focusing on the practical application of planning and scheduling methods have tended to emphasize traditional methods such as CCPM, LSM, and CPM while focusing less on BIM and SM. Regarding the integrated planning and 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 wastes), and F3 (considering the continuous flow of work) are the main functionalities employed in integrated planning and scheduling methods. These results also underline the importance of lean construction principles, such as planning reliability, transparency, waste elimination, and continuous workflow in integrated planning and scheduling techniques. In contrast, the findings indicate that integrated planning and scheduling methods need to pay more attention to one of the LPS's significant flaws, non-performance of root cause analysis and corrective actions. Furthermore, although offsite and modular construction is receiving a great deal of attention

in practice and academia, more focus should be given to the required functionalities of the planning and scheduling methods for offsite construction.

Another finding illustrates several combinations of functionalities have been considered most often. These include 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). These results indicate that integrated planning and scheduling methods can handle the requirement of multi-levels of schedule plan, including long-term, medium-term, and short-term planning. Moreover, the pareto chart analysis applied to determine the most important functionalities in integrated planning and scheduling methods. 80% of integrated planning and scheduling methods utilize 43% of the forty-four functionalities. To validate the SNA method's findings, a simplified analysis approach is used. The spearman correlation, variance, and standard deviation results reveal that minor differences between the two approaches are acceptable.

Ultimately, this research contributes to the body of knowledge by providing a better understanding the integrated planning and 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 planning and 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.

2.2. Section 2: An Advanced Exploration of Functionalities as the Underlying Principles of Construction Control Metrics

This section is part of the review and analysis of literature on planning and control systems, aligned with the first objective of this thesis. The aim is to identify and analyze a holistic list of control metrics and their functionalities in the construction industry. A multi-step analytical approach was conducted to achieve the study's objectives. First, a holistic list of control metrics and their functionalities in the construction industry was identified. Second, a quantitative analysis based on social network analysis (SNA) was implemented to discover the most important functionalities. The results revealed that the most important control metrics' functionalities could differ depending on the type of metrics (lagging and leading) and levels of control. However, in general, the most significant functionalities include managing project progress and performance, evaluating the lookahead level's performance, measuring the reliability and stability of workflow, measuring the make-ready process, constraint management, and measuring the quality of construction flow. This research will assist the project team in getting a comprehensive sensemaking of control systems and their functionalities to control different dynamic aspects of the project.

2.2.1. Introduction

The construction industry is highly complex, involving multiple stakeholders, a multi-organizational and multi-cultural system, and various variables that can significantly impact project outcomes (Aaltonen and Kujala 2016). Effective planning and control are essential to ensure the project is delivered on time, within budget, and according to the defined objectives. Planning determines the project's objectives and how to accomplish them, while control ensures that the project stays within its scope and achieves its objectives (Hamzeh et al. 2020b). To ensure the task remains on schedule and achieves the desired results, developing a set of metrics to monitor and analyze the project's progress, performance, and other vital dynamic aspects is a must.

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

Most of the developed metrics are embedded within the Last Planner System (LPS), which is

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

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

The number of control metrics that facilitate project performance analysis has grown over time. Although various control metrics have increased the scope of options available to the project team for selecting aligned metrics with project objectives, it has also increased the complexity of determining which control metrics are most appropriate. The lack of knowledge and information among project stakeholders on the potential application and effectiveness of project planning and control metrics is cited as another issue (Al Nasser et al. 2016; Sheikhhoshkar et al. 2023b). Furthermore, it mindlessly matches appropriate planning skills to various planning activities without understanding the underlying requirements. Another gap that can be mentioned is the lack of knowledge about the functionalities required at the early stages as opposed to the late stages of the project planning process, particularly those needed for planning, control, and both; functionalities can either be applied proactively (leading) or reactively (lagging); those can be used in the short-term to impact crew production versus long-term ones that influence design decisions, logistics, supply chain management, procurement, subcontractors onboarding time, etc.

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

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

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

2.2.2. Research Methodology

The authors adopted a multi-step analytical approach to accomplish the aims and objectives of this paper. The methodology process is indicated in Fig. 2.15. The approach consists of two primary and interconnected processes: data collection and processing, and data analysis. Each is described more deeply in the following subsections.

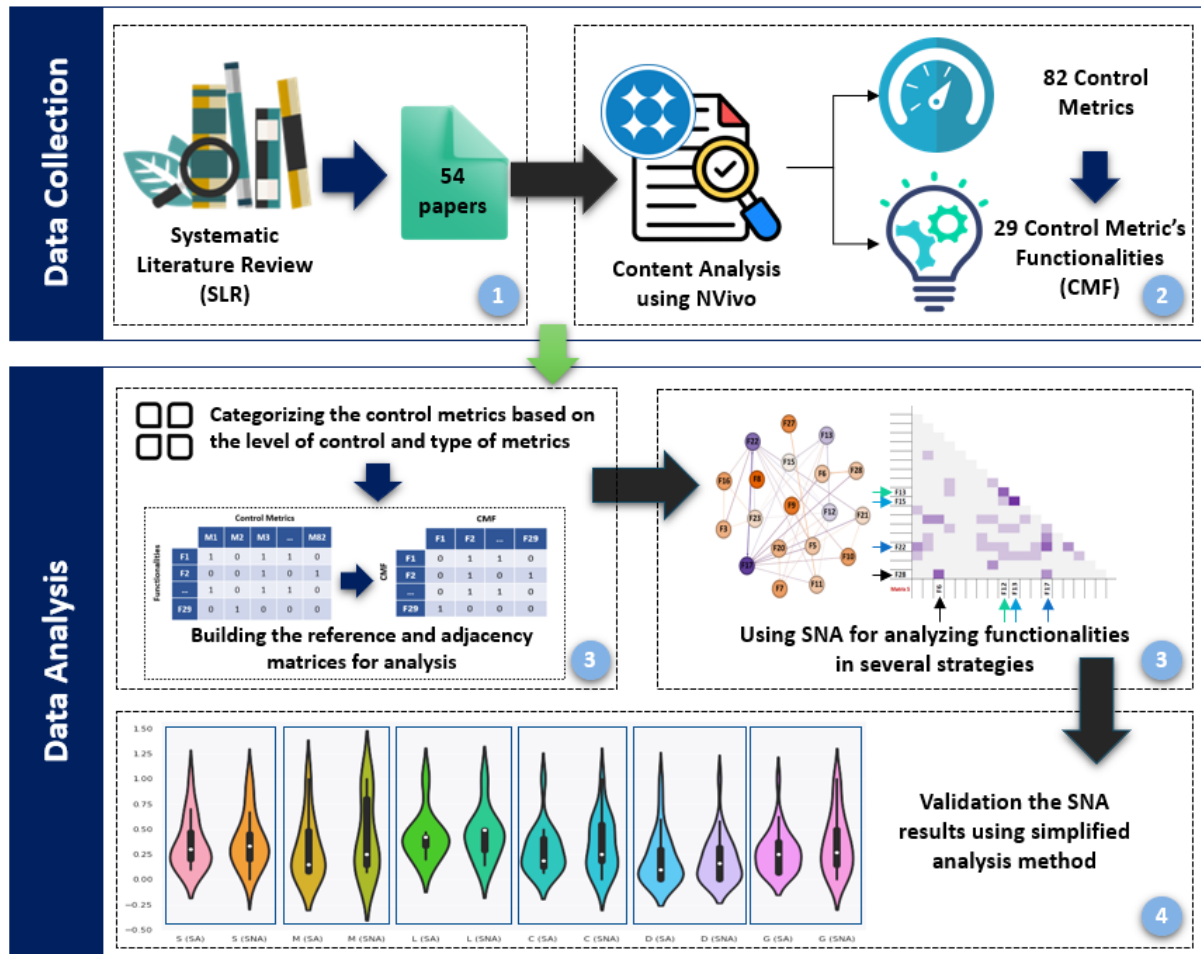


Fig. 2.15. Overview of the considered research methodology

As seen in Fig. 2.15, the authors (1) carried out a systematic review and content analysis of the literature on construction site control metrics to gather relevant information, (2) identified the underlying principles of control metrics and defined them as Control Metrics' Functionalities (CMF), (3) applied social network analysis (SNA) to evaluate the significance of each identified functionality and determine the most crucial ones based on their interdependencies in terms of control levels and type of metrics, and (4) validated the SNA results using simplified analysis. The following subsections delve into each component of the research methodology in detail.

2.2.2.1. Data Collection

Systematic Literature Review (SLR) and content analysis were employed to acquire the data

required for this study. A detailed explanation of these procedures is provided below.

Systematic Literature Review (SLR)

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

○ **Stage 1 - Planning the Review**

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

1. RQ1: what are the metrics used to control construction projects?
2. RQ2: what are the underlying principles of control metrics?

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

○ **Stage 2 - Conducting the Review**

Two key bibliographic databases, Scopus and Web of Science (WoS), were employed to perform an exhaustive search in the "Title, Abstract, Keywords". The search query was created by decomposing RQ1 and RQ2 and combining the pertinent terms and synonyms regarding project control metrics using Boolean operators "AND" and "OR", as shown in Table 2.8. No restrictions were placed on the data collection timeframe, and all records available up to February 2023 were considered. Moreover, several inclusion and exclusion criteria (

Table 2.9) were utilized to ensure the selected articles were relevant to the research questions.

Table 2.8. Combined search terms

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

Table 2.9. Inclusion and exclusion criteria for the paper’s screening

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

The screening phase was conducted by the first author and evaluated and approved by the

other authors of the article. Also, backward and forward citation searches were used to cover all relevant articles.

- **Stage 3 - Presenting the Review Results**

The review process results are indicated in Fig. 2.16. The initial attempt to collect data yielded 943 articles. This first collection of papers was screened and reviewed using a multi-step procedure that involves applying filtering functions in Scopus and WoS, such as document type, subject area, and source title, removing duplicates, assessing titles and abstracts for relevance, and applying inclusion and exclusion criteria. These steps reduced the number of papers to 47, and after applying backward and forward citation searching to them, seven further related articles were discovered, bringing the total number of articles for content analysis to 54.

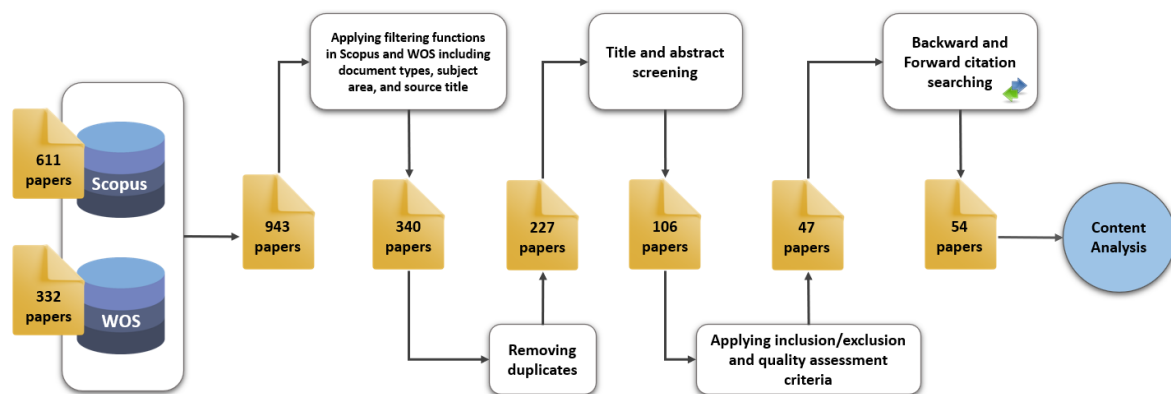


Fig. 2.16. Adopted review process

Content Analysis

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

2.2.2.2. Data Analysis

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

Classifying the Control Metrics and Developing Reference Matrices

The first step of quantitative studies with social network analysis is to prepare a reference matrix. To do this, after retrieving the control metrics and their functionalities from the literature, the authors categorized the control metrics to analyze their functionalities from different aspects according to the following perspectives:

- **Perspective 1: Level of Control**

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

- **Perspective 2: Type of Metrics**

This perspective categorized metrics based on their type, lagging and leading. Lagging measures assess past performance, while leading ones predict future performance. Table 2.10 depicts the classification of control metrics, the number of metrics in each class and the related matrix for further analysis.

Table 2.10. Classification perspectives of control metrics

Class	Perspective	Perspectives details	Related matrix	No. metrics
1	Level of control	Short-term	S	29
1	Level of control	Mid-term	M	18
1	Level of control	Long-term	L	4
1	Level of control	<i>Multi-level</i> : short-term and long-term, short-term and mid-term, long-term and mid-term, long-term and mid-term and short-term	C	31
2	Metrics type	Lagging	G	57
2	Metrics type	Leading	D	25

After grouping the control metrics for studying the identified functionalities, six reference matrices were generated based on the provided classes in Table 2.10. The identified functionalities are represented as rows, and the control metrics as columns in a reference matrix. If functionality reflects a control metric, the cell for it would have a value of 1; if it does not, it would have a value of 0. In Fig. 2.17, a reference matrix is illustrated as an example. In this example, F_i is an identified functionality, and M_j refers to a control metric. As shown in Fig. 2.17, the functionality F_i is associated with the control metrics M_j and M_k . Consequently, a value of one is entered in the respective cells, while cells below the other control metrics receive a value of zero. Leveraging the created reference matrices and utilizing the SNA approach, the authors conducted a quantitative analysis and subsequently validated their results via a simplified analysis. Further details are provided in the following subsections.

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

Fig. 2.17. An example of a reference matrix

Applying Social Network Analysis

Developing the Social Network

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

Using Eq. (2.6), the weighted adjacency matrix is computed by multiplying the reference matrix by its transpose and then replacing zeros for its diagonal values.

$$A_{f \times f} = \begin{cases} R_{f \times m} \times R_{f \times m}^T & \text{for } i \neq j \\ 0 & \text{for } i = j \end{cases} \quad (2.6)$$

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

To efficiently evaluate the network and quantify the significance of the discovered functionalities, the authors adopted Degree of Centrality (DC), which quantifies the number of times each functionality occurred with other functionalities in the same control metric. The DC for each functionality of control metrics F_i is calculated by summing the values of the i th row of the weighted adjacency matrix, illustrated by Eq. (2.7).

$$DC_i = \sum_{j=1}^n a_{ij} \quad (2.7)$$

where DC_i = degree centrality of functionality i ; and a_{ij} = value of i th row and j th column of the weighted adjacency matrix. As the number of links and functionalities of the networks in this study are different, a normalized scale, ranging from 0 to 1, of the DC values is calculated to make it easier to compare the functionalities. As illustrated in Eq. (2.8), normalized DC is determined by dividing the DC of each functionality by the maximum DC value in the associated network.

$$\overline{DC}_i = \frac{DC_i}{\max\{DC_m\}} \quad (2.8)$$

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

Simplified Analysis

Several studies considered the simplified analysis for validating SNA findings (Assaad and El-Adaway 2020; Elsayegh and El-adaway 2021b; Sheikhhoshkar et al. 2023a). The same manner was used to verify the SNA outcomes in this research. In this method, a score is determined for each functionality by summing all related cells in the row using Eq. (2.9). For instance, a score of 16 for functionality $F5$ using reference matrix \mathbf{G} indicates that this functionality is regarded in 16 of the lagging control metrics.

$$S_i = \sum_{j=1}^n r_{ij} \quad (2.9)$$

where S_i = normalized simplified score of functionalities i ; and r_{ij} = value of i th row and j th column of the reference matrix. Following the normalization reason and process for DCs, the normalized score for the simplified analysis approach is calculated via Eq. (2.10).

$$\overline{S}_i = \frac{S_i}{\max\{S_m\}} \quad (2.10)$$

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

2.2.3. Results and Analysis

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

2.2.3.1. Data Collection Efforts

The performed systematic review efforts by the authors included 54 research papers to meet the requirements of this study, illustrated in Table 2.11. The distribution of the published articles across three decades indicates that most publications were conducted after 2013. The complexity of construction projects and the availability of data collection and analysis methods and technologies have led to a dramatic increase in the focus on this field of study over the last decade.

Table 2.11. Final papers for the content analysis

Time scope	Full-text analyzed papers	No. of papers
1994-2003	Ballard and Howell (1998), Chitla and Abdelhamid (2003)	2
2004-2013	Mitropoulos (2005), Kenley and Seppänen (2006), Jang and Kim (2007), Jung and Kang (2007), González et al. (2008), Plaza (2008), Kim and Ballard (2010), Hamzeh and Aridi (2013)	8
2014-2023	Wang et al. (2014), Colin et al. (2015), Colin and Vanhoucke (2015), Hamzeh et al. (2015a), Hamzeh et al. (2015b), Hazır (2015), Kim (2015), Roofigari-Esfahan et al. (2015), Emdanat and Azambuja (2016), Hamzeh et al. (2016), Hu et al. (2016), Kim et al. (2016), Rouhana and Hamzeh (2016), Binninger et al. (2017), El Samad et al. (2017), Hamledari et al. (2017), Lin and Golparvar-Fard (2017), Martens and Vanhoucke (2017), Rizk et al.	44

(2017), Sacks et al. (2017), Hammad et al. (2018), Nguyen and Waikar (2018), Orgut et al. (2018), Zhang et al. (2018), Ballesteros-Pérez et al. (2019), Hamzeh et al. (2019a), Hamzeh et al. (2019b), Chen et al. (2020), Hamzeh et al. (2020a), Hamzeh et al. (2020b), Haugen et al. (2020), Lagos et al. (2020), Demachkieh and Abdul-Malak (2021), Keskiniva et al. (2021), Lagos and Alarcón (2021), Lin and Golparvar-Fard (2021), Abusalem (2022), Aramali et al. (2022), Ezzeddine et al. (2022), Mayo-Alvarez et al. (2022), Pérez et al. (2022), Shehab et al. (2022b), Shehab et al. (2022c), Hansen et al. (2023)

By studying the papers in Table 2.11, the authors identified 82 control metrics and their definitions in the construction sector, as detailed in Appendix A. To assess these control metrics from various perspectives, Table A1 in the Appendix furnishes supplementary details for each metric, encompassing considerations such as the level of control and the type of metric. Moreover, as described in the content analysis section, authors found 29 control metrics' functionalities based on 54 finalized articles and 82 control metrics mentioned above, illustrated in Table 2.12.

Table 2.12. Control metrics' functionalities

ID	Control metrics' functionalities
F1	Achieve an integrated cost/schedule progress monitoring and control
F2	Manage constraints removal
F3	Maintain continuity of trade work
F4	Control of uncertainty
F5	Control project progress and performance
F6	Manage corrective actions
F7	Evaluate the performance of the lookahead level
F8	Forecast project duration
F9	Control the cost of the project in progress
F10	Identify highly sensitive activities
F11	Measure labor productivity
F12	Measure labor resource reliability
F13	Measure the efficiency of resource allocation
F14	Measure long-term and short-term plans alignment
F15	Measure the quality of capacity planning
F16	Measure the quality of the construction flow
F17	Measure reliability and effectiveness of weekly work plan and lookahead plan
F18	Measure the achievability of a target project duration
F19	Measure the make-ready process
F20	Measure the percentage of differentiate tasks in the WWP
F21	Measure the quality of the commitments
F22	Measure the reliability and stability of the workflow
F23	Maintain production rate stability
F24	Provide managerial information
F25	Quantify the reliability of starting or finishing the task on time
F26	Identify root causes for deviations.
F27	Relate workflow reliability to productivity
F28	Improve continuous learning
F29	Align the work plan assignment with the lookahead

To analyze the control metrics' functionalities from several aspects, the authors created six reference matrices and networks based on the classification perspectives described in the research methodology section, Table 2.10. The classification of each control metric, along with the corresponding matrix within perspectives 1 and 2, is exhaustively delineated and presented in Table A2 in the Appendix.

2.2.3.2. Investigating the Planning and scheduling Methods Associated with Control Metrics

There is a tight relationship between planning and scheduling methods and control metrics. Planning and scheduling methods are utilized to plan and manage a construction project, while control metrics are used to assess and monitor progress against the planned schedule (Hamzeh et al. 2012). In order to evaluate the planning and scheduling methods associated with control metrics, Fig. 2.18 depicts the distribution of control metrics across the seven planning and scheduling methods. As seen, although the Critical Path Method (CPM) is the most common and traditional method of planning and scheduling in construction projects, most control metrics (55%) are related to the Last Planner System (LPS). Since the monitoring and control of the project require data from the construction site, it makes sense that the LPS, with its frequent huddle meetings and more emphasis on the short-term and weekly plan, provides the most appropriate data for project control from various aspects. This fact can be a reason for more attention being paid to control metrics in this method compared to other methods. Furthermore, several studies have emphasized increasing the efficiency of LPS using Location-Based Management System (LBMS) and Takt Time Planning (TTP) techniques (Ballard and Tommelein 2021; Nutt III et al. 2020; Seppänen et al. 2010). However, the analysis of control metrics related to planning and scheduling methods in Fig. 2.18 indicates little focus on control metrics of LBMS and TTP methods, with 10% and 6%, respectively. This highlights the need for more research and focus on developing control metrics for these methods. Lin and Golparvar-Fard (2021)'s study can be cited as one of the limited studies on the metrics related to these techniques. They proposed location-related metrics such as the Location Risk Index (LRI) to measure workflow stability based on activities' completion risk and readiness per work location. Moreover, it should be noted that due to prevalent contractual constraints that often hinder the widespread adoption of the Last Planner System (LPS) in construction projects, integrating control metrics associated with both the Critical Path Method (CPM) and LPS becomes imperative for a practical and comprehensive approach to effectively address delay concerns in construction projects.

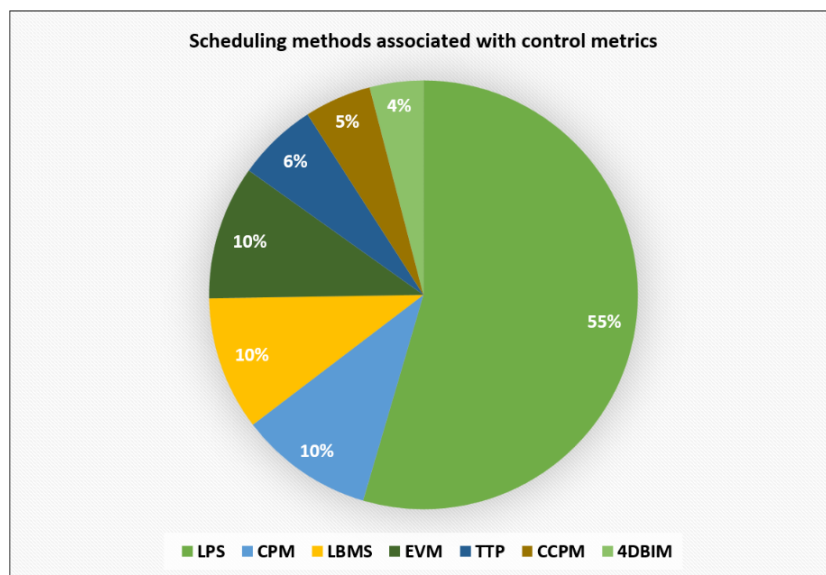


Fig. 2.18. Planning and scheduling methods associated with control metrics

2.2.3.3. Quantitative Analysis of the Control Metrics' Functionalities

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

Social Network Analysis

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

Analyzing the Networks of Perspective 1

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

In Fig. 2.19 (a), network *S*, focusing on short-term control metrics' functionalities, 18 out of 29 functionalities are supported. Notable functionalities include F17 (measure reliability and effectiveness of weekly planning), F22 (measure the reliability and stability of workflow), F13 (measure the efficiency of resource allocation), and F12 (measure labor resource reliability), while F9 (control the cost of the project in progress), F27 (relate workflow reliability to productivity), F28 (improve continuous learning), and F16 (measure the quality of construction flow) receive less attention. The color-coded matrix reveals specific pairs with high co-occurrence in short-term control metrics' functionalities. The co-occurrence of F15 (measure the quality of capacity planning) and F13 (measure the efficiency of resource allocation), F13 (measure the efficiency of resource allocation) and F12 (measure labor resource reliability), F28 (improve continuous learning) and F6 (manage corrective actions), and F22 (measure the reliability and stability of workflow) and F17 (measure reliability and effectiveness of weekly planning) have been employed the most in the short-term control metrics.

Fig. 2.19 (b) explores mid-term control metrics, indicating that 10 out of 29 functionalities are addressed. Prominent functionalities include F7 (evaluate the performance of the lookahead level), F2 (manage constraints removal), and F19 (measure the make-ready process), with less attention given to F9 (control the cost of the project in progress), F25 (quantify the reliability of starting or finishing the task on time), and F4 (control of uncertainty). Regarding the co-occurrence analysis of the functionalities at the mid-term level of control, the combination of F7 (evaluate the performance of the lookahead level) and F2 (manage constraints removal), F19 (measure the make-ready process) and F2 (manage constraints removal), and F19 (measure the make-ready process) and F7 (evaluate the performance of the lookahead level) have been considered the most in the mid-term control metrics.

Fig. 2.19 (c) delves into long-term control metrics, covering nine functionalities out of 29. It should be noted that in this research, the long-term level refers to the master and phase planning of the last planner system. F5 (control project progress and performance) is identified as the most crucial functionality, while F4 (control of uncertainty) and F10 (identify

highly sensitive activities) receive minimal attention. Moreover, the color-coded matrix displays co-occurrence patterns, with, F5 (control project progress and performance) and F24 (provide managerial information) standing out.

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

Fig. 2.19 (d) illustrates a multi-level control class (**C**) with 18 functionalities. F5 (control project progress and performance), F28 (improve continuous learning), F26 (identify root causes for deviations), and F16 (measure the quality of construction flow) are frequently used, while F25 (quantify the reliability of starting or finishing the task on time), F14 (measure long-term and short-term plans alignment), and F1 (achieve an integrated cost/schedule progress monitoring and control) receive less attention. In addition, co-occurrence analysis in the color-coded matrix highlights that the combination of F4 (control of uncertainty) and F5 (control project progress and performance), F24 (provide managerial information) and F5 (control project progress and performance), and F26 (identify root causes for deviations) and F28 (improve continuous learning) have been utilized the most often in multi-level control metrics.

To summarize the analysis related to the control metrics' functionalities at different schedule levels, word clouds of top-ranked functionalities at each control level were created. Identifying the occurrence of words in each word cloud can facilitate grasping the main underlying control concepts for each scheduling level provided by its corresponding control metrics. As shown in Fig. 2.20, the main control concepts at the long-term level of control are project cost/time progress monitoring and project performance monitoring. At the mid-term level, constraint management, make-ready process control, and lookahead performance monitoring are the most critical concepts of control. Also, resource allocation, commitment management, and workflow management are the highlighted concepts of control at the short-term level of control.

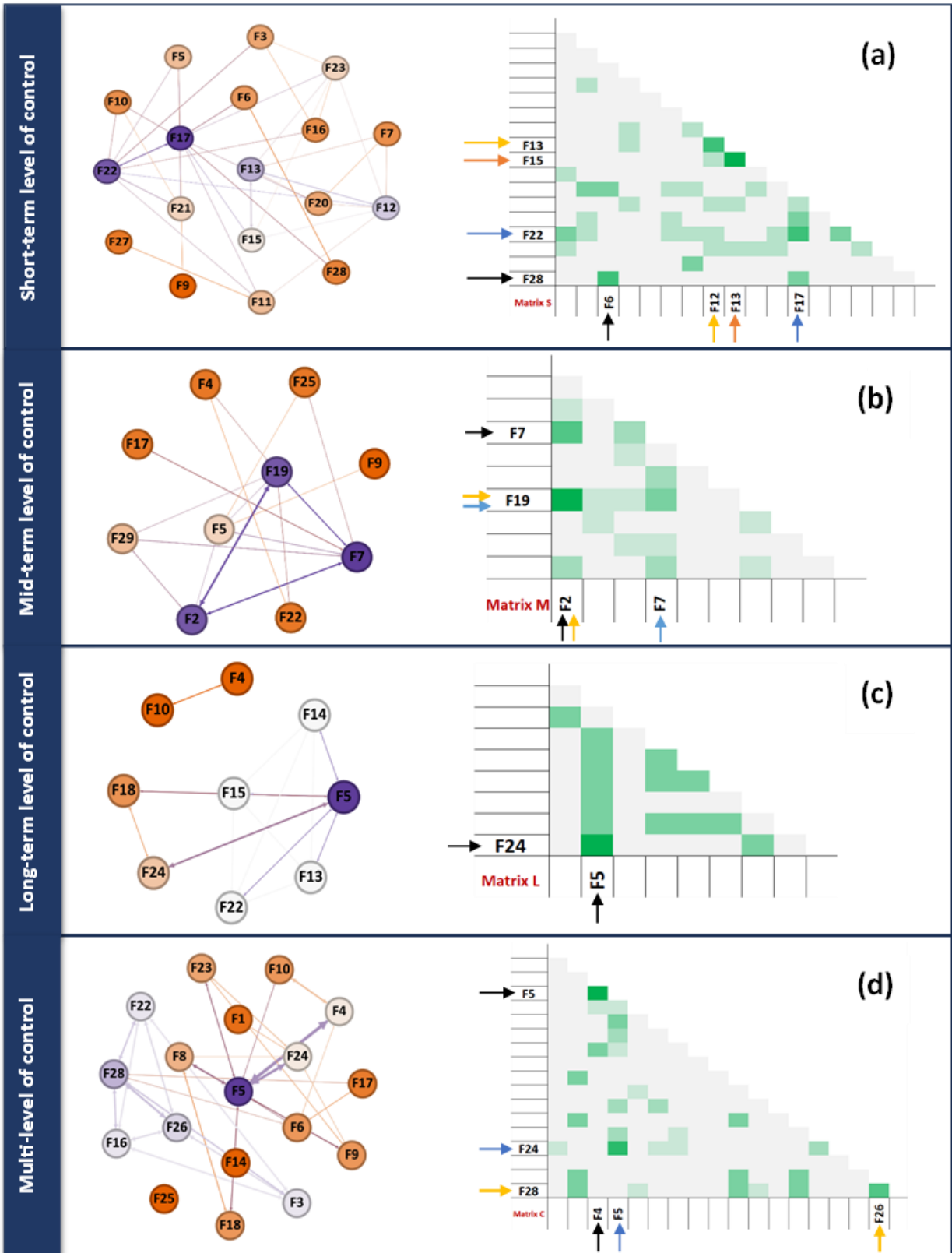


Fig. 2.19. Networks and color-coded matrices of metrics' functionalities for different levels of control

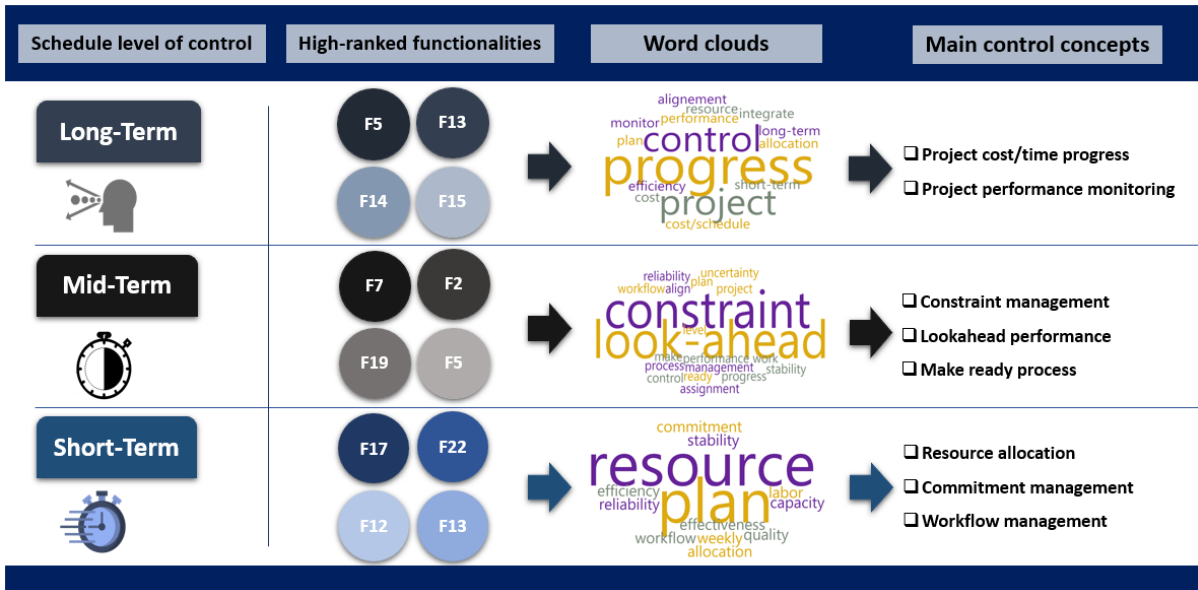


Fig. 2.20. Underlying concepts of control at each schedule level

Analyzing the Networks of Perspective 2

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

On the other hand, through predictive analytics, project teams are able to estimate and highlight future schedule delays and other issues before they occur on the construction site by evaluating production data. This enables them to resolve issues proactively before they occur. Therefore, it is imperative that actionable information be shared in a proactive manner regarding probable delays and other concerns on construction sites to enhance schedule reliability (Lin and Golparvar-Fard 2021). This is accomplished using a second set of control metrics, leading metrics, to predict future performance. Most of these leading metrics are based on lean principles and support regular monitoring of planning reliability during the project execution phase (Hamzeh et al. 2020b). So, adequate understanding and awareness of both types of metrics and their functionalities are crucial for the project's control. This section's analyses will considerably assist the project manager in understanding and evaluating various metrics and their functionalities to decide on the most appropriate metrics.

There are two networks in this perspective: networks **D** and **G**. Fig. 2.21 (a) shows the network and color-coded matrix of leading metrics' functionalities. Network **D** addresses 18 out of 29 functionalities, emphasizing its capability to handle the majority. Notably, F5 (control project progress and performance) and F7 (evaluate the performance of the lookahead level) receive the most attention, while F29 (align the work plan assignment with the lookahead), F25 (quantify the reliability of starting or finishing the task on time), F20 (measure the percentage of differentiate tasks in the Weekly Work Plan (WWP)), and F21 (measure the quality of the commitments) are given the least focus. Also, the co-occurrence of F7 (evaluate the performance of the lookahead level) and F2 (manage constraints removal), F19 (measure the

make-ready process) and F2 (manage constraint removal), F8 (forecast project duration) and F5 (control project progress and performance), F18 (measure the achievability of a target project duration) and F5 (control project progress and performance), and F10 (identify highly sensitive activities) and F4 (control of uncertainty) have been employed as the most often combinations of functionalities in the leading control metrics.

Table 2.10 in the methodology section indicates that 70% of control metrics are linked to lagging metrics, suggesting their broader support functionalities. This is visually depicted in Fig. 2.21 (b), where the network and matrix G associated with lagging metrics appear denser than those for leading metrics. Notably, Network G 's 25 nodes predominantly address key functionalities, with F5 (control project progress and performance), F22 (measure the reliability and stability of workflow), F28 (improve continuous learning), and F16 (measure the quality of construction flow) being crucial for lagging control metrics. Conversely, F1 (achieve an integrated cost/schedule progress monitoring and control), F10 (identify highly sensitive activities), F27 (relate workflow reliability to productivity), and F21 (measure the quality of the commitments) have the least focus in this context. Furthermore, co-occurrence analysis in the color-coded matrix of Network G reveals frequent combinations, such as F5 (control project progress and performance) and F4(control of uncertainty), F3 (maintain continuity of trade work) and F22 (measure the reliability and stability of workflow), and F24 (provide managerial information) and F5 (control project progress and performance) emphasizing their importance in lagging control metrics.

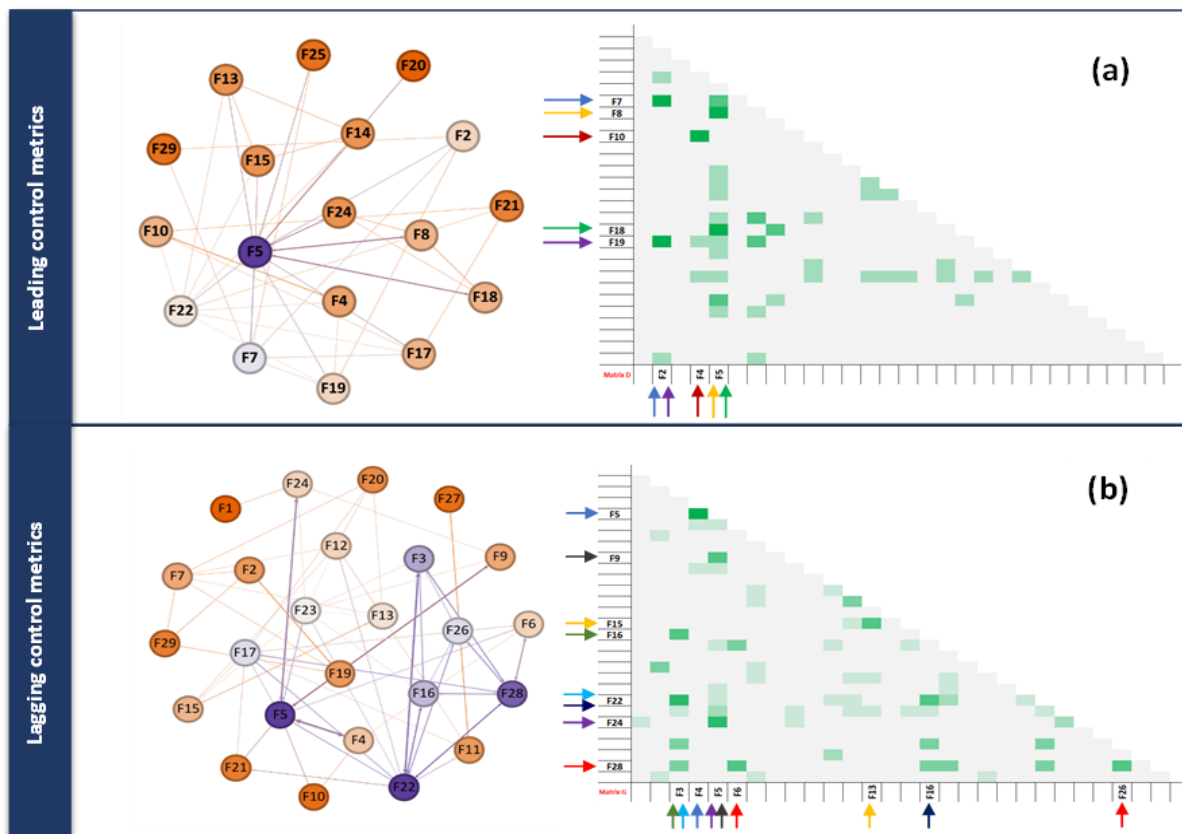


Fig. 2.21. Networks and color-coded matrices of the leading and lagging control metrics' functionalities

To clearly illustrate and understand the differences between the most significant functionalities in leading and lagging control metrics presented above, the authors developed Fig. 2.22, which represents the difference in normalized DCs of the D and G (D-G) networks. The positive values imply that the leading control metrics have emphasized the corresponding functionalities more. On the other hand, the negative values indicate that the related functionalities have been supported more by the lagging control metrics. Fig. 2.22 also clearly shows that lagging metrics have significantly supported most control metrics' functionalities (negative values). Although leading metrics, as previously mentioned, are crucial for project management and control, insufficient attention has been paid to them and their functionalities in research and industry. This issue can direct future studies on these types of metrics.

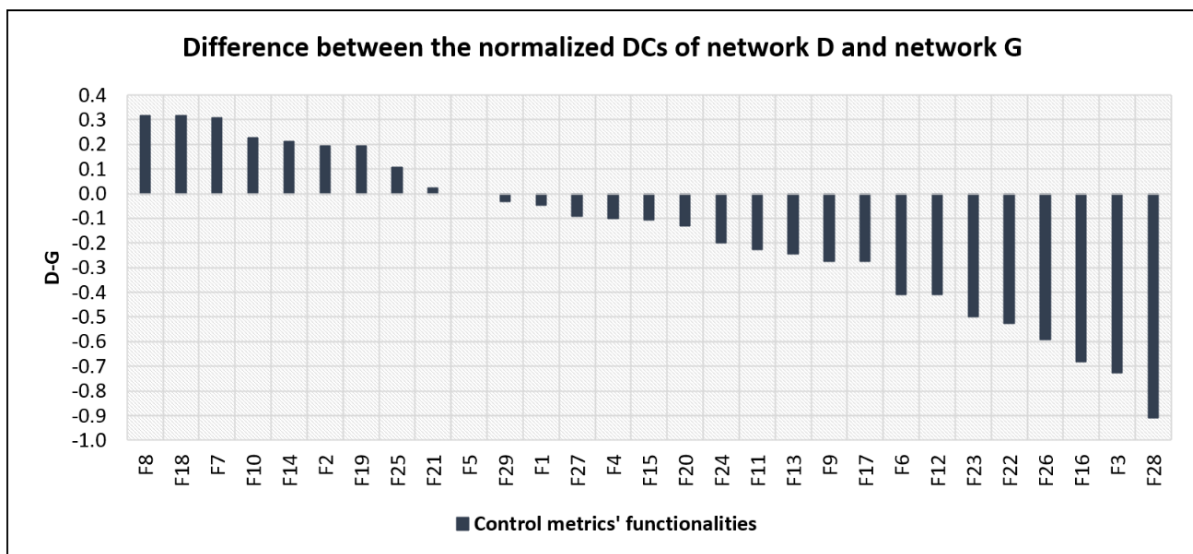


Fig. 2.22. Calculated differences between the DCs of the D and G networks

2.2.4. Validation

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

Additionally, variance and standard deviation serve as measures to gauge the extent of deviation of data points from the mean, allowing them to quantify the degree of variability or dispersion within the dataset. The results of the mentioned statistics tests are presented in Table 2.13. Furthermore, to demonstrate the differences in normalized scores between the SNA and the simplified analysis, Fig. 2.23 depicts violin plots for the findings of two techniques for all matrices. A violin plot combines a box plot and a kernel density plot. In addition to summary statistics, it can also display the probability density of the data. As seen in Table 2.13, Pearson correlation results above 0.85 indicate a high linear relationship between the results of these two methods presented in this study. Moreover, in the case of violin plots for

each matrix, both violin plots, representing simplified analysis and SNA, reveal identical distribution shapes with smooth and symmetric kernel density curves. This similarity indicates that data points are concentrated around similar values, leading to comparable distribution patterns. Moreover, the box plots of both violin plots exhibit striking similarities, suggesting that the data sets share comparable measures of central tendency, spread, and overall distribution. Consequently, it can be reasonably concluded that the two compared methods possess similar characteristics and statistical properties. As a result, the presented statistics in Fig. 2.23 and Table 2.13 reveal that the SNA is performing as expected.

Table 2.13. Statistical test results on the simplified analysis and SNA for all matrices of this study

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

*SA: Simplified Analysis, SNA: Social Network Analysis

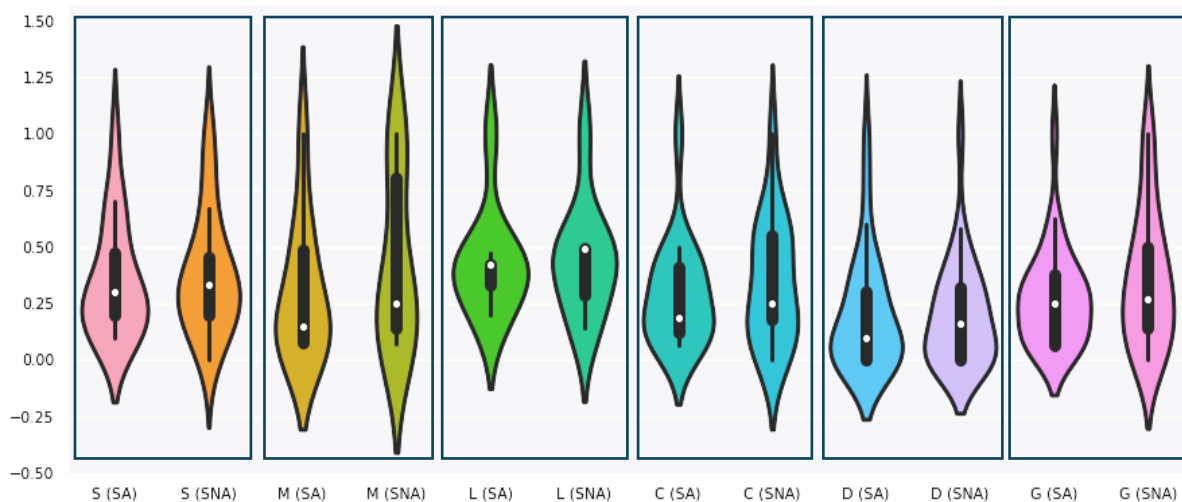


Fig. 2.23. Violin plots for the findings of Simplified Analysis (SA) and SNA for all matrices

2.2.5. Research Discussions, Contributions, and Future Recommendations

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

Many control metrics and inadequate comprehension and awareness of project planning and control theories and methods among project stakeholders (Al Nasser et al. 2016) led to the definition of the functionality concept. This research found and analyzed control metrics' functionalities to enhance the sensemaking of control metrics. The findings can assist project teams in choosing the most appropriate metrics for keeping track of their projects,

attentively matching the right planning skills to various planning activities, and promoting the knowledge and understanding of the functionalities required at the early stages and late stages of the project planning process, particularly those needed for planning, control, and both; functionalities can either be applied proactively (leading) or reactively (lagging); those can be used in the short-term, mid-term, and long-term.

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

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

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

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

(control of uncertainty) at the mid-term level reflects the limited coverage for this functionality in the available control metrics at this level of the schedule. To handle the monitoring and management of process uncertainties at this level, the authors propose adopting buffer control metrics in combination with advanced lean-based control metrics.

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

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

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

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

2.2.6. The Implications of the Findings:

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

2.2.6.1. Theoretical Implications

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

2.2.6.2. Practical Implications

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

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

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

2.2.7. Conclusion and Limitations

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

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

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

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

2.3. Section 3: From Process-based to Technology-driven: A Study on Functionalities as Key Elements of Collaborative Planning Methods for Construction Projects

This section also is part of the review and analysis of literature on planning and control systems, aligned with the first objective of this thesis. The aim is to identify and analyze various types of collaborative planning methods from process-based to technology driven approaches. To deal with this, a multi-stage methodology was carried out to achieve the aims of this section. The first step was identifying collaborative planning methods and their functionalities in the construction sector. Further, a quantitative analysis based on social network analysis (SNA) was conducted to determine the most frequently utilized functionalities in collaborative planning methods. The results revealed that process-based collaborative planning methods' functionalities prioritized process and people-related characteristics such as team trust and promise, as well as social interactions, whereas technology-driven methods highlighted visualization along with collaboration and communication as a key element of collaborative planning. Subsequently, this study contributes to the body of construction project planning and control knowledge from both theoretical and practical perspectives by enhancing the understanding and sensemaking of project stakeholders toward the underlying concepts and objectives of collaborative planning methods.

2.3.1. Introduction

Over the past decades, the construction industry has been known for its poor productivity performance compared to other sectors (Momade et al. 2023). The lack of effective communication, the fragmented and temporary nature, the uncertain and dynamic environment, and the lack of efficient collaboration between stakeholders are among the important factors contributing to this issue (Durdyev et al. 2019; Sheikhhoshkar et al. 2023a). Significant efforts, especially with emerging new technologies, have been made to enhance collaboration in the planning process to address any issues posed by poor productivity due to inefficient construction planning and control (CII 2021).

In construction projects, schedules are crucial for determining payments, completion dates, coordinating various stakeholders, and controlling project progress (Sheikhhoshkar et al. 2024c). Predominantly, the construction industry employs Critical Path Method (CPM) logic as the primary planning and scheduling tool, acknowledged for its efficiency in formulating plans and schedules for projects characterized by high complexity (Olivieri et al. 2019). However, it falls short in fostering collaboration during project planning and scheduling processes (Koolwijk et al. 2018). Due to the complexity of projects and the involvement of many stakeholders, the industry realized the need for better integration in project planning and control. This recognition led to the essential adoption of collaboration as a key process to align participants toward the common goal of delivering projects (He et al. 2022). In this

context, the introduction of the Last Planner System (LPS) marked a pivotal transformation in project planning (Ballard and Howell 2003; Ballard 2000), enhancing the productivity of trades (Ballard and Tommelein 2021), reducing waste (Sheikhhoshkar et al. 2023a), improving collaboration through social conversations (Daniel et al. 2017), increasing the reliability of project planning (Javanmardi et al. 2018; Sheikhhoshkar et al. 2023), boosting transparency (Salhab et al. 2021), enhancing the network of commitments (Scala et al. 2022), and improving communication and teamwork among the project team (Daniel et al. 2019). Further advancements have seen the application of agile methodologies, such as Scrum and Kanban, alongside innovative approaches like Advanced Work Packaging (AWP) to bolster planning efficiency and project execution (Guerra and Leite 2020; Rebai et al. 2022; Sakikhales 2021).

Emerging Building Information Modeling (BIM) has further revolutionized collaborative planning, enhancing information exchange and project visualization throughout the lifecycle of construction projects (Ayman et al. 2022). Moreover, the integration of Industry 4.0 technologies with BIM applications has opened new avenues for engaging stakeholders more in project planning and control processes (Dawood et al. 2022; Sheikhhoshkar et al. 2019).

Despite these advancements, adopting modern collaborative planning methods faces barriers primarily due to a reluctance to move away from traditional practices and a lack of awareness regarding the underlying concepts and benefits of these innovative approaches (AlNasseri and Aulin 2015; Sheikhhoshkar et al. 2023a). This gap underscores the need for a deeper understanding of collaborative planning principles and their practical application within the construction industry, leading to the introduction of the "functionality concept" in this study based on Sheikhhoshkar et al. (2023)'s definition for integrated planning and scheduling methods. Functionality refers to the operations and primary goals within collaborative planning methods. In this study, identifying and analyzing functionalities can enhance understanding and sensemaking among project stakeholders, such as the engineering team (contractors/engineering cross-disciplinary), project owners, as well as suppliers toward the key features and objectives of technology-driven and process-based collaborative planning approaches. This augmented understanding is pivotal in facilitating the informed selection of the most efficacious collaborative strategy for the planning and control of construction sites, thereby optimizing project outcomes through improved stakeholder alignment and decision-making processes.

This paper aims to address these challenges by providing a comprehensive analysis of collaborative planning methods in construction, focusing on their functionalities and the interconnections between different approaches. To this end, the objectives of this study include:

1. Identify the most significant collaborative planning methods in the construction industry
2. Identify underlying concepts of collaborative planning methods as their functionalities
3. Analyze the identified functionalities based on their interconnections and figure out the most frequently utilized functionalities in collaborative planning methods

It should be noted that this paper focuses on collaborative planning methods for planning and operation phase of the projects and applicable to all types of project delivery including Integrated Project Delivery (IPD)/Alliancing and those employing traditional delivery

methods.

The following sections address research methodology, then results and analyses, validation, discussion, and future directions, and finally conclusions and limitations.

2.3.2. Literature Review

Throughout the review of collaborative planning methods over time, several topics have been discussed, including general discussions regarding collaboration within project planning and scheduling as well as in-depth analyses of specific collaborative planning approaches. Regarding the former, Elsayegh and El-adaway (2021b) conducted a comprehensive study into the factors influencing collaborative planning within the construction sector. Elsayegh and El-adaway (2021a) proposed a Collaborative Planning Index (CPI) to measure the effectiveness of collaborative planning practices within construction projects. Scala et al. (2022) presented a practical maturity model for Collaborative Scheduling (CS), enabling practitioners to assess the current state of collaboration in their projects across five distinct dimensions or pillars and identify actionable steps for enhancing collaboration. As for the latter category, Pourrahimian et al. (2023) delved into the effect of collaboration across various phases of the Last Planner System (LPS). According to Daniel et al. (2020), while current construction planning methods, such as CPM and waterfall models, lack adaptability and collaboration support, scrum methods and last planner systems (LPS) are innovative approaches that integrate 'transformation', 'flow' and 'value' view theory, promoting effective collaboration and workflow within projects.

Moreover, the recent technological advancements, particularly in Industry 4.0, have spurred numerous studies on enhancing collaborative planning and control through the integration of BIM applications, notably the fourth dimension (4D), Virtual Reality (VR) (Boton 2018; Rashidi et al. 2023), digital twin that created and continuously updated through integrating of artificial intelligence (AI), internet of things (IoT), machine learning and cognitive computing (Alizadehsalehi and Yitmen 2023; Kim et al. 2021), multi-user VR (Truong et al. 2021; Zhou et al. 2012), touch table and touch wall screens (Boje et al. 2019; Boje et al. 2022), as well as web-based platforms (Kang et al. 2007; Lin and Golparvar-Fard 2016) have emerged as key technologies integrated with 4DBIM. These technologies address a range of objectives, including identifying sequencing planning issues, enhancing project and process comprehension, conducting constructability analysis, promoting safety and disaster management, optimizing resource allocation for schedule management, decentralizing work tracking and information sharing on construction sites, facilitating collaborative interactions among team professionals and stakeholders within a unified environment, and embracing a user-centric approach in collaborative planning.

It's worth noting that while collaborative planning literature includes applications in various fields such as urban planning (Lin 2022), digital manufacturing (Wang et al. 2009), process planning and manufacturing in product lifecycle management (Ming et al. 2008), low-carbon innovation strategy development (Wu et al. 2023), and so on, this paper specifically focuses on its relevance within the construction industry.

The analysis of existing literature has consistently highlighted the lack of comprehensive studies on the diverse range of collaborative planning methods employed within the construction industry (Bolshakova et al. 2019; Elsayegh 2021; Scala et al. 2022; Sheikhhoshkar et al. 2023a). Furthermore, there has been an inadequate exploration of the

fundamental principles and concepts that form the foundation of collaborative planning methods. Additionally, there is a notable dearth of knowledge regarding the functionalities that are most commonly utilized in real-world collaborative planning scenarios. These gaps highlight the need for further investigation and a more comprehensive understanding of collaborative planning methods to address the challenges faced in construction planning and control.

2.3.3. Research Methodology

A multi-stage methodology is adopted to achieve the goals and objectives of this research. The steps of the approach are shown in Fig. 2.24. Data collection using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), content analysis, and Social Network Analysis (SNA) are the main pillars of the adopted methodology. The following sections elaborate on each of these steps.

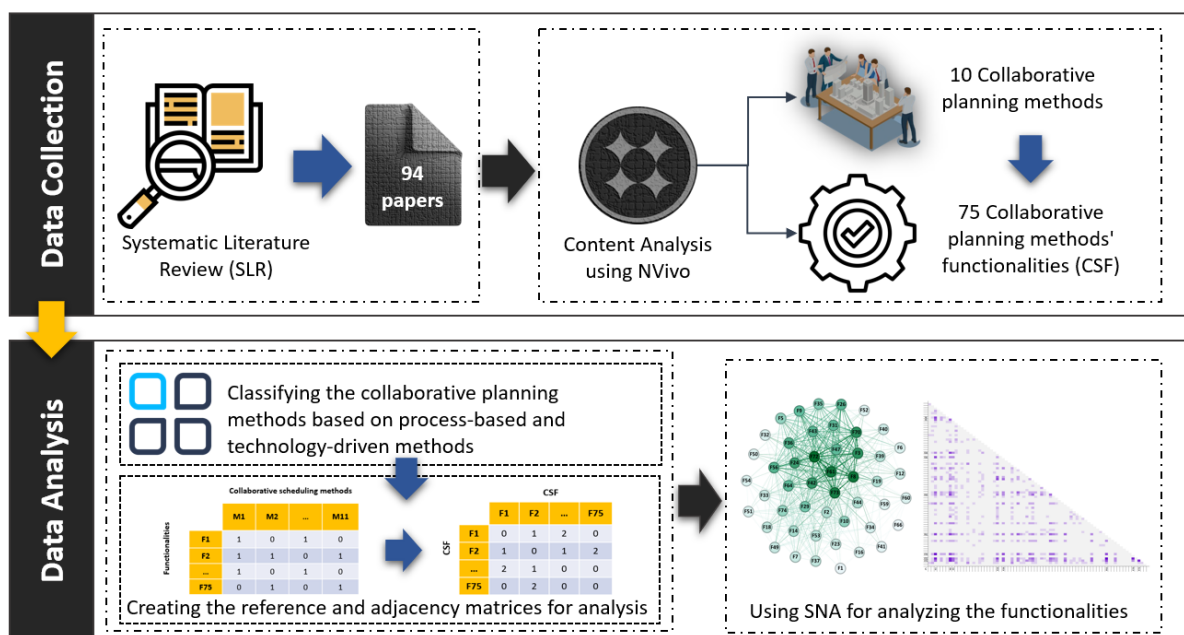


Fig. 2.24. The process of applied methodology

2.3.3.1. Systematic Literature Review (SLR)

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline and content analysis were followed to collect the required data for this study's objectives. PRISMA offers a standard approach that employs a guideline checklist, which was precisely considered in this paper to ensure the quality assurance and replicability of the review process (Abelha et al. 2020). To do so, a review protocol was established providing a search strategy, the article selection criteria, a screening procedure, and data extraction, as shown in Fig. 2.25.

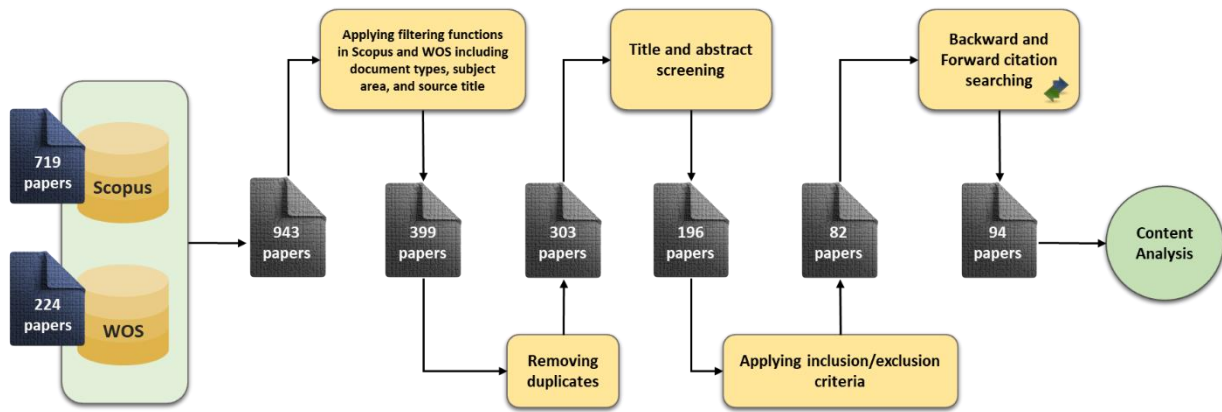


Fig. 2.25. Applied review process

Search Procedure

A systematic search was conducted on two electronic databases, Web of Science and Scopus, addressing collaborative planning methods in the construction industry over the last three decades. The search term was formulated by incorporating the relevant keywords and synonyms to collaborative planning methods using the Boolean operators "AND" and "OR" (Table 2.14) and conducted for the topic (WoS), article title, abstract, and keywords (Scopus). The initial search identified a total of 943 articles.

Table 2.14. Search query

Search databases	Search term
Web of Science & Scopus	("collaborative scheduling" OR "collaborative planning" OR "4D" OR "4DBIM" OR "last planner system" OR "LPS" OR "VR" OR "virtual reality" OR "Metaverse" OR "Digital Twins" OR "Agile") AND ("project planning" OR "project scheduling" OR "project control" OR "construction planning" OR "construction scheduling")

Eligibility Criteria

In order to evaluate the quality of the selected articles, several inclusion and exclusion criteria were employed to ensure that they were relevant to the research objectives as well as methodologically rigorous, as shown in Table 2.15.

Table 2.15. Employed eligibility criteria

Inclusion criteria	Exclusion criteria
Written in English	Papers in languages other than English
Peer-reviewed publications from reputable construction and manufacturing journals and conferences	Not peer-reviewed scientific reports and documents
Relevant to the aims of this study (collaborative planning methods)	Outside the scope of this research
Within the scope of the construction industry	Not applicable to the construction industry

Screening Process

The initial identified papers were screened and reviewed using a multi-step process. The

filters available in Scopus and WoS, including document type, subject area, and source title, were used in the first stage to reduce the number of articles and eliminate those not meeting the eligibility criteria. Furthermore, the screening process involved removing duplicates, screening the title and abstract and applying inclusion and exclusion criteria in the full-text review stage. Also, to ensure the key publications were included, backward and forward citation searching were applied. In the end, 94 papers were selected for content analysis. The whole procedure of screening is depicted in Fig. 2.25.

Content Analysis

The content analysis was performed on 94 finalized papers that passed the screening process to extract the collaborative planning methods and their functionalities for further analysis. To do this, NVivo 12 was used to codify the required contents. Considering Sheikhhoshkar et al. (2023a)'s study, the authors established three distinct codes to extract the functionality of collaborative planning methods. These codes include (1) the goals and objectives of collaborative planning methods, (2) the research questions of each paper, and (3) the advantages of each collaborative planning method. The analysis and coding of 94 finalized papers identified 157 objectives and underlying concepts related to collaborative planning methods in the initial stage. In order to streamline the functionalities, duplicate functionalities were eliminated, and those with similar concepts were merged. The first author carried out the aggregation of functionalities and assessed and approved by the other authors of the paper. Finally, ten collaborative planning methods and 75 functionalities were identified for further analysis.

2.3.3.2. Quantitative Data Analysis

After performing a content analysis, the authors formulated two reference matrices, C and T , to analyze the identified functionalities. To do so, the finalized papers were classified according to their collaborative planning methods. This study divided collaborative planning methods into two groups. The first category consisted of process-based collaborative planning methods, such as the Last Planner System (LPS), agile (Scrum and Kanban), Advanced Work Packaging (AWP), and some papers that discussed this topic in a general sense and were considered to be general collaborative planning. The second category comprised technology-driven collaborative planning methods, such as web-based 4DBIM, conventional 4D (refers to stand-alone dedicated 4DBIM tools), 4D-VR, multi-user VR, multi-touch screen-based 4D, and 4D-digital twins. The articles discussing process-based collaborative planning methods were included in the reference matrix C . In addition, the articles that covered the technology-driven collaborative planning methods were included in the reference matrix T . In a reference matrix, the columns indicate the analyzed articles and the rows correspond to the identified functionalities. A value of 1 is entered into the cell that corresponds to a functionality if it is specified in the article; otherwise, a value of 0 is provided. The Social Network Analysis (SNA) approach was employed to analyze the developed reference matrices quantitatively, and the simplified analysis approach was used to verify the results. Further details regarding these approaches are provided as follows.

Social Network Analysis

Social Network Analysis (SNA) is a mathematical approach based on graph theory that considers the interconnections of a network's variables to study its behavior (Elsayegh and El-adaway 2021b). In SNA, nodes and edges are used to illustrate relationships and various metrics and statistics can be utilized for analyzing these networks. As measuring a node's centrality in a network is the easiest and most reliable method of discovering its significance (Hosseini et al. 2018a), in this study degree centrality (DC) is utilized to analyze and quantify each node's importance. The preference for the SNA method stems from its ability to evaluate interactions among various aspects of collaborative planning methods discussed in various papers. It also provides visual representations of findings and patterns, as well as uncovering connections and patterns among functionalities that would otherwise remain hidden in a simplified analysis (Elsayegh and El-adaway 2021b; Sheikhhoshkar et al. 2023a).

Weighted Adjacency Matrices and Metrics

In order to calculate the DC metric for reference matrices \mathbf{C} and \mathbf{T} , it is necessary to construct the weighted adjacency matrices. The weighted adjacency matrix is a square matrix of dimensions $f \times f$, where f indicates the number of functionalities, and the values v_{ij} are the weights of the edges depicting the interconnectivity or co-occurrences between each pair of functionalities. This matrix is calculated using Eq. (2.11).

$$W_{f \times f} = \begin{cases} M_{f \times p} \times M_{f \times p}^T & \text{for } i \neq j \\ 0 & \text{for } i = j \end{cases} \quad (2.11)$$

where $W_{f \times f}$ = weighted adjacency matrix; $M_{f \times p}$ = reference matrix; $M_{f \times p}^T$ = transpose of the reference matrix; f = number of identified functionalities (i.e., 75); and p = number analyzed papers (i.e., 64 in matrix \mathbf{T}). The procedure of developing the weighted adjacency matrix is performed for both matrices, \mathbf{C} and \mathbf{T} .

Following the development of the weighted adjacency matrices, the DC for each functionality of collaborative planning methods is calculated based on Eq. (2.12).

$$DC_i = \sum_{j=1}^n v_{ij} \quad (2.12)$$

where DC_i = degree centrality of functionality i ; v_{ij} = value of i th row and j th column of the weighted adjacency matrix; and n = number of functionalities. Given the varying number of articles employed in each matrix, to ensure score consistency and facilitate functionalities comparison, a normalized DC_i was computed within a range of 0 to 1. The calculation of normalized DC values is shown in Eq. (2.13), whereby the DC value of each functionality is divided by the maximum DC value in the corresponding network.

$$\overline{DC}_i = \frac{DC_i}{\max\{DC_f\}} \quad (2.13)$$

Validation Method

To evaluate whether the SNA is working as expected, several studies utilized the simplified analysis technique (Elsayegh and El-adaway 2021b; Sheikhhoshkar et al. 2023a). The same approach was applied to validate the SNA results in this paper. This method calculates a score

for each functionality by summing all related cells in the row using Eq. (2.14).

$$S_i = \sum_{j=1}^n a_{ij} \quad (2.14)$$

where S_i = normalized simplified score of a functionality i ; and a_{ij} = value of i th row and j th column of the reference matrix. Considering the normalization reason and procedure for DCs, the normalized score for the simplified analysis is calculated using Eq. (2.15).

$$\bar{S}_i = \frac{S_i}{\max\{S_p\}} \quad (2.15)$$

2.3.4. Results and Analysis

In this section, the research results are presented and discussed, from data collection to analysis.

2.3.4.1. Data Collection Efforts

Through a systematic literature analysis, 94 papers were deemed to meet the necessary quality requirements for further analysis. Table 2.16 indicates the details of the selected papers in three decades. As can be seen in Table 2.16 and the right side of Fig. 2.26, most of the approved papers were published after 2019. This highlights that collaborative planning methods are a research domain that has attracted increasing interest in recent years. In addition to the published articles, this claim is supported by the attention of the Construction Industry Institute (CII) in 2021 to investigate the challenges and opportunities associated with implementing collaborative planning and scheduling in construction projects (CII 2021). The distribution of publications throughout the research period is depicted in Fig. 2.26. As shown on the left side of Fig. 2.26, despite variations in the number of papers published between 2016 and 2023, there is a considerable rise in the number of publications compared to 1999 to 2016. This increase in focus on this domain is a reaction to the challenges construction project managers are still facing in deploying methods to promote collaboration in construction project planning, despite the availability of various tools, technologies and methods to enhance collaborative planning and scheduling (He et al. 2022).

Table 2.16. Reviewed articles list

Years	Finalized papers	No. of papers
1999-2008	(Jongeling et al. 2008; Kang et al. 2007; Li et al. 2006; Retik and Shapira 1999; Shelbourn et al. 2007; Sriprasert and Dawood 2003; Strelzoff and Sulbaran 2008; Verheij and Augenbroe 2006; Yerrapathruni et al. 2003)	9
2009-2018	(Altun and Akcamete 2018; Bataglin et al. 2017; Bolshakova et al. 2017; Boton 2018; Boton et al. 2013; Daniel et al. 2017; Dawood and Sikka 2009; De Vargas et al. 2018; El-Sabek and McCabe 2018; Ganah and John 2017; Guerriero et al. 2017; Hamledari et al. 2017; Lin and Golparvar-Fard 2016; Lin and Golparvar-Fard 2017; Mirzaei et al. 2018; Olivieri et al. 2017; Peñaloza et al. 2016; Pratama 2015; Priven and Sacks 2016; Ratajczak et al. 2018; Ribeiro and Costa 2018; Romigh et al. 2017; Sacks et al. 2013; Schimanski et al. 2018; Su and Cai 2016; Su and Cai 2018; Von Heyl and Teizer 2017; Zegarra and Alarcón 2015; Zhao and An 2016; Zhou et al. 2012; Zhou et al. 2014)	31
2019-2023	(Afzal and Shafiq 2021; Alizadehsalehi and Yitmen 2023; Alzarrad et al. 2021; Ayman et al. 2022; Ballard and Tommelein 2021; Ballard et al. 2020; Boje et al. 2019; Boje et al. 2022; Bolshakova et al. 2020; Bolshakova et al. 2019; Bortolini et al. 2019; Boton et al. 2022; Bourlon and Boton 2019; CII 2021; Daniel et al. 2020; Daniel et al. 2019; Doukari et al.	54

2022a; Doukari et al. 2022b; Elghaish and Abrishami 2020; Elmughrabi et al. 2020; Elsayegh and El-adaway 2021a; Elsayegh and El-adaway 2021b; Fazeli et al. 2022; Guerra and Leite 2020; He et al. 2022; He et al. 2020; Huang et al. 2022; Huang et al. 2021; Jimenez Anders 2022; Kandregula and Le 2020; Khan et al. 2021; Khataei et al. 2020; Kim et al. 2021; Korb and Sacks 2021; Ma et al. 2020; Pérez and Bastos Costa 2021; Poudel et al. 2020; Rashidi et al. 2023; Rebai et al. 2022; Roupé et al. 2020; Sakikhales 2021; Salhab et al. 2021; Scala et al. 2022; Schiavi et al. 2022; Sheikhhoshkar et al. 2019; Tallgren et al. 2022; Tallgren et al. 2021; Tomar and Bansal 2022; Torres-Calderon et al. 2019; Truong et al. 2021; Wu et al. 2021; Yang et al. 2021)

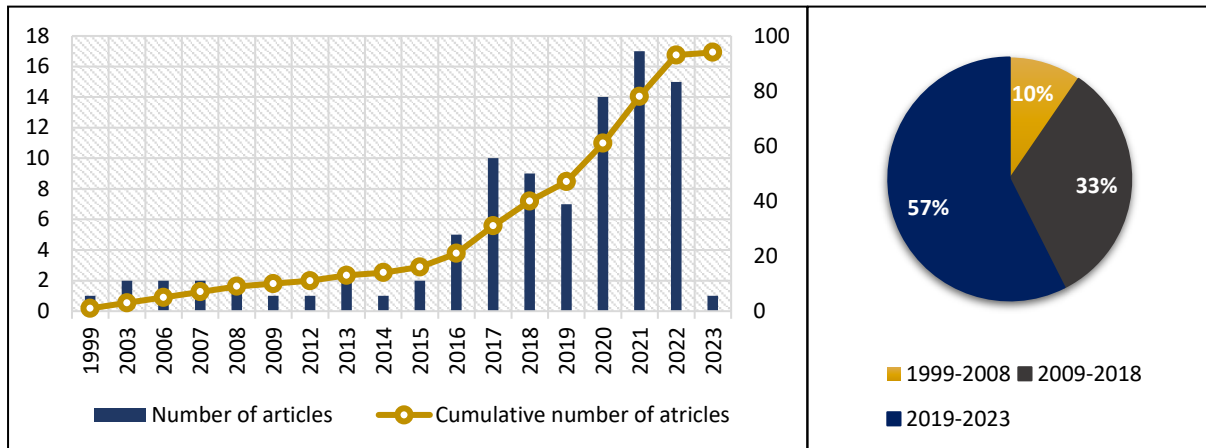


Fig. 2.26. The distribution of articles over time

2.3.4.2. Identified Collaborative Planning Methods

After reviewing the full text of the selected articles, ten collaborative planning methods were discovered. In order to investigate the different perspectives of their functionalities, these methods were divided into two groups: process-based collaborative planning methods and technology-driven methods. Table 2.17 presents the methods assigned to each group; the details are explained below.

Table 2.17. Identified collaborative methods

ID	Collaborative planning methods	References
1	Web-based 4D BIM	(Kang et al. 2007; Lin and Golparvar-Fard 2016; Olivieri et al. 2017)
2	Conventional 4D BIM	(Bortolini et al. 2019; Doukari et al. 2022b; Fazeli et al. 2022; Huang et al. 2022; Ma et al. 2020; Torres-Calderon et al. 2019)
3	Multi-user virtual reality (VR)	(Truong et al. 2021; Zhou et al. 2012; Zhou et al. 2014)
4	Multi-touch screen-based 4D	(Boje et al. 2022; Bolshakova et al. 2020; Bolshakova et al. 2019)
5	4D – virtual reality (4D-VR)	(Bourlon and Botton 2019; Rashidi et al. 2023; Roupé et al. 2020; Schiavi et al. 2022; Tallgren et al. 2022)
6	4D – digital twins (4D-DT)	(Alizadehsalehi and Yitmen 2023; Huang et al. 2021; Kim et al. 2021; Von Heyl and Teizer 2017)
7	General collaborative planning	(Daniel et al. 2020; Elsayegh and El-adaway 2021a; He et al. 2022; Scala et al. 2022; Verheij and Augenbroe 2006)
8	Last planner system (LPS)	(Ballard and Tommelein 2021; Ballard et al. 2020; Daniel et al. 2017; Priven and Sacks 2016; Roupé et al. 2020; Salhab et al. 2021)
9	Advanced work packaging (AWP)	(Guerra and Leite 2020; Rebai et al. 2022; Wu et al. 2021)
10	Agile (scrum, kanban)	(Daniel et al. 2020; Jimenez Anders 2022; Poudel et al. 2020; Sakikhales 2021)

In the context of this research, technology-driven collaborative planning methods are those that have used technologies such as Building Information Modeling (BIM), Virtual Reality (VR), touch table or touch wall screen, digital twins, and web-based platforms to facilitate collaboration between project stakeholders in project planning and control. Web-based 4D Building Information Modeling (BIM) emerges as a pivotal facilitator of remote collaboration. Leveraging accessible platforms, this technology enables real-time collaboration among stakeholders situated in disparate locations. Concurrently, Conventional 4D BIM assumes significance in its role as a visual representation tool for project timelines. Its utility lies in aiding project teams in comprehending temporal aspects and identifying potential conflicts during the planning phase. Multi-user Virtual Reality (VR) presents a critical role by creating an immersive shared environment, providing stakeholders with a virtual construction site experience that enhances comprehension and decision-making through realistic simulations. Furthermore, Multi-touch Screen-based 4D offers an interactive platform, fostering collaborative planning sessions where multiple team members can contribute concurrently. The integration of time into Virtual Reality, as exemplified by 4D-VR, provides a unique immersive perspective of the project's temporal evolution. Lastly, 4D-Digital Twins (4D-DT) integrates real-time monitoring and predictive analysis, collectively enhancing decision-making efficacy. The combination of these technologies contributes synergistically to a paradigm shift in collaborative planning, fostering real-time collaboration, augmenting visualization, and incorporating temporal dimensions into the decision-making process. This synthesis underscores the profound impact of these technologies within the academic discourse on construction project planning.

It should be mentioned that conventional 4D BIM in this group refers to the 4D model created by integrating the 3D model and Critical Path Method (CPM)-based scheduling in stand-alone software such as Navisworks, Synchro, or similar ones.

In addition, process-based collaborative planning methods are those that attempt to involve stakeholders by changing and simplifying the process and improving communication, such as the Last Planner System (LPS) and Advanced Work Packaging (AWP). It is worth noting that some articles have discussed collaborative planning methods in general, and without focusing on a specific method or technique, these articles were categorized in the form of general collaborative planning methods and put in the process-based methods group.

Fig. 2.27 depicts the evolution of collaborative planning methods over twenty-four years. The diagram is divided into two sections, the upper part for technology-driven methods and the lower part for process-based methods, each representing a specific period for their corresponding methods. The left section of the diagram represents the starting point 24 years ago, illustrating the emphasis placed on the last planner system to incorporate the project team into the project planning process (Ballard 2000). Despite the emergence of technology-driven methods such as conventional 4D and 4D-VR in the early years (Retik and Shapira 1999), the technological, organizational, hardware, and software maturity required to use them for collaborative planning in the construction industry was not available. Moving to the right and with technological advancement, the diagram depicts technology integration into collaborative planning methods. In recent years, with the development of technology in the era of the fourth industrial revolution, the focus has shifted towards the use of technologies such as virtual reality, web-based platforms, multi-user touch screens, digital twins and metaverse for collaborative planning (Boje et al. 2022; Huang et al. 2021; Rashidi et al. 2023; Truong et al. 2021), although the focus on process-based collaborative methods has also been

an integral part of collaborative planning.

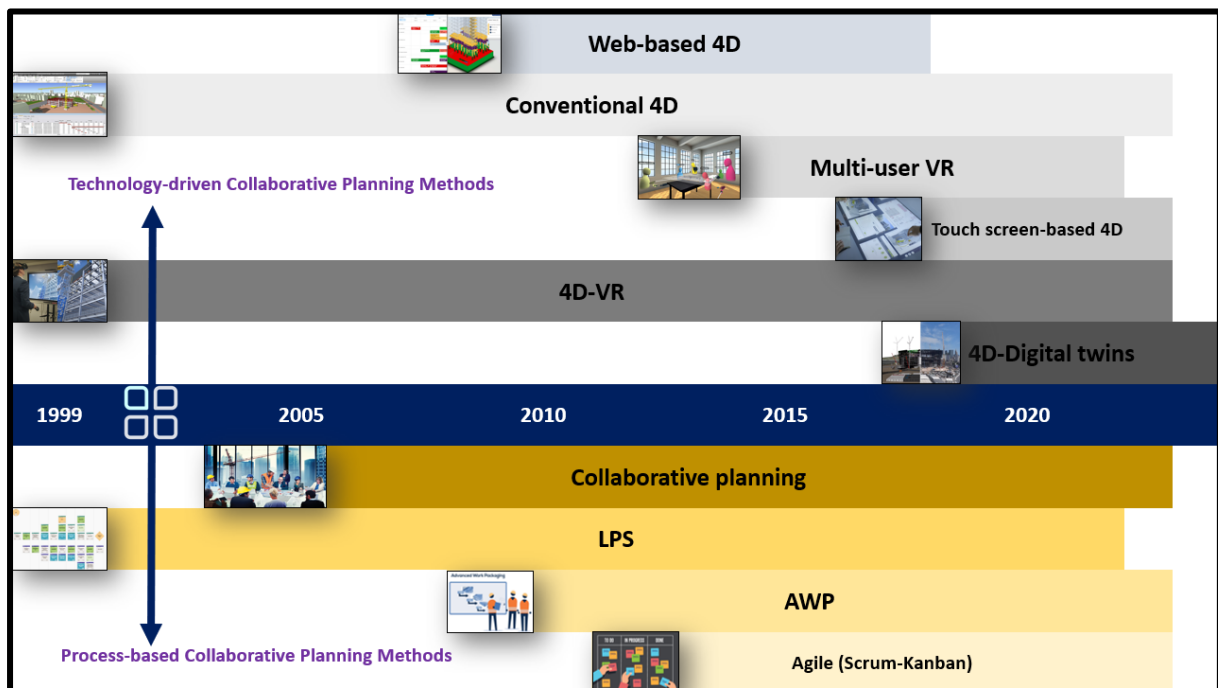


Fig. 2.27. Evolution of collaborative planning methods over time

2.3.4.3. Quantitative Analysis of Collaborative Planning Methods' Functionalities

By reviewing the papers provided in Table 2.16, in addition to identifying collaborative planning methods, the authors discovered 75 of their functionalities in the construction industry, illustrated in Table 2.18. As detailed in the methodology part, two reference matrices, T and C , were created to analyze these functionalities. The matrix T contains 64 papers and 64 functionalities, resulting in a matrix of dimensions 64 by 64. Similarly, matrix C consists of 30 papers and 46 functionalities, creating a matrix of dimensions 46 by 30. After constructing the reference matrices, SNA was utilized as a quantitative technique to analyze the functionalities of collaborative planning methods. The following explains the results of the functionalities analysis.

Table 2.18. Collaborative planning methods' functionalities

ID	Collaborative planning methods' functionalities
F1	Allowing just-in-time (JIT) purchasing and delivery of material
F2	Allowing the interactions of multiple team professionals and stakeholders in a common environment.
F3	Assisting in reducing waste
F4	Automated planning of concrete joint layouts
F5	Automatic generation of the as-built real-time 4D simulation
F6	Better flow of information
F7	Constructability evaluation
F8	Continuous improvement process
F9	Continuous learning
F10	Creativity, option generation, and innovation
F11	Decentralized work tracking and information communication on construction sites
F12	Detected more logical errors faster with less need for intrateam communication
F13	Dynamic collision detection and spatial-temporal conflict analysis
F14	Early involvement of key project stakeholders
F15	Easing of access and low training time
F16	Effective supply chain practices
F17	Empowering automated project progress monitoring
F18	Enabling lean construction adoption and situation awareness
F19	Enabling project performance prediction
F20	Enabling real-time collaborative 4D planning to gain a robust construction plan
F21	Enabling real-time communication with workers
F22	Enabling real-time tracking in construction site
F23	Enabling value management/engineering
F24	Enhancing transparency
F25	Experiencing and reviewing scheduled sequences on a 1:1 scale
F26	Facilitating communication with subcontractors
F27	Fosters the convergence of 4D uses with project documents
F28	Generating real-time interactive project visualization
F29	Aligning goals with owner
F30	Higher sense of immersion and interaction
F31	Highlighting the importance of short-term planning at crew level
F32	Identifying possible optimizations
F33	Identifying time-space conflicts
F34	Improving alignment of engineering & procurement with construction and commissioning
F35	Improving collaborative sensemaking
F36	Improving communication and teamworking between the project team
F37	Improving decision making among geographically dispersed industry practitioners
F38	Improving engineering curriculum
F39	Improving organizational agility
F40	Improving role description and responsibilities
F41	Improving safety management on site
F42	Improving the involvement and the commitment of all the professional groups
F43	Increasing the work-flow reliability onsite
F44	Maintaining a workable backlog
F45	Making decision under a user-centric approach
F46	Monitoring worker motion and worker location
F47	More efficient resources management.

Table 2.18. (Continued)

ID	Collaborative planning methods' functionalities
F48	More natural and industry-adapted interactions during a collaboration session
F49	Moving participants from passive receivers of a schedule to active contributors to the schedule
F50	Permitting real-time virtual collaboration for stakeholders from different locations
F51	Providing predictive control methods to make the best decisions with forwarding simulation
F52	Providing a digital equivalence to face-to-face communication in construction projects
F53	Providing better budget control
F54	Providing enhanced awareness of ongoing work
F55	Providing ergonomic interactions with the session workflow.
F56	Pull planning effectiveness
F57	Real-time safety monitoring
F58	Reducing information loss in data exchange
F59	Reducing the change orders during construction
F60	Reducing the impacts of potential causes of delay
F61	Reducing uncertainty and risk
F62	Reshaping an individual's cognitive patterns to influence collaboration throughout project delivery
F63	Safer learning environment
F64	Sharing the knowledge and lessons learned
F65	Site layout and environment management
F66	Solving disputes more efficiently
F67	Solving site logistic problems
F68	Supporting the learning and process of offsite construction production planning challenges
F69	Supporting co-navigate, co-sort, co-plan, co-simulate and co-talk
F70	Supporting collaboration through social conversations
F71	Supporting multi-functional review meetings
F72	Supporting the trust and reliable promises among the team
F73	Systematic identification and removal of constraints
F74	Visualizing alternative construction sequences based on various what-if scenarios
F75	Workspace planning

Social Network Analysis

As a result of the constructed reference matrices, the weighted adjacency matrices, $C_{46 \times 46}$ and $T_{64 \times 64}$, were developed to calculate the degree of centrality (DC) for identified functionalities. The results of the scores for each functionality are provided in the Appendix, Table A3. Using this metric within this study's context can emphasize the understudied and extensively studied functionalities in both technology-driven and process-based collaborative planning methods. In this regard, Fig. 2.28 (a) and Fig. 2.29 (a) show the networks of functionalities for process-based and technology-driven collaborative planning methods, respectively. The process-based collaborative planning methods' functionalities network (Network C) includes 864 edges and 46 nodes, indicating that process-based collaborative planning methods covered 46 functionalities out of 75. Also, the functionalities network for technology-driven collaborative planning methods (Network T) consists of 1558 edges and 64 nodes, demonstrating that technology-driven collaborative planning methods can support 64 out of 75 functionalities. The network nodes reflect the functionalities, whereas the edges indicate the interdependence or co-occurrence of each pair of functionalities. The node's color corresponds to the computed DC of the associated functionality, higher DC values equate to darker colors. Furthermore, the thickness of the edges reveals the degree of interconnection between functionalities, with greater thickness indicating a higher degree of co-occurrence. As networks have a significant number of connections, color-coded matrices

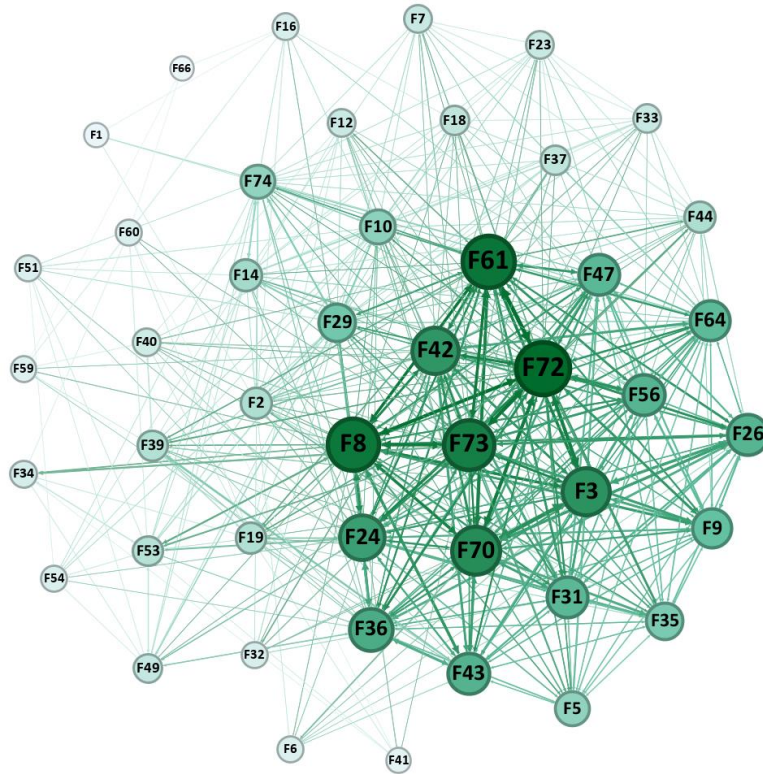
are provided to illustrate the co-occurrence of functionalities more clearly, Fig. 2.28 (b) and Fig. 2.29 (b). The matrices are color-coded according to the strength of the link between the two functionalities. The blank cells correspond to a pair of functionalities that never co-occurred in any of the collaborative planning methods, while darker cells indicate high weights and, so, a high co-occurrence between functionalities in the collaborative planning methods. The collaborative planning methods' functionalities in each network can be discussed from two perspectives: (1) the functionalities that were extensively studied or considered in collaborative planning methods, and (2) the functionalities that were neglected or understudied.

Addressing the first point of view, Fig. 2.28 (a) reveals that the most often utilized functionalities in process-based collaborative planning methods are F72 (supporting the trust and reliable promises among the team), F61 (reducing uncertainty and risk), F8 (continuous improvement process), F73 (systematic identification and removal of constraints), F70 (supporting collaboration through social conversations), and F3 (assisting in reducing waste). In addition, as shown in Fig. 2.29 (a), F36 (improving communication and teamwork between the project team), F41 (improving safety management on site), and F74 (visualizing alternative construction sequences based on various what-if scenarios) are the most frequently employed functionalities in technology-driven collaborative planning methods.

Concerning the second perspective, based on Fig. 2.28 (a) and Fig. 2.29 (a), F66 (solving disputes more efficiently), F1 (allowing just-in-time (JIT) purchasing and delivery of material), F41 (improving safety management on site), and F59 (reducing the change orders during construction) have received the least attention in process-based collaborative planning methods. Also, the results indicate that F1 (allowing just-in-time (JIT) purchasing and delivery of material), F73 (improving decision-making among geographically dispersed industry practitioners), F60 (reducing the impacts of potential causes of delay), and F20 (enabling real-time collaborative 4D planning to gain a robust construction plan) are functionalities with little consideration in technology-driven collaborative planning methods.

The interesting point is that F41 (improving safety management on site) is one of the most used functionalities in technology-driven collaborative planning methods, while it has been one of the least used functionalities in process-based methods. This indicates that technology-driven methods pay more attention to various project planning aspects, including safety. Moreover, another finding indicates a weakness in supply chain management within current collaborative planning methods, as evidenced by the low DC value for F1 (allowing just-in-time (JIT) purchasing and delivery of material) in both process-based and technology-driven approaches. Further study and investigation will be required to address this issue.

(a)



(b)

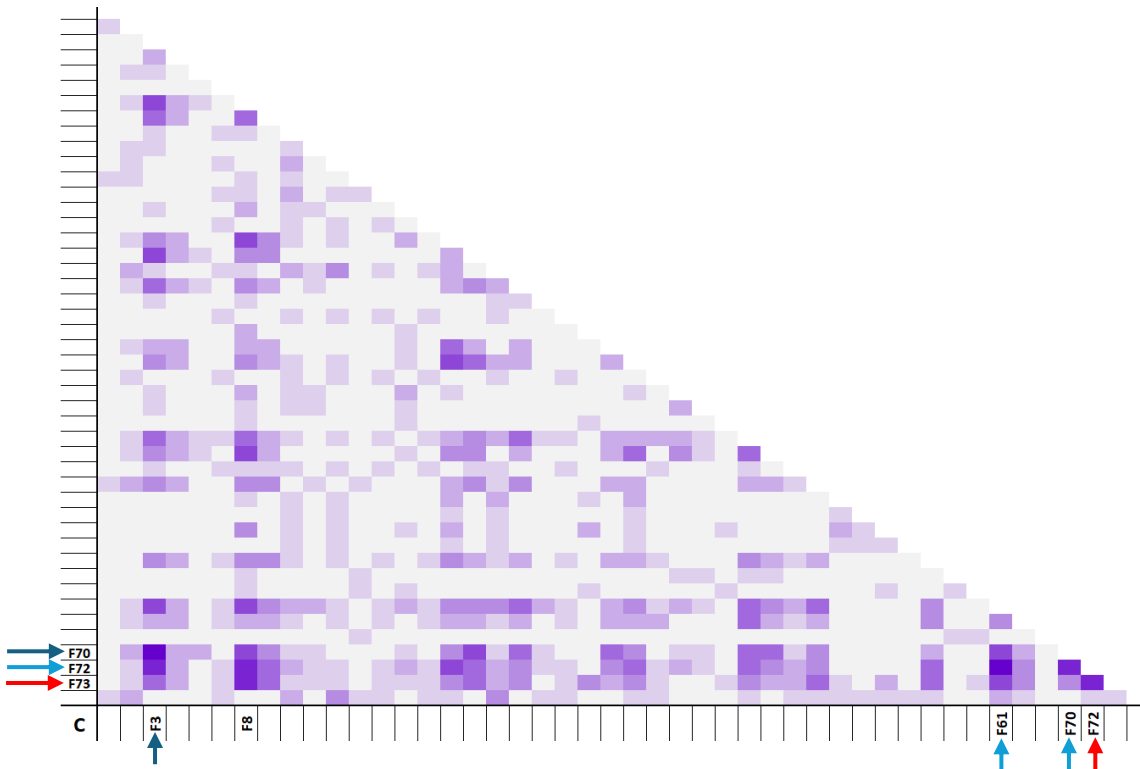
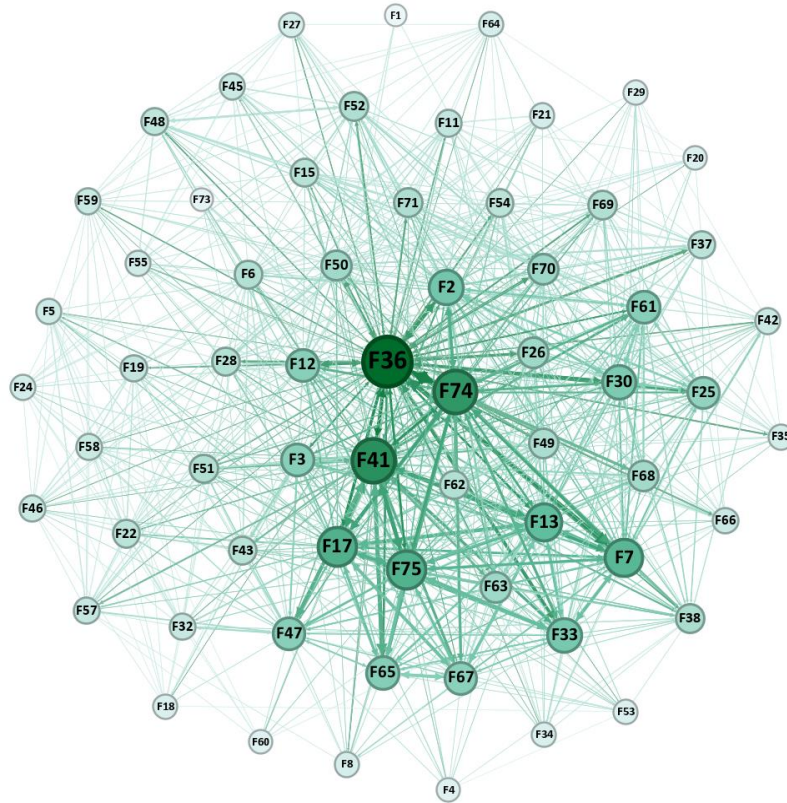


Fig. 2.28. (a) Process-based collaborative planning methods' functionalities network, (b) Color-coded matrix of functionalities

(a)



(b)

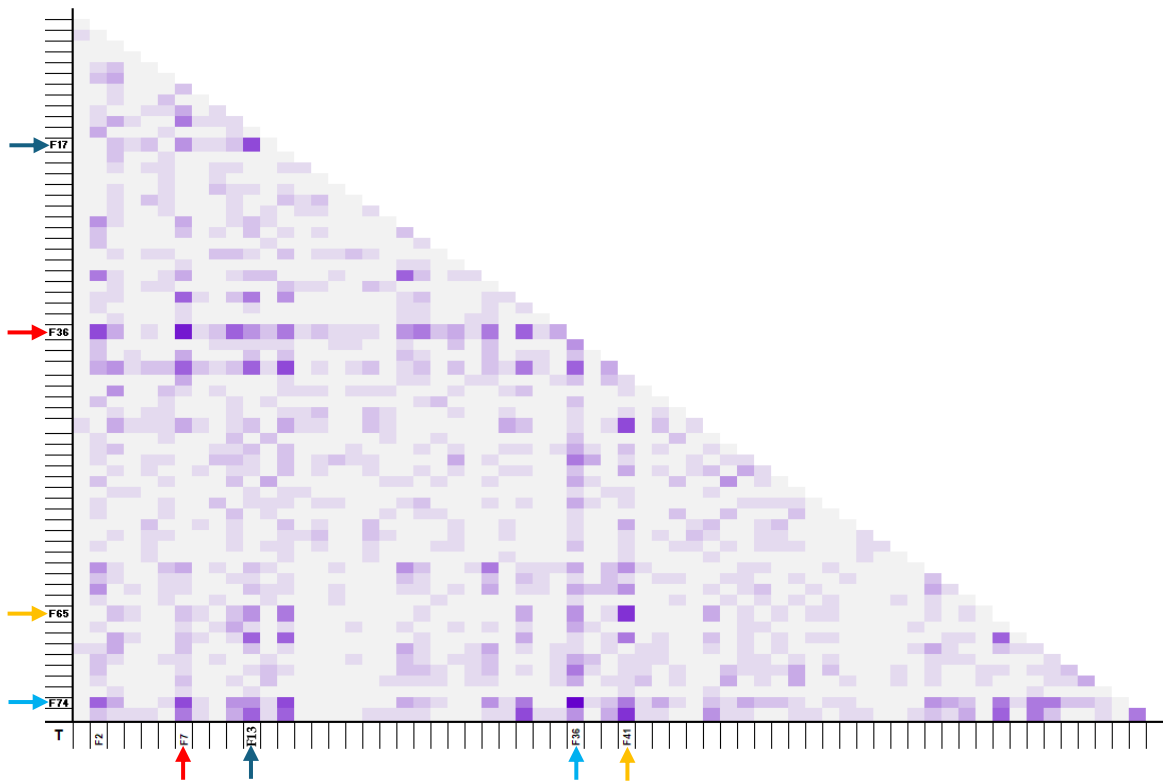


Fig. 2.29. Technology-driven collaborative planning methods' functionalities network, (b) Color-coded matrix of functionalities

The co-occurrence analysis of functionalities, based on the color-coded matrix of Fig. 2.28 (b) and Fig. 2.29 (b), shows that the pairs of F70 (supporting collaboration through social conversations) and F3 (assisting in reducing waste), F72 (supporting the trust and reliable

promises among the team) and F61 (reshaping an individual’s cognitive determinants to influence collaboration throughout project delivery), F72 (supporting the trust and reliable promises among the team) and F73 (systematic identification and removal of constraints), and F72 (supporting the trust and reliable promises among the team) and F70 (supporting collaboration through social conversations) are considered most in process-based collaborative planning methods. Also, F36 (improving communication and teamwork between the project team) and F74 (visualizing alternative construction sequences based on various what-if scenarios), F36 (improving communication and teamwork between the project team) and F7 (constructability evaluation), F65 (site layout and environment management) and F41 (improving safety management on site), and F13 (dynamic collision detection and spatial-temporal conflict analysis) and F17 (empowering automated project progress monitoring) are received the most co-occurrence in technology-driven collaborative planning methods.

Fig. 2.30 illustrates the derived differences of normalized DC (C-T) for the functionalities of collaborative planning methods in the construction industry to better make sense of and visualize the differences between the most utilized functionalities presented in Fig. 2.28 and Fig. 2.29. Large positive values in Fig. 2.30 indicate that process-based collaborative planning methods have emphasized the respective functionalities more. Large negative values, on the other hand, indicate those associated functionalities have been supported more by technology-driven collaborative planning methods.

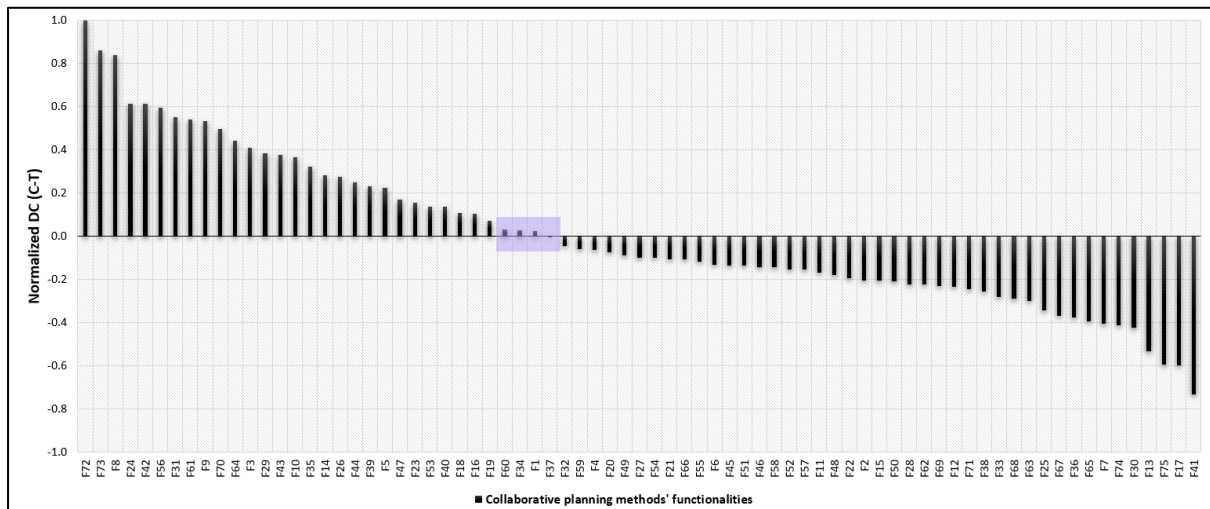


Fig. 2.30. Difference between network C and network T normalized DCs

As can be seen in Fig. 2.30, Only four out of 75 functionalities have closely comparable DC scores in process-based and technology-driven collaborative planning methods, which are F37 (improving decision-making among geographically dispersed industry practitioners), F1 (allowing just-in-time (JIT) purchasing and delivery of material), F34 (improving alignment of engineering & procurement with construction and commissioning), and F60 (reducing the impacts of potential causes of delay). These functionalities are among the least considered in both methods. Moreover, although the technology-driven methods have covered more functionalities, as seen in the C&T network in Fig. 2.28 (a) and Fig. 2.29 (a), the network corresponding to the process-based methods is denser, and functionalities have obtained more DC values. To discover the reason for this, collaborative planning methods for each

group (process-based and technology-driven) were evaluated concerning their ability to support people, process and technology aspects, as depicted in Fig. 2.31. The explanation for taking into account these three aspects is that, according to Shelbourn et al. (2007) and Dave et al. (2008), effective collaborative works in construction, including collaborative planning, can be performed by bringing together and integrating these three strategic areas of process, people, and technology.

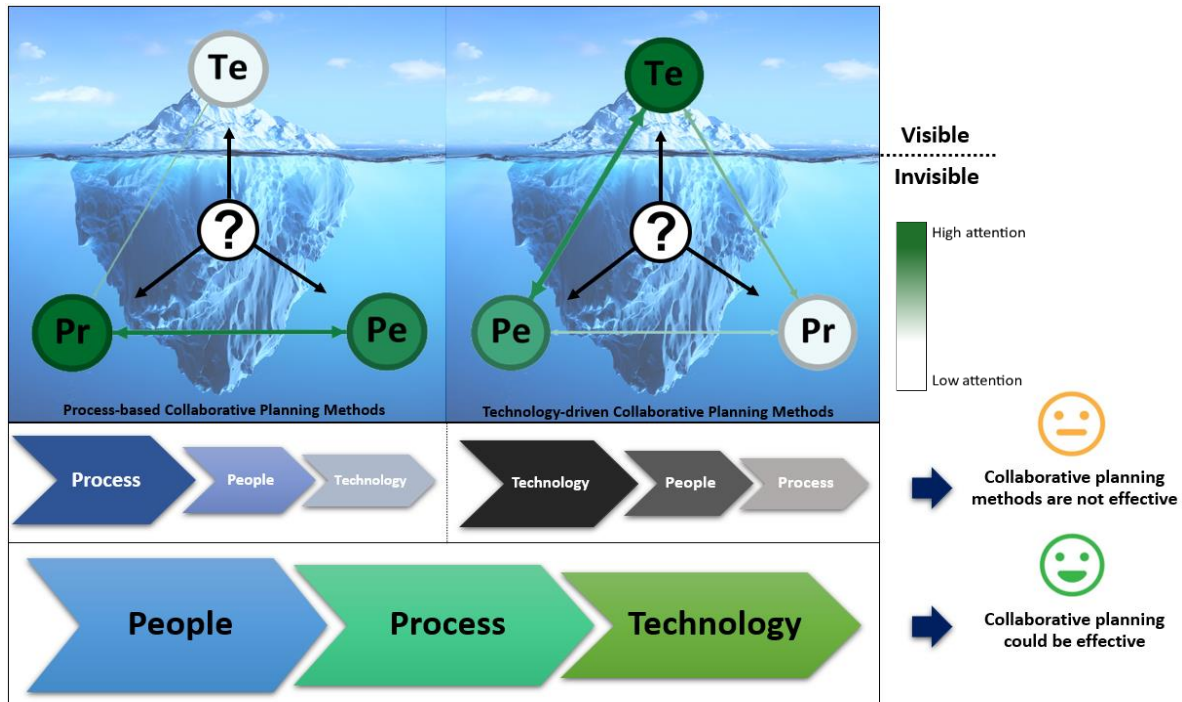


Fig. 2.31. Evaluating collaborative planning methods in view of people, process and technology

As seen in Fig. 2.31, process and people aspects have received considerable attention in process-based collaborative planning methods, while in technology-driven collaborative planning methods, the emphasis has been on people and technology. In a survey conducted by Shelbourn et al. (2007) regarding the significance of three essential strategies for effective collaboration, respondents assigned 40% importance to people, 34% value to processes, and 26% to technology. Moreover, Wilkinson (2005) argued that for adopting and implementing any collaboration technologies in the construction industry, people, process, and technology should be considered in proportions of 40%, 40%, and 20%, respectively. These findings reveal that current collaborative planning methods, whether process-based or technology-driven are ineffective since the necessary and sufficient attention has not been paid to integrate the aspects of people, process, and technology in their development, adoption, and implementation. For instance, in technology-driven collaborative planning methods, a great deal of effort has been spent on developing functionalities by focusing on the visible aspect, technology, while the process side has received less attention. Also, the technology dimension is almost ignored in process-based collaborative planning methods. Considering previous studies' findings (Dave et al. 2008) and based on the beliefs of this paper's authors, the collaborative planning methods could be more effective by a paradigm shift and bringing together and leveraging the people, process, and technology components by following this order and putting a greater emphasis on the people and process aspects first. These findings offer a transformative opportunity for construction projects by facilitating customized implementations tailored precisely to the unique needs of each project. This personalized

approach enhances overall efficiency and contributes significantly to project success. It achieves this by fostering collaborative decision-making and actively involving project stakeholders and considering their skills and knowledge in the planning and control process. In summary, these insights empower construction projects to make informed decisions, fostering a holistic and adaptive approaches, optimizing resource allocation for adoption and implementation of more fitted collaborative planning methods that improve efficiency, reduce risks, and enhance collaboration during the project lifecycle.

2.3.5. Validation of SNA Results

This study uses a simplified analysis to verify the SNA outcomes. The normalized scores were computed to compare with the DC values for two reference matrices. Based on normalized degree centrality values for the SNA and normalized score for simplified analysis, Pearson correlation, variance, and standard deviation, the same as Sheikhhoshkar et al. (2023a), have been utilized to evaluate the correlation between the findings of these two methodologies and validate the SNA results. The Pearson correlation is a statistical measure used to assess linear relationships between variables. Using a scale of -1 to +1, it calculates the strength and direction of their association, where -1 means a perfect negative correlation, +1 means a perfect positive correlation, and 0 indicates no correlation at all. Furthermore, variance and standard deviation are measures of how far the values of a dataset deviate from the mean. In this manner, they are able to quantify the degree of variability or dispersion within the data points.

Table 2.19 displays the outcomes of the aforementioned statistical tests. In addition, to visualize the statistical tests' results, violin plots for the findings of two techniques are provided in Fig. 2.32. A violin plot integrates a box plot and a kernel density plot to present summary statistics and distribution shapes of the data. For instance, in the case of violin plots for matrix T, both violin plots (simplified analysis and SNA) exhibit similar distribution shapes, as indicated by smooth and symmetric kernel density curves. Thus, the data points are concentrated around similar values, resulting in comparable distribution patterns. In addition, based on the similarities between the box plots of the two violin plots, we can conclude that the data sets have comparable measures of central tendency, spread, and overall distribution. In light of this, it is reasonable to conclude that the two methods being compared have similar characteristics and statistical properties.

There are minor differences in the results of the two analytical techniques when considering the box plots, distribution shapes, and statistical test scores for each matrix. The fact that SNA employs more sophisticated criteria to evaluate the functionalities' interrelationships may help explain this slight variation (Elsayegh and El-adaway 2021b; Sheikhhoshkar et al. 2023a). Therefore, the statistics and violin plots in Table 2.19 and Fig. 2.32 confirm that the SNA functions as anticipated.

Table 2.19. Results of statistical tests on the simplified analysis and SNA

Statistics tests	Matrix C		Matrix T	
	Simplified Analysis	SNA	Simplified Analysis	SNA
Mean	0.333	0.255	0.160	0.206
Variance	0.061	0.080	0.047	0.037
Standard Deviation	0.246	0.282	0.217	0.192
Pearson Correlation	0.928		0.966	

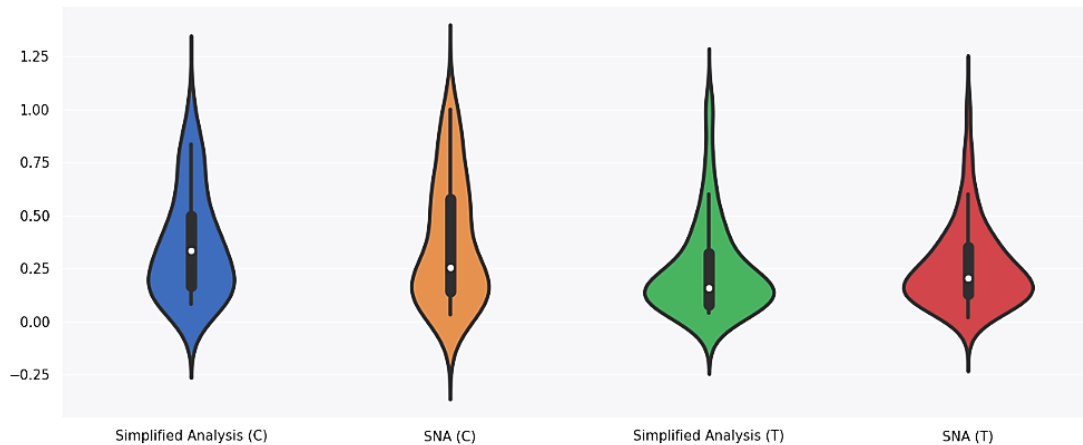


Fig. 2.32. Violin plots for the simplified analysis and SNA

2.3.6. Discussion, and Future Directions

This study contributes to the body of collaborative planning methods knowledge by identifying and analyzing the collaborative planning methods and their functionalities in the construction industry. In this regard, the analysis of collaborative planning methods indicates that in recent years, with technological advancement, particularly industry 4.0 technologies, researchers and the market have focused on developing technology-driven solutions, including virtual reality, web-based platforms, multi-user touch screens, digital twins and metaverse for collaborative project planning and control in the construction industry. Even though these technologies facilitate communication, collaboration, and processes among project stakeholders for planning and control, several studies (Dave et al. 2008; Shelbourn et al. 2007; Wilkinson 2005) revealed that for effective collaborative planning, people and process aspects are more crucial than technology. Indeed, for effective collaborative planning, focusing on technology-first approaches is difficult to successfully implement if the human resource challenges are not considered. Thus, before determining the appropriate technology for the particular needs of the collaboration, it is necessary to identify the staff's challenges, define a process, and then decide which technology would be most appropriate. It is worth noting that although BIM, especially 4D, has been utilized in all technology-driven collaborative planning methods to improve collaboration, communication and visualization of what-if scenarios, it has only been used as a tool. However, BIM is not only a tool; rather, it is a process that can support all three aspects of people, process, and technology. As a result, it is recommended that future research and market platforms integrate people and process characteristics in process-based methods such as the last planner system with new technologies to have more effective collaborative planning methods.

Concerning the collaborative planning methods' functionalities, the analysis followed by highlighting functionalities that have gotten the most attention and the ones that have received the least in both process-based and technology-driven collaborative planning methods. In light of this, the results of process-based collaborative planning methods' functionalities network indicated that supporting the trust and reliable promises among the team, reducing uncertainty and risk, continuous improvement process, systematic identification and removal of constraints, supporting collaboration through social conversations, and assisting in reducing waste are the most often employed functionalities in process-based collaborative planning methods. These outcomes reflect a special focus on

process and people-related characteristics such as team trust and promise, systematic identification and elimination of constraints, and collaboration via social interactions. Moreover, solving disputes more efficiently, allowing just-in-time (JIT) purchasing and delivery of material, improving safety management on site, and reducing the change orders during construction are the least received focus in process-based collaborative planning methods. Since project planning, scheduling, and control is a complex and dynamic process, it must integrate numerous concepts, including safety, supply chain, cost, quality, teamwork, and so forth, to be successful. As a practical matter, contractors and owners tend to pay more attention to contractual, legal, and technical concerns, and these should be included in the fundamental functionalities of project planning and control methods. However, the results of the functionalities analysis revealed that in both process-based and technology-driven collaborative planning methods, little attention is paid to the essential aspects of project planning and control, such as effective delay and claim management, change order management, procurement and supply chain management, and site safety management. These issues have the potential to be studied in the future.

Addressing the findings of technology-driven collaborative planning methods' functionalities, improving communication and teamwork between the project team, improving safety management on site, and visualizing alternative construction sequences based on various what-if scenarios have been considered frequently used functionalities. This analysis highlights that although technology-driven collaborative planning methods cover more functionalities than process-based methods, there is still confusion regarding the functionalities that must be prioritized to develop an effective collaborative planning method. This is due to the fact that only 3 out of 64 functionalities achieved high degree centrality scores in technology-driven methods. Furthermore, besides concentrating on collaboration and communication among stakeholders, these methods have significantly emphasized visualization as a central function in collaborative planning. Visualization examples include utilizing fourth dimension (4D) simulation, Virtual Reality (VR), digital twins, multi-user VR experiences, and interactive touch table and touch wall screens. These tools enable stakeholders to immerse themselves in the project environment, explore scenarios, and gain a comprehensive view of construction processes. Visualization fosters better communication, facilitates real-time collaboration, and aids in identifying potential issues early in the planning phase, contributing to more efficient and informed decision-making throughout the project lifecycle.

Additionally, the outcomes illustrate that allowing just-in-time (JIT) material purchasing and delivery, improving decision-making among geographically dispersed industry practitioners, reducing the impacts of potential causes of delay, and enabling real-time collaborative 4D planning to gain a robust construction plan are functionalities that acquire least scores in technology-driven collaborative planning methods. It can be discovered that despite the necessity of geographically dispersed and real-time communication and collaboration throughout the COVID period and thereafter, they are still in infantile maturity in collaborative planning methods. Focusing on technologies such as digital twins and metaverse can considerably improve the possibility of practical implementation of these two functions. Future studies can investigate this concern as well. Also, technology-driven collaborative methods often focus on the technology, such as real-time solutions, without taking full advantage of their collaborative potential.

Due to the growing interest in using integrated project delivery (IPD) and other collaborative

project delivery methods such as early contractor involvement or progressive Design-Build (DB) and prefabrication methods in the construction industry (Hosseini et al. 2018b; Rashed and Mutis 2023), there will be an increased demand to develop integrated project planning, scheduling and control methods to combine planning and control of design and engineering, procurement and construction phases. While the functionalities analysis in this article reveals that in both collaborative planning methods, the functionalities related to the supply chain and procurement, allowing just-in-time (JIT) material purchasing and delivery, have been neglected, highlighting the need for more research in the future.

2.3.7. The Implications of the Findings

The implications of the findings are thoroughly discussed in this section concerning the identified collaborative planning methods and their functionalities from both theoretical and practical standpoints.

2.3.7.1. Theoretical Implications

The findings of this study significantly contribute to the body of production planning and control knowledge within the construction management domain. This contribution is achieved by the identification and thorough examination of both process-based and technology-driven collaborative planning methods, along with a comprehensive analysis of their respective functionalities. In particular, this examination sheds light on the functionalities that have garnered the greatest attention, as well as those that have received comparatively less focus within both process-based and technology-driven collaborative planning approaches. Theoretical implications underscore a shift towards a more people-centric and process-oriented perspective, harmonized with emerging technologies in collaborative planning within construction. They also highlight the need for further exploration and development of methodologies that incorporate crucial aspects like dispute resolution, change order management, and the integration of dimensions such as delay management, claim resolution, and supply chain optimization into collaborative planning methods. Moreover, the emphasis on visualization in technology-driven collaborative planning methods indicates a move towards data-driven decision-making and improved project visualization.

In summary, these theoretical implications not only guide future research endeavors but also reflect the evolving nature of collaborative planning in construction, emphasizing the importance of human dynamics, process considerations, and technological integration in shaping the industry's practices.

2.3.7.2. Practical Implications

This research also holds substantial practical implications for the construction industry. Firstly, it provides and analyzes a comprehensive list of collaborative planning methods' functionalities, enhancing various stakeholders' understanding, sensemaking, and situational awareness, including designers, contractors, owners, and project participants. This, in turn, empowers these stakeholders to make informed decisions when selecting the most suitable collaborative planning methods for their construction projects. In addition, the result's emphasis on trust-building, collaboration through social conversations, continuous improvement, and constraint removal suggests that organizations should prioritize fostering a collaborative culture that encourages open communication, and trustworthiness among

team members. Additionally, the research illuminates a significant challenge in technology adoption within organizations and construction companies. Often, decisions regarding technology adoption are driven by upper-level management in construction companies (Alinaitwe et al. 2007; Elsayegh 2021) without considering the perspectives and needs of engineers responsible for on-site implementation. This top-down approach has led to fragmented and inefficient technology utilization, including collaborative planning methods and tools. To address this challenge effectively, this study emphasizes the importance of thoroughly assessing human resource challenges and establishing clear processes before implementing technology-driven solutions. Organizations are encouraged to prioritize understanding their staff's specific requirements and capabilities at lower organizational levels and on construction sites. Consequently, technology adoption can be tailored to align with these unique needs. Furthermore, it is highlighted that specific areas within collaborative planning methods have received limited attention, including dispute resolution, just-in-time material procurement, safety management, and change order management. In light of these gaps, contractors and owners need to recognize these shortcomings and consider integrating appropriate strategies and tools into their collaborative planning practices.

2.3.8. Contributions to the Body of Collaborative Planning Knowledge

This study significantly advances collaborative planning methods knowledge in construction by examining both process-based and technology-driven approaches. While recognizing the increasing focus on technology-driven solutions, it emphasizes the pivotal roles of people and processes in effective collaborative planning, challenging the prevalent technology-first approach. The findings recommend a paradigm shift, prioritizing people and processes before selecting suitable technology. The analysis highlights specific strengths in process-based methods, such as trust-building and constraint removal, and in technology-driven methods, particularly communication enhancement and visualization. The study underscores the need for more attention to essential aspects like delay management, claim resolution, and procurement functions in both approaches. Practical implications stress the importance of a balanced focus on people, processes, and technology, advocating for a thorough understanding of staff requirements before technology implementation. Overall, the research guides future endeavors, emphasizing a holistic approach and clearer prioritization of functionalities for effective collaborative planning in construction.

2.3.9. Conclusion and Limitations

This study extensively examined collaborative planning methods and their functionalities in the construction industry. Identifying ten collaborative planning methods and 75 associated functionalities, categorized into process-based and technology-driven groups, has revealed a need for a more balanced focus on people, process, and technology aspects. Process-based methods emphasize people and processes, while technology-driven methods lean towards people and technology, often overlooking the process. In this regard, to develop more effective collaborative planning methods, it is recommended to direct future studies and construction companies' strategies on thinking about a paradigm shift and bringing together and leveraging the people, process, and technology components by following this order and putting a greater emphasis on the people and process aspects first.

Additionally, Social Network Analysis (SNA) for functionality assessment has demonstrated a prevalent focus on process and people-oriented functionalities in process-based collaborative

planning methods. Even so, critical aspects of project planning and control, such as delay and claim management, change order management, procurement and supply chain management, and site safety management, require additional attention. Also, the findings highlight the need for clarity when it comes to technology-driven collaborative planning methods. Even though it encompasses a broad range of functionalities, there needs to be more clarity regarding prioritizing these functionalities for effective and practical implementation. Notably, visualization plays a vital role in these methods; however, the development of geographically distributed and real-time collaboration functions remains in its infancy. Moreover, both process-based and technology-driven methods have been overlooked in supply chain and procurement functions, providing an avenue for further research.

It is also evident that the process-based methods' functionalities network is characterized by a dense network that facilitates collaborative activities. In contrast, the network of technology-driven methods' functionalities reveals a great deal of potential for more collaborative functionalities that are sometimes not harnessed. Companies often deploy technology-driven methods without understanding process-based methods, which leads to a lack of full utilization of collaboration's potential. To harness this potential fully, organizations and projects should consider integrating the foundational concepts of both process-based and technology-driven approaches.

This article's evaluation relied on data gathered through an extensive review of the existing literature. Given the practical nature of project planning and control, it is necessary to incorporate insight from industry experts to conduct a more comprehensive and pragmatic assessment. Furthermore, future investigations could explore the application of clustering algorithms and expert opinions to refine the categorization of functionalities based on their underlying knowledge domain. Moreover, while this study examined collaborative planning methods by categorizing them into process-based versus technology-driven approaches, there is potential for future research to explore additional divisions. These might include distinctions such as input versus output-focused, process versus product-focused, tools versus processes, project management versus project-focused, result versus effect-focused, people versus data-focused, visualization versus communication-focused, and quality versus time-focused, among others. This approach could pave the way for further advancements and insights in collaborative planning methods within the construction industry. Eventually, this research focuses on collaborative approaches for project planning and control, excluding collaborative delivery models and specific techniques such as Integrated Project Delivery (IPD), alliancing, co-location, big room, and so on. Although these models and techniques have been recognized for their comprehensive and stakeholder-inclusive approach, they are not explicitly explored in this study. Future research might expand on this foundation by looking at how different delivery models interact with collaborative planning and control approaches, resulting in a more complete understanding of collaboration in construction projects.

2.4. Section 4: General Conclusion of the Literature Reviews

The construction industry has undergone a significant transition from traditional planning methods to more integrated and collaborative planning methods, driven by advanced technologies. These integrated methods have demonstrated their potential to enhance project efficiency by improving communication and fostering stronger collaboration among stakeholders. However, with this shift comes a growing complexity in the planning and control processes.

As part of this review, 46 distinct planning methods and 82 control metrics were identified and analyzed, underscoring the vast array of methods available to construction professionals. This variety, while offering flexibility, often leads to confusion among project stakeholders when selecting the most appropriate approach for their specific projects. The analysis demonstrated that while traditional methods like Critical Path Method (CPM) remain the most widely used in the industry, lean-based planning systems, including the Last Planner System (LPS), Location-Based Management System (LBMS), and Takt Time Planning (TTP), have garnered substantial attention in recent years.

Moreover, the integration of single planning methods into more complex, collaborative frameworks is frequently undertaken without a clear understanding of the underlying objectives. This has contributed to a low level of comprehension and sensemaking among project stakeholders, who may struggle to grasp the functionalities and purposes of various planning and control systems. To address this challenge, the concept of functionality was introduced, offering a way to define and clarify the goals of different planning methods and control metrics. By doing so, stakeholders can better understand how these systems align with project objectives and make more informed decisions.

In these reviews, 148 functionalities were extracted and analyzed. These functionalities can serve as a simple and understandable mechanism for both experts and non-experts within the project team to better comprehend the functionalities of planning and control systems. However, the sheer number of 148 functionalities is overwhelming for the human mind to effectively process. This highlights the need to narrow down these functionalities to a more manageable set of key concepts, making the systems more accessible and practical for stakeholders.

Moreover, the three systematic literature reviews illustrated a clear absence of a framework and decision-support system that caters to both experts and non-experts. This lack of guidance complicates the selection process, leaving many stakeholders without the necessary tools to identify fit-for-purpose planning and control systems.

In conclusion, while integrated and collaborative planning methods hold great promise for enhancing construction project outcomes, there is a critical need for clearer guidelines and decision-support mechanisms. Simplifying the decision-making process and improving stakeholder understanding will be essential to fully leverage the benefits of these advanced planning systems within the construction industry.

Chapter 3. From NLP to Taxonomy: Identifying and Classifying Key Functionality Concepts of Multi-level Project Planning and Control Systems

This chapter is a copy of the following accepted paper:

- **Sheikhkhoshkar, M.,** Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Rahimian, F. (2024). "From NLP to Taxonomy: Identifying and Classifying Key Functionality Concepts of Multi-level Project Planning and Control Systems." *Journal of Information Technology in Construction*, *Accepted/In press*, <https://hal.univ-lorraine.fr/hal-04701660v1>.

This chapter addresses the second objective of this thesis: identifying the core functional concepts of planning and control systems and developing a taxonomy for these concepts. Building upon the previous chapter, which presented 148 distinct functionalities of planning and control systems, the sheer number of functionalities posed a challenge for effective stakeholder understanding and sensemaking. To address this complexity, this chapter concentrates on discerning the key functionality concepts and formulating a taxonomy of these concepts. The proposed taxonomy aims to facilitate a deeper understanding and more efficient utilization of planning methods and control metrics across various levels by project stakeholders. To do so, a mixed method using advanced text-mining techniques and clustering analysis were employed. First, sentence-bidirectional encoder representations from transformers (SBERT) for semantic analysis, hierarchical clustering, and word cloud visualization were applied to classify and validate project planning and control system functionality concepts into coherent clusters. Furthermore, a robust taxonomy of functionality concepts was developed by meticulously analysing the findings as well as considering the domain experts' insights. As a result, 148 project planning and control systems' functionalities were classified into 20 coherent clusters with an average 87% alignment rate. A robust taxonomy of these functionalities was then formulated, emphasizing their importance across various scheduling levels. This taxonomy captures the complexities of project planning and control systems, facilitating informed decision-making and the integration of diverse planning and control systems to handle project complexities. The research significantly contributes to the field by clarifying the core concepts of project planning and control systems, making them more understandable and actionable for project stakeholders.

3.1. Introduction

Effective production planning and control are crucial for achieving project objectives in construction projects that are characterized by significant uncertainties (Nwadigo et al. 2021; Viana et al. 2017). The primary objectives of planning and control systems are to facilitate managerial decision-making, orchestrate communication and coordination among various project stakeholders, and establish benchmarks for performance measurement and evaluation (Laufer and Tucker 1987). Despite its significance, the implementation and outcomes of production planning and control often evoke dissatisfaction within the construction industry. Indeed, deficiencies in effective planning and control processes have been reported as one of the major contributors to project delays and cost overruns (Sheikhhoshkar et al. 2023a; Viana et al. 2017). Furthermore, studies have highlighted a pervasive lack of understanding and experience among project stakeholders concerning planning and control systems (AlNasseri and Aulin 2015; Salling et al. 2023; Sheikhhoshkar et al. 2024c).

As construction projects grow in complexity and markets evolve with increased dynamism and fragmentation, the prevalence of outsourcing and subcontracting escalates, presenting additional challenges in coordinating supply chains. These challenges necessitate managing numerous planning alternatives and divergent stakeholder interests, alongside a pervasive lack of comprehensive project understanding among participants (Viana et al. 2017; Wiendahl et al. 2005). In this regard, various single and integrated planning and control systems have been proposed in the last decade to address these challenges. Systems such as the Last Planner System (LPS) (Ballard and Tommelein 2021), Takt Time Planning (TTP) (Frandsen 2019), and Location-Based Management System (LBMS) (Ghanem et al. 2022) have contributed to the body of production planning and control knowledge through enhancing communication and collaboration, standardizing workflows, improving resource utilization, optimizing scheduling and logistics, and facilitating continuous improvement (Ezzeddine et al. 2022; O. AlSehaimi et al. 2014). Furthermore, these systems have been combined with one another to augment their effectiveness and address the drawbacks inherent in each, resulting in hybrid systems such as the Building Information Modelling (BIM)-LPS-Kanban (Arayici et al. 2023; Sacks et al. 2010), Critical Chain Project Management (CCPM)-LPS-Linear Scheduling Method (LSM) (Salama et al. 2021), LBMS-LPS-Critical Path Method (CPM) (Olivieri et al. 2016), and 4DBIM-LPS-LBMS (Silveira and Costa 2023), LPS-LBMS (Seppänen et al. 2010), BIM-Kanban (Zeng et al. 2023), and others. The objectives behind the development of these approaches include improving the reliability of planning, decreasing workflow variability, increasing teamwork and communication among all stakeholders, and enhancing the understanding of the project's progress, among many others.

Additionally, advancements in control systems aspects have been pursued with the introduction of systems such as Earned Value Management (EVM) (Lipke et al. 2009; William 1996), lean-based control systems (Hamzeh et al. 2019b), and buffer control systems (Hu et al. 2016; Zohrehvandi et al. 2021). These systems are designed to measure and monitor various aspects of projects including uncertainties, quality of capacity planning, commitments' quality, workflows' reliability and stability, project progress and performance, and the efficiency of resource allocation.

Despite the awareness of these advancements among academics and some policymakers in the construction sector, a significant gap exists in the knowledge and utilization of these

systems among on-the-ground project teams, including project managers, planners, and superintendents (Salling et al. 2023; Sheikhhoshkar et al. 2023a). This disconnect underscores the necessity of clarifying the main objectives and underlying principles of these developments to enhance the level of understanding and awareness among project teams. Such clarity will enable more effective implementation of these systems in construction projects. Moreover, there is a lack of a structured framework to classify and organize the various functionalities of the planning and control systems, making it challenging for stakeholders to determine the appropriate level of effort needed at each schedule level to effectively address specific functional requirements for a planning and control system. These gaps necessitate extraction and analysis of the underlying concepts and objectives of planning and control systems as well as developing a taxonomy to systematically classify and organize project planning and control systems' functionalities, enhancing stakeholders' understanding and utilization.

In this regard, the studies conducted by Sheikhhoshkar et al. (2023a), Sheikhhoshkar et al. (2023a), and Sheikhhoshkar et al. (2024c) defined the underlying concepts and objectives of planning and control systems as their functionalities. They then extracted and analysed a holistic list of functionalities through systematic literature reviews and meta-analyses. However, the resulting list of 148 functionalities is overly extensive, making it challenging to clearly grasp the core ideas and principles of planning and control systems. Therefore, this study aims first to analyze a comprehensive list of functionalities and identify the main concepts behind them using a Natural Language Processing (NLP) approach. Next, it seeks to develop a taxonomy to simplify complex concepts and support informed decision-making. In pursuit of this aim, the outlined objectives of this research include:

1. Analyse the project planning and control system's functionalities and identify the main functionality concepts
2. Develop a taxonomy to classify the identified functionality concepts

This research contributes to the body of knowledge in production planning and control by shedding light on the underlying concepts of project planning and control systems and making them more tangible and clear for project stakeholders. Additionally, through the development of a taxonomy of functionality concepts, the research will highlight the importance of each concept at different scheduling levels. This will enable project teams to better understand their functional requirements associated with planning and control systems at each schedule level. Moreover, this study helps translate the tacit knowledge of domain experts into formalized knowledge that can be easily shared and used by practitioners. Additionally, it lays the groundwork for creating a knowledge repository that can incorporate semantic technologies to infer new knowledge and develop expert systems.

The subsequent sections of this paper are organized as follows:

An exploration of NLP within the Architecture, Engineering, and Construction (AEC) domain; the research methodology employed; the findings, analysis, and validation of the results, research discussion and implications; and finally, the conclusion, limitations and suggestions for future endeavours.

3.2. NLP in AEC domain

NLP presents a viable computational methodology to process and analyze large amounts of natural language data, enabling them to understand and interpret in a valuable way (Kang et al. 2020). NLP is making significant progress in the AEC domain, addressing complex challenges such as efficient information extraction, project planning, and compliance management (Li et al. 2024). Leveraging NLP technology improves the processing of the extensive unstructured textual data embedded in construction documents, schedules, and contracts, which is crucial for improving project management and operational efficiency. One significant application of NLP in the AEC is extracting semantics from regulatory texts, where NLP can efficiently parse and interpret complex documents to aid compliance checks, risk and contract management. In this context, Moon et al. (2022) applied the Bidirectional Encoder Representations from Transformers (BERT) method in natural language processing to detect contractual risk clauses from construction specifications. Ko et al. (2021) proposed an NLP-driven model to extract and analyze contract change reasons, enhancing the precision of change order management systems. A parser was utilized by Al Qady and Kandil (2010) to extract semantic knowledge from construction contract documents to improve electronic document management capabilities.

Another critical application of NLP in the AEC sector is in project planning and scheduling. NLP models may discover and extract actionable insights from textual data in project documents, such as schedule information and task dependencies, which are fed into project management processes. This capability not only streamlines project planning and scheduling processes but also ensures that they are more aligned with operational realities, which enhances overall project efficiency. Taking this into account, Jung and Golparvar-Fard (2023) employed NLP for both master and lookahead schedules to automatically learn and map their respective activities and tasks. This approach aimed to address the gap in alignment between schedule levels, thereby streamlining the manual reconciliation process, which is susceptible to errors and inefficiencies. Jung et al. (2024) introduced a novel NLP-based model to automate the linkage between textual descriptions of scheduled activities and ASTM Unifomat categories. This automation seeks to ease manual processes and organizational challenges in implementing 4D BIM. Key features include automated creation of 4D BIM, mapping schedule activities to payment applications, and computer vision progress monitoring without reliance on BIM. This approach eliminates the need for manual efforts in synchronizing activity IDs with corresponding BIM elements across Virtual Design and Construction (VDC) and planning departments.

Furthermore, Zhao et al. (2020) developed a system that employs automatic project schedule checking (APSC) and NLP to extract construction methods from project schedules, thereby aiding in the automated assessment of schedule quality in the construction sector. This solution combines NLP techniques with OWL-based ontology models to derive semantic and syntactic features for construction activities. Ko et al. (2023) explored a method that employs NLP to systematically measure the similarity between project scope statements to recommend similar projects for reliable project development and planning in the preconstruction phase.

To sum up, NLP is used in the construction industry for various purposes involving textual data, ranging from compliance and risk management to project planning and scheduling. This paper also aims to apply a new application of NLP, leveraging its capabilities to discover and

formalize the key underlying concepts of project planning and control systems.

3.3. Research Methodology

A multi-stage methodology was implemented to fulfil the objectives of this paper, as depicted in Fig. 3.1. The methodology comprises two main processes: data collection and data analysis. In the data collection phase, a comprehensive systematic literature review on planning and control systems in construction was conducted to extract the functionalities of planning methods and control metrics. During the data analysis phase, following the data preprocessing, the Sentence- Bidirectional Encoder Representations from Transformers (SBERT) model, a specialized variant of BERT (Reimers and Gurevych 2019), was employed for vectorization and text embedding. The hierarchical clustering technique was then applied to cluster the extracted functionalities. Finally, word cloud generation, keyword extraction, and semi-structured interviews with domain experts were conducted to identify the primary concepts and construct the taxonomy of project planning and control systems' functionalities. Each facet of the research methodology is described in detail in the following subsections.

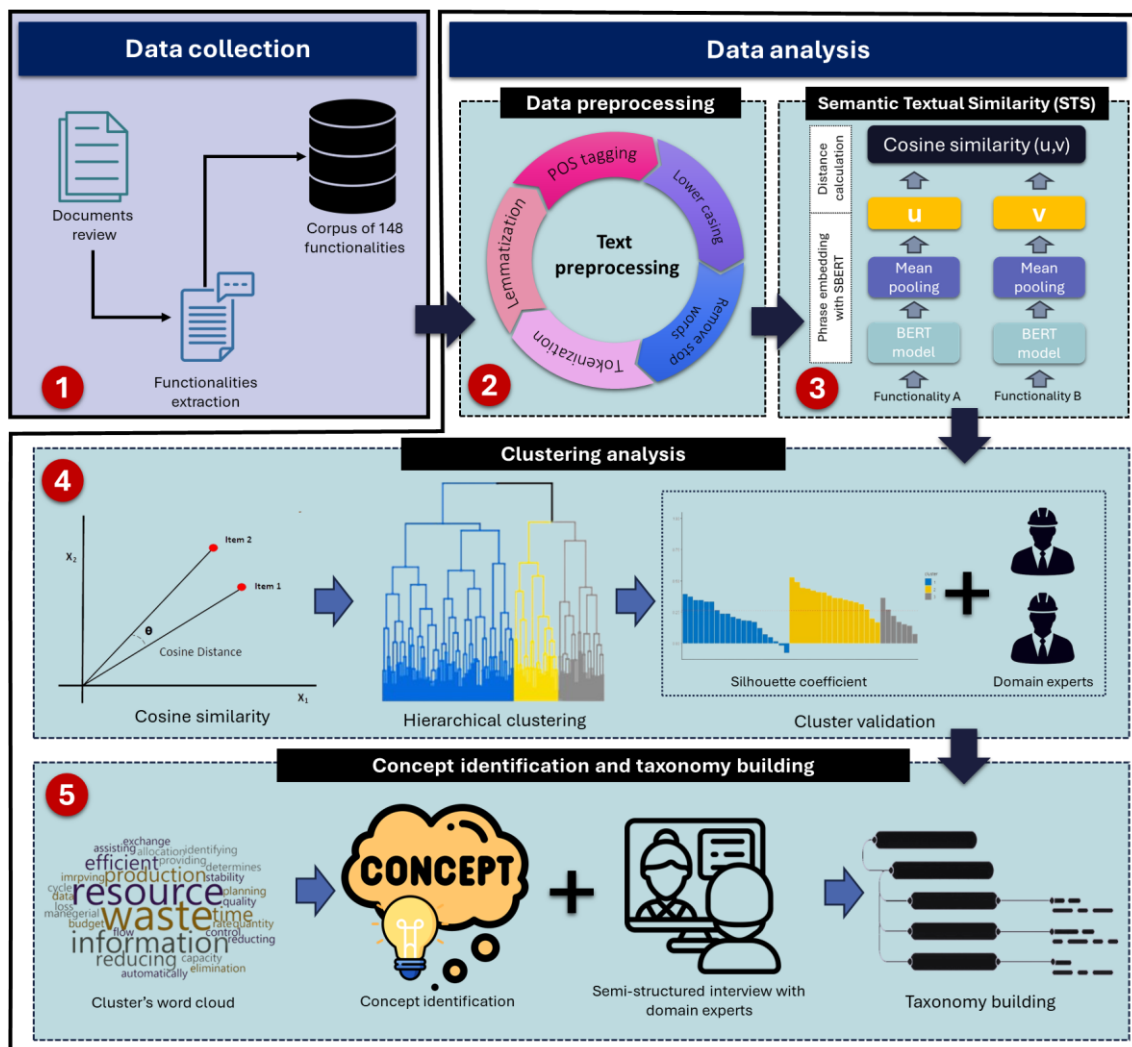


Fig. 3.1. An overview of the adopted methodology

3.3.1. Data Collection

Three systematic literature reviews and meta-analyses were carried out to investigate project planning and control systems and their functionalities. Through meticulous analysis of the content of 204 papers, a total of 36 single and integrated planning methods, 82 control metrics, and 10 collaborative planning methods were subject to comprehensive examination. The objectives and aims inherent to these planning and control systems were defined as their respective functionalities. The processes of extracting and analyzing functionalities are detailed in studies by Sheikhhoshkar et al. (2023a), Sheikhhoshkar et al. (2024c), and Sheikhhoshkar et al. (2024b). This phase of the research yielded a total of 148 functionalities as input data for further analysis, as illustrated in Fig. 3.2 and drafted in Table A4 within the Appendix. It is noteworthy that all functionalities were extracted verbatim, maintaining the exact phrasing as presented in each respective paper, without altering their structure.

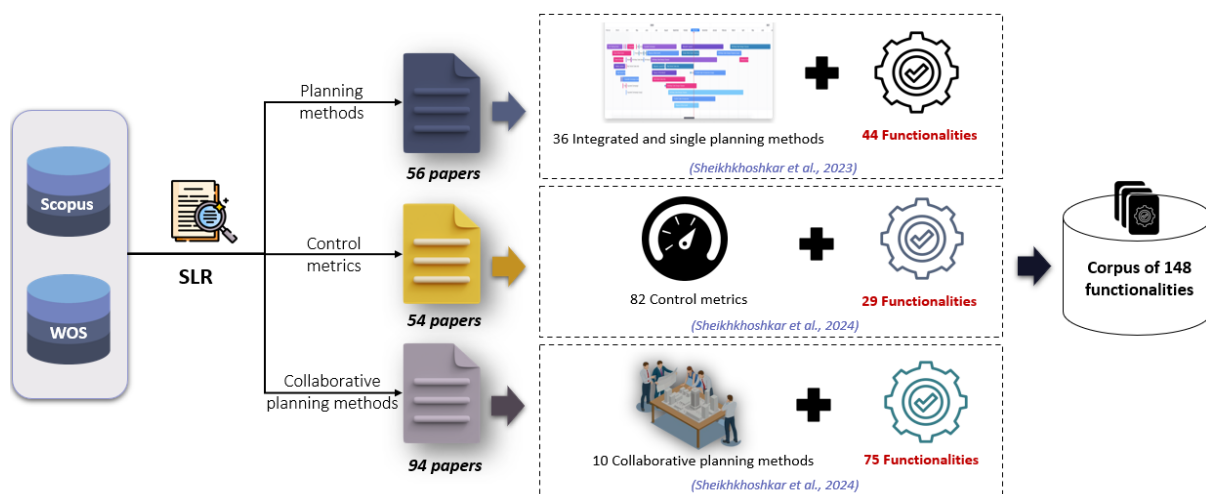


Fig. 3.2. An outline of the procedure for extracting functionalities

3.3.2. Data Analysis

This research has adopted advanced text mining analysis as the main approach to analyze data and meet the study's goals. Text mining involves examining text to extract useful information for various purposes (Zhou et al. 2019). A variety of text mining techniques have been employed, utilizing the Orange data mining tool (Demšar et al. 2004), which allows workflows to be designed and created by connecting predefined or user-designed components called widgets. This part examines the sequential steps employed for the data analysis, as outlined in Fig. 3.3. The data analysis phase encompasses several pivotal processes, including data preprocessing, vectorization and text embedding using SBERT, clustering analysis, and the generation of word clouds alongside keyword extraction. The following sections delve into the specifics of each step.

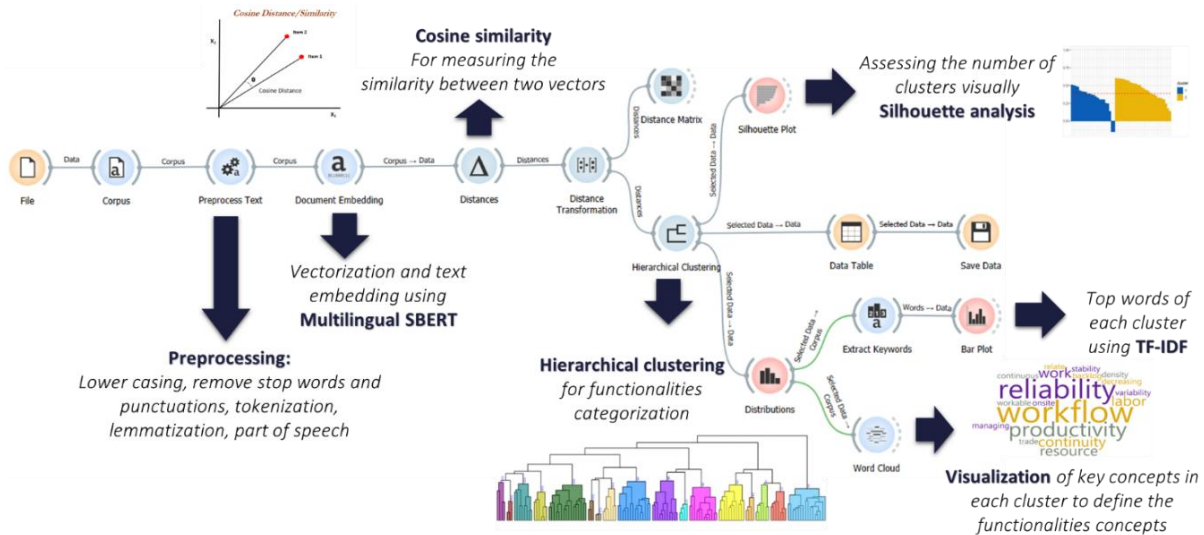


Fig. 3.3. The employed steps for data analysis

Adopting this complex and quantitative approach offers significant advantages over purely qualitative analysis and classification. While qualitative methods provide valuable insights and deep understanding through subjective interpretation, they often lack the scalability needed for comprehensive analysis across large datasets (Jacobs and Tschötschel 2019). Therefore, automated clustering approaches are more scalable and efficient than manual qualitative analysis for a large number of phrases. Integration of the semantic textual similarity and clustering methods allows a more objective and data-driven analysis of the 148 phrases (functionalities). These techniques minimize the potential for subjective bias that can sometimes affect qualitative analysis. Moreover, advanced computational methods in such studies can uncover patterns and relationships that may not be immediately apparent through qualitative methods (Abdullah et al. 2023). Clustering, in particular, can reveal natural groupings within the data, offering a deeper understanding of the underlying concepts.

The results from these quantitative methods provide a robust foundation for subsequent qualitative analysis. Once the initial clusters and underlying concepts are identified, they can be further explored and validated through qualitative methods such as expert interviews, offering a comprehensive mixed-method approach. By integrating semantic textual similarity and clustering with potential subsequent qualitative analysis, we aim to provide a balanced, thorough, and methodologically sound exploration of the functionalities in project planning and control systems. This approach leverages the strengths of both quantitative and qualitative methodologies to achieve a holistic understanding.

3.3.2.1. Data Preprocessing

To prepare the raw text data for further processing and analysis, several preprocessing steps were executed on the extracted functionalities. These steps include converting all letters to lowercase, removing stop words and punctuation, tokenization, lemmatization, and part-of-speech tagging. Lowercasing normalizes the text by equating variations in capitalization, thus providing a uniform basis for analysis. The elimination of stop words and punctuation concentrates the analysis on more substantive words and purifies the textual data. Tokenization segments the text into discrete units, or tokens, which are crucial for subsequent processing steps. Lemmatization simplifies words to their lemma forms, enhancing the

model’s capacity to generalize by focusing on the fundamental meaning of words across various morphological manifestations. Part of speech tagging adds syntactic information, aiding in understanding the grammatical context of words. These preprocessing steps are pivotal in transforming raw text into a structured format, which is critical for various NLP applications such as semantic textual similarity. **Error! Reference source not found.** presents the applied preprocessing steps to a functionality.

Table 3.1. Applied preprocessing steps to a sample functionality

Original extracted functionality	Preprocessing steps	Preprocessed functionality
Visualization of the schedules to understand/communicate content to a variety of stakeholders	Lowercasing	<i>visualization of the schedules to understand/communicate content to a variety of stakeholders</i>
	Removing stop words	<i>visualization schedules understand/communicate content variety stakeholders</i>
	Removing punctuation	<i>visualization schedules understand communicate content variety stakeholders</i>
	Tokenization	<i>visualization, schedules, understand, communicate, content, variety, stakeholders</i>
	Lemmatization	<i>visualization, schedule, understand, communicate, content, variety, stakeholder</i>
	Part of speech tags	<i>visualization/NN, schedules/NNS, understand/VBP, communicate/NN, content/NN, variety/NN, stakeholders/NNS</i>

3.3.2.2. Semantic Textual Similarity (STS)

To capture the semantic similarity between functionalities, the Sentence-BERT (SBERT) neural network model was employed, which generates vector representations for sentences and phrases. The BERT model is a deep learning algorithm based on the transformer architecture that is designed to understand the context of language in text. It utilizes a mechanism known as attention, which weighs the relative importance of words in a phrase. BERT models are pre-trained on a large corpus of text and then fine-tuned for specific tasks (Moon et al. 2022). While BERT is highly effective at understanding context and meaning, the original model was not optimized for generating sentence-level embeddings. To address this, the Sentence-BERT (SBERT) model was developed (Reimers and Gurevych 2019). SBERT is a modification of the pre-trained BERT network that uses Siamese and triplet network structures to derive semantically meaningful embeddings that are well-suited for clustering, semantic search, and other similarity tasks (Reimers and Gurevych 2019). SBERT modifies the final embedding process to produce fixed-length vector representations of entire sentences rather than individual tokens. The SBERT architecture comprises the following elements:

1. **Tokenizer:** It first tokenizes sentences into a series of word pieces
2. **BERT encoders:** are composed of several layers of transformer blocks that process the tokenized input, applying self-attention and feed-forward neural network operations to encode contextual information into vector form.
3. **Pooling layer:** SBERT applies a pooling strategy to the output of the encoders to derive a single fixed-size sentence embedding.
4. **Fine-Tuning:** SBERT is fine-tuned on Natural Language Inference (NLI) tasks, which

helps the embeddings to capture sentence-level semantic relationships effectively.

3.3.2.3. Clustering Analysis

Following vector embeddings by the SBERT model, the cosine similarity was used to evaluate the semantic similarity between functionalities. It computes the cosine of the angle between two vectors in a multi-dimensional space, with values ranging from -1 (dissimilar) to 1 (very similar). Based on this metric, hierarchical clustering was applied to classify the functionalities into distinct clusters. Hierarchical clustering is an unsupervised machine-learning technique that groups entities by their similarity or distance to form a multi-level hierarchy of clusters (Reddy and Vinzamuri 2018). The success of hierarchical clustering significantly depends on the considered linkage method, which determines the metric for calculating distances between clusters (Contreras and Murtagh 2015). The linkage methods, including single, complete, average, and ward linkage, offer different approaches to defining inter-cluster similarity. Throughout the clustering process, various linkage methods were iteratively employed, with Silhouette analysis utilized at each iteration to assess clustering performance. Subsequently, ward linkage emerged as the preferred method due to its ability to generate well-defined and coherent clusters.

The hierarchical clustering technique was particularly suitable for this study as it enabled the establishment of a multi-level taxonomy of sentence groupings, which reflects the fine spectrum of semantic relationships within our corpus. The dendrogram structure derived from hierarchical clustering furnished a visual depiction of the functionalities clusters, thereby aiding in the intuitive understanding of the diverse categories inherent in the functionalities.

To validate the results of hierarchical clustering and ensure that functionalities with similar meanings were appropriately grouped, a Silhouette analysis was performed complemented by the insights of domain experts. The Silhouette analysis provided a quantitative measure of how well each sentence fit within its cluster, which was crucial for assessing the cohesion and separation of the clusters (Abdul Nabi and El-adaway 2022). In parallel, semi-structured interviews and surveys were conducted to seek the qualitative judgment of domain experts. To do so, using a purposive sampling approach, experts were selected based on three key factors: 1) their practical experience and theoretical understanding 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 willingness to actively engage in feedback sessions. A targeted cohort of 18 individuals was identified by reviewing LinkedIn profiles, the IsoBIM project's partners, and various online repositories. Invitations to participate were then sent via email and direct messaging channels. Of these, ten individuals responded affirmatively and were subsequently scheduled for interviews. This sample size was sufficient, as many studies employing purposive sampling opt for sample sizes ranging from 5 to 25 (Jepson et al. 2020; Zulu et al. 2023). The selected experts qualifications are outlined in Table 3.2. The interview sessions constituted a component of a six-month endeavor involving the design and evaluation of a comprehensive multi-level and collaborative project planning and control framework within the IsoBIM project which outlines a collaborative approach for renovating buildings with external insulation based on lean and BIM paradigms.

This allowed the incorporation of their knowledge and expertise in the evaluation process,

creating a robust mechanism for verifying the semantic integrity of the clustering approach. The combination of these methods ensured a thorough validation of the clustering, confirming that similar functionalities were indeed categorized together.

Table 3.2. Experts' profile

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

3.3.2.4. Concept Identification and Taxonomy Building

Word clouds and keyword extractions for each cluster were created after the functionalities had been clustered, serving as tools for concept identification. These visualizations aid in simplifying each cluster by highlighting the most prevalent terms and facilitating an intuitive grasp of the underlying concepts. Subsequently, domain experts were engaged through semi-structured interviews and surveys to carefully examine and match the identified concepts to the schedule levels. Their invaluable insights allowed us to organize these concepts into a structured hierarchy, laying the foundation for a comprehensive taxonomy of project planning and control systems' functionalities.

3.4. Results and Analysis

This section presents and discusses the research findings.

3.4.1. Clustering and Concept Identification Results

The dendrogram plot of hierarchical clustering, depicted in Fig. 3.4, outlines the hierarchical arrangement of 17 distinct clusters devised to categorize 148 functionalities. A Silhouette plot was used to assess cluster integrity. The silhouette coefficient ranges from -1 to 1, where a high value indicates that the object is well-matched to its own cluster and poorly matched to neighbouring clusters. The analysis indicates that the majority of functionalities possess positive Silhouette scores, which point to well-defined clusters. Nonetheless, a few clusters display bars nearing zero or dipping into negative values, signalling a potential overlap between clusters or a less robust clustering configuration for certain functionalities. This indicates areas where cluster structure might be improved. These findings underscore the importance of continuous refinement in the clustering process to ensure precise and meaningful categorization.

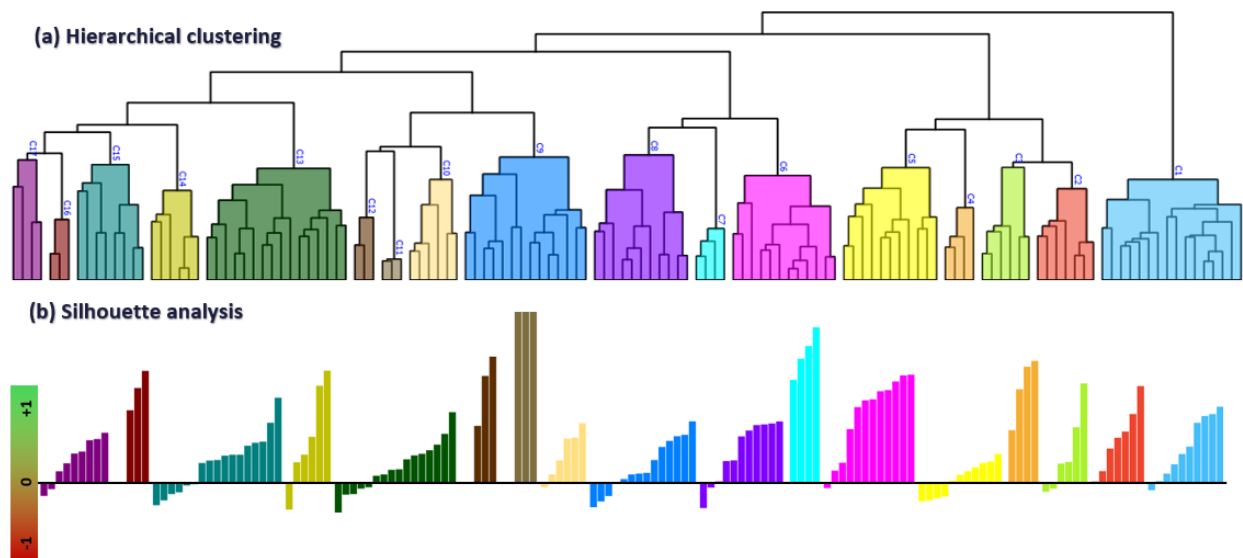


Fig. 3.4. Hierarchical clustering results

Furthermore, Table 3.3 provides more details on the clustering outcomes, encompassing details such as the number of functionalities, top words, silhouette plots, word clouds, and pivotal concepts associated with each cluster. Notably, the clusters exhibited variance in size and thematic focus, with the count of functionalities per cluster ranging from 3 to 17. The identified key concepts within these clusters spanned a wide spectrum of project management activities crucial for planning and control, like collaboration and communication management and data-driven decision-making. The importance of specific terms and concepts within each cluster was visualized through word clouds. As illustrated in Table 3.3, most clusters, such as clusters 4, 5, 7, 10, 11, 12, 13, 14, 15, 16, and 17 exhibit a singular key concept, whereas in other clusters, multiple concepts are identified. For instance, within cluster 6, the concepts of productivity, reliability, and workflow management were observed concurrently.

The silhouette plots provide a quantitative evaluation of the fit for each functionality within its cluster. Some clusters, including 5, 9, 13, and 15, exhibited less cohesion than anticipated. This suboptimal clustering may be ascribed to the inherent characteristics of the SBERT model, which is principally optimized for sentence-level inputs rather than phrases. The input data for this study consisted of phrases, which typically do not encapsulate the full semantic breadth that complete sentences offer, posing a challenge for effective embedding by SBERT. Moreover, due to the absence of a robust and comprehensive dataset characterizing the functionalities of project planning and control systems, essential for the training and fine-tuning of domain-specific models, this study adopted a pre-trained SBERT model. Such pre-trained models may encounter constraints when attempting to effectively generalize to domain-specific textual data (Wang et al. 2021). This may constitute an additional rationale for the presence of multiple concepts within certain clusters.

Table 3.3. (Continued)

Cluster	No. of functionalities	Top words	Silhouette plot			Word cloud	Key concept
			-1	0	+1		
12	3	Root, cause, analysis, corrective, action					Root cause analysis
13	16	Construction, planning, integration, alignment					Integration management
14	6	Continuous, learning, improvement, lesson, learn					Learning and knowledge sharing
15	17	Project, performance, control, progress, monitoring					Project performance management
16	3	Commitment, reliability, plan					Commitment management
17	9	Managerial, decision, information, making, process					Information-driven decision making

To deal with these challenges, an evaluation by domain experts was deemed necessary. To do so, Based on the results of clustering and identified concepts, clusters 1, 2, 6, and 8, which initially contained two or more concepts, were modified so that each cluster contained a single concept. Consequently, a total of 20 clusters were considered, each containing only one key concept to validate the identified concepts within each cluster using experts' insights. This decision was made to ensure a more granular and thorough analysis, allowing for identifying and validating specific concepts that might have been grouped initially due to the pre-trained SBERT model's domain-specific limitations.

Semi-structured interviews and surveys were utilized to capture the experts' specialized insights into the meaning and pertinence of functionalities within the clusters. During the interviews, the participants were asked about the number of functionalities in each cluster that matched the cluster's main concept and their meaningful grouping. They were also queried concerning the functionalities inside a cluster that did not follow the same concept as others. Table 3.4 presents the outcomes obtained from expert evaluations regarding how well functionalities align with each cluster's core concept.

The findings reveal that, with an average 87% alignment rate, the functionalities received consistency with their respective primary concepts. Further elaboration on the alignment of functionalities within each cluster is provided in Table 3.4. Despite the refinement of clusters guided by experts' feedback, the identified key concepts for constructing the taxonomy remained consistent with those established through hierarchical clustering. As a result, 20 key concepts were identified and considered for building the taxonomy of project planning and control systems' functionalities. The identified functional concepts serve dual roles within the context of project planning and control systems. From one angle, these concepts highlight the complexity and underlying managerial facets inherent to these systems. From another perspective, they function as essential requirements for the design and implementation of project planning and control systems. By mapping both single and integrated planning methods and control systems with these identified concepts, a deeper level of understanding and sense-making will be fostered among project stakeholders regarding these methods and systems. This will pave the way for future research endeavours in this domain. Consequently, this enhanced comprehension enables stakeholders to make more informed decisions when selecting the most suitable planning and control approach based on the specific requirements of their projects.

Table 3.4. Outcomes derived from experts' evaluation

Functionality main concepts	No. of items	Experts										Average alignment rate
		1	2	3	4	5	6	7	8	9	10	
Collaboration management	8	100%	100%	88%	88%	100%	100%	88%	100%	100%	100%	96%
Commitment management	5	80%	80%	100%	100%	80%	80%	100%	80%	80%	80%	86%
Communication management	11	64%	73%	82%	82%	91%	82%	73%	73%	82%	73%	77%
Conflict management	4	100%	100%	100%	75%	100%	100%	100%	75%	75%	75%	90%
Constraint management	6	83%	67%	67%	83%	83%	83%	83%	67%	67%	83%	77%
Contract and delay management	13	77%	85%	77%	69%	77%	77%	69%	85%	77%	85%	78%
Integration management	14	57%	57%	64%	71%	64%	79%	71%	64%	64%	57%	65%
Learning and knowledge sharing	6	100%	100%	83%	83%	83%	100%	83%	83%	100%	100%	92%
Workflow management	7	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Project performance management	17	94%	88%	100%	100%	94%	94%	88%	88%	100%	100%	95%
Real-time monitoring	4	100%	100%	100%	75%	75%	100%	100%	100%	75%	100%	93%
Reliability management	5	60%	80%	60%	60%	80%	80%	60%	80%	60%	80%	70%
Resources management	7	86%	86%	71%	86%	86%	71%	71%	71%	86%	86%	80%
Root cause analysis	3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Safety and logistics management	4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Supply chain management	4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Uncertainty and risk management	4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Visualization	11	73%	73%	82%	82%	73%	91%	82%	73%	82%	91%	80%
Waste management	6	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Information-driven decision making	9	67%	67%	78%	78%	78%	67%	67%	56%	78%	67%	70%
Total average alignment rate											87%	

In contrast to the conventional perspective regarding the primary objectives of project planning and control systems, which typically emphasize time and cost management, this research has illustrated that these systems encompass a variety of functions and concepts, including collaboration management, communication management, conflict management, resource management, safety and logistics management, among others. As such, it becomes imperative for project managers and their teams to initially find out their functional requirements based on these identified concepts. They can then endeavour to identify the most suitable planning and control system tailored to meet these requirements. These insights not only highlight the multifaceted nature of project planning and control systems but also underscore the significance of considering diverse managerial aspects and functions. Such considerations are instrumental in empowering project teams to make more informed and effective decisions regarding their planning and control systems.

3.4.2. Taxonomy Development

After the validation of functionality concepts, to construct the taxonomy, a survey was designed and shared with selected experts during another round of semi-structured interviews. The experts were asked to assess the significance of each functionality concept across various schedule levels using a Likert scale ranging from 0 (no importance) to 4 (very high importance). Following that, a taxonomy for project planning and control systems' functionalities was developed based on the experts' average rating of the relative importance of each functionality concept across schedule levels (Fig. 3.5).

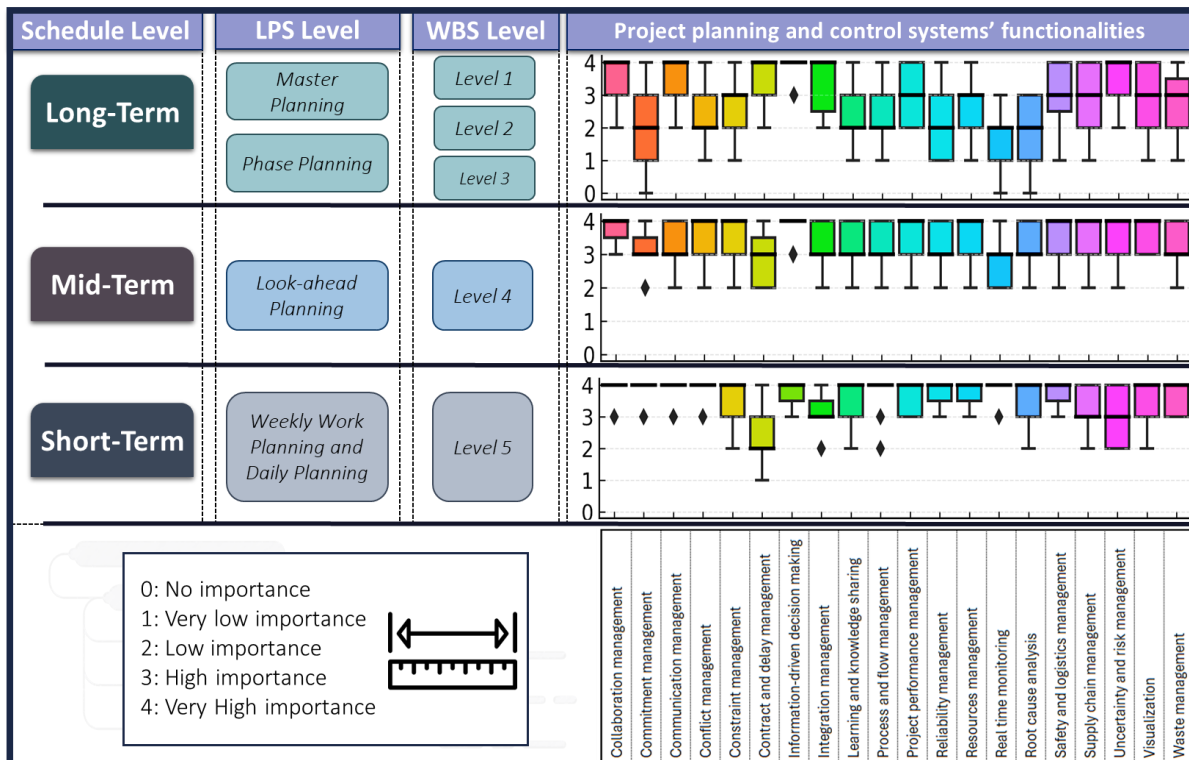


Fig. 3.5. Taxonomy of multi-level project planning and control systems' functionalities

Fig. 3.5 represents the importance of various functions across different scheduling levels. As can be seen, certain functions are deemed more critical than others, denoted by the importance ratings (2 for low importance, 3 for high importance, and 4 for very high importance). Based on the standard deviations observed in the box plots, the results generally

exhibit high reliability due to the low variability in expert evaluations for each functionality across short-term and mid-term schedule levels. However, for the long-term level, there is a slight increase in deviation, suggesting that opinions vary more regarding the importance of some functionalities in the long term. Despite this, the overall consistency across all schedule levels indicates a broad consensus among experts, making the assessments reliable for decision-making and strategic planning.

Information-driven decision-making is highlighted as having very high importance across all scheduling levels. This emphasis across long-term, mid-term, and short-term schedules underscores the critical role of accurate and timely information in guiding all stages of project management. At the long-term level, data-driven decisions are fundamental to establishing project objectives and aligning them with strategic goals. In mid-term scheduling, such decision-making is vital to adapting the project plan based on progress and external changes, ensuring the project remains on track. At the short-term level, it is necessary for daily operations, where immediate decisions can have significant impacts on the day-to-day success of project tasks.

In the mid-term schedule level, supply chain management, uncertainty and risk management, and collaboration management are particularly emphasized. Supply chain management is crucial in this phase as it ensures the timely availability of materials and resources, which are essential for maintaining project momentum. Uncertainty and risk management are also critical since this is the stage where potential risks must be identified and mitigated to prevent project delays. Collaboration management gains significance due to the increasing need for coordinating multiple teams and stakeholders as the project moves from planning to execution. Furthermore, at this level, constraint management, conflict resolution, resource allocation, and visualization are recognized for their pivotal roles in project planning and control. Effective constraint management facilitates teams in anticipating and navigating project limitations and bottlenecks to ensure the achievement of project objectives. Conflict resolution ensures smooth collaboration by addressing team disputes and identifying and resolving temporal or spatial conflicts to maintain project continuity. To mitigate delays and enhance operational efficiency, it is crucial to allocate resources as effectively as possible to optimize capacities and make effective use of materials and equipment. Moreover, visualization facilitates transparent communication, which enables stakeholders to understand various what-if scenarios and construction sequences to make well-informed decisions promptly. Collectively, these elements provide the foundation for successful project execution, aligning team endeavours with project objectives.

At the short-term level, most functions receive very high importance based on expert feedback, which can be attributed to the immediacy and tactical nature of this phase. Effective execution at this stage is essential for the daily progress and ultimate success of the project. This phase is where planning is translated into action, and as such, all functions, from resource allocation to safety and logistics, must be managed with a high degree of precision and responsiveness. The feedback from experts likely reflects the reality that, at this level, there is a smaller margin for error, and the impact of each function is immediately observable on the project's progress.

By systematically classifying and organizing identified functionality concepts according to their significance at each scheduling level, it becomes feasible to align the features and functions of various planning methods with the corresponding functionalities at each

scheduling level, thereby facilitating the selection of the most effective approach for managing that specific level. For instance, at the mid-term schedule level, where collaboration management, constraint management, supply chain management, and workflow management are prioritized, the features and functionalities of planning systems such as the last planner system and takt time planning, particularly in managing lookahead plans, are crucial. These systems can significantly influence the management of these aspects, enhancing overall project coordination and efficiency.

This taxonomy acts as a scaffold for future research, providing a structured framework to explore the interplay between different planning and control systems and their respective functionalities and project teams' functional requirements at each scheduling level. It invites scholars and practitioners to consider project planning and control not merely as a collection of disparate methods but as a cohesive system that operates across multiple levels, each with its distinct functions and requirements.

By identifying the specific functionalities pertinent to each level of scheduling, the proposed taxonomy paves the way for developing a multi-level project planning and control system that integrates various functions and methods to address the unique demands of each scheduling level. The approach advances the field by encouraging a systemic view of project planning and control, where the synergy between different levels and functions can lead to more robust and adaptive management practices. Consequently, this perspective enhances the potential for achieving strategic alignment and operational efficiency, leading to improved project performance and successful outcomes.

3.5. Discussion

This research adopts a comprehensive and multi-stage methodology to investigate the functionalities of project planning and control systems in the construction industry. Initially, a thorough data collection process is conducted through systematic literature reviews and meta-analyses, focusing on various planning methods and control metrics. This phase extracts 148 functionalities, serving as a foundational dataset for deeper analysis. The extracted data undergo a series of preprocessing steps, including lowercasing, removal of stop words and punctuation, tokenization, lemmatization, and part-of-speech tagging. These preprocessing efforts are crucial for standardizing the data, thus facilitating more sophisticated text-mining techniques.

Semantic analysis plays a pivotal role in the methodology, where the Sentence-BERT (SBERT) model is employed to generate text embeddings. This model captures the semantic similarities between the functionalities, enabling the application of hierarchical clustering to group functionalities into semantically coherent clusters. This clustering is crucial for developing a structured taxonomy of functionalities, reflecting the semantic relationships within the data.

The results from the clustering process are rigorously analyzed, with the study achieving 17 distinct clusters of functionalities. The integrity and appropriateness of these clusters are quantitatively assessed using Silhouette analysis, which generally indicates a strong alignment of functionalities within their respective clusters. However, some clusters exhibit potential overlaps or less distinct boundaries, suggesting areas for further refinement. The reason could be that this study utilized a pre-trained SBERT model due to the lack of a thorough dataset on functionalities of project planning and control systems. While pre-trained models like SBERT

are useful, they may struggle to generalize effectively to domain-specific data, potentially leading to multiple concepts within certain clusters.

The validation of the clustering results involves a comprehensive approach, employing word clouds, keyword extraction, and expert interviews. These methods ensure that the clusters are not only statistically valid but also practically relevant and intuitive. Experts from the industry and academia are engaged to assess the alignment of functionalities within clusters, with findings showing an average 87% alignment rate. This high rate of consistency confirms the effectiveness of the semantic clustering approach and underscores the robustness of the taxonomy developed.

Finally, the construction of a functional taxonomy discusses based on the importance of each functionality concept across different scheduling levels, considering experts' insight. This taxonomy is instrumental for practitioners, allowing project managers to select and implement planning and control systems that are best suited to the specific needs of their projects at various stages. By systematically classifying and organizing functionality concepts, the research provides a valuable framework that aids in understanding the multifaceted nature of project planning and control systems.

The importance of functionalities, as reflected in the standard deviations of experts' feedback, shows high reliability due to the generally low variability in expert assessments for each functionality across various schedule levels. This consistency across all schedule levels points to broad agreement among experts, making these evaluations dependable for decision-making and strategic planning.

The identified functionality concepts extracted from various planning methods and control metrics as a common concept across these systems can play a role as a primary key concept in the database management domain. This unique position allows them to integrate planning methods and control metrics across different scheduling levels, paving the way for developing a multi-level and integrated planning and control system. Such an approach can effectively address the limitations inherent in individual planning methods and control systems by leveraging and integrating the advantages and functionalities of each. In forthcoming research, efforts will be concentrated on exploring this integration further. The established taxonomy and functionality concepts will form the foundational basis for developing a comprehensive, multi-level, and integrated planning and control system. This innovative approach aims to enhance the robustness and adaptability of project management strategies, ensuring that they are well-suited to meet the diverse and dynamic needs of construction projects.

In essence, this study exemplifies a methodologically rigorous approach to dissecting and categorizing project planning functionalities, highlighting the importance of combining quantitative methods with qualitative insights to develop tools that are not only theoretically sound but also practically applicable in improving project management practices.

3.6. The Implications of the Findings

The findings from this research offer profound scientific and practical implications in the project planning and control body of knowledge. Scientifically, the research introduces a novel and robust multi-step methodology that combines advanced text mining techniques with expert validation, setting a new benchmark for future studies in project management

and related disciplines. This approach allows for a systematic understanding and integration of various project planning methods and control metrics, enhancing the theoretical framework within which these systems are analyzed and applied.

Practically, the identified functionality concepts and developed taxonomy from this research provide actionable benefits for project managers and stakeholders. Given the often low level of knowledge about planning and control systems among stakeholders, it is challenging for them to select an appropriate planning and control system for their projects. To deal with this issue, the identified functionality concepts in this study can act as the functional requirement of project planning and control systems that will aid the project team to more effectively determine their requirements and then see what planning and control system is more aligned with those requirements. Additionally, the developed taxonomy will help the project team understand how much effort should be put into each level of schedule for each functionality, optimizing efforts and resources. Furthermore, the identified functionality concepts and developed taxonomy can be used as a foundation for extracting and formulating the tacit knowledge of the domain expert and building a knowledge repository of project planning and control systems. This knowledge repository can act as a database in an expert system to suggest the most-fitted planning and control systems for the construction project, considering the project team's requirements.

3.7. Conclusion, Limitations, and Future Directions

This study developed a robust taxonomy of functionalities within project planning and control systems through a rigorous methodology. A wide range of planning and control systems' functionalities were identified and classified into distinct and semantically coherent clusters by combining systematic literature reviews with advanced text mining techniques, including sentence-BERT for semantic analysis and hierarchical clustering. Incorporating both a quantitative approach and qualitative analysis through expert feedback in validating the clusters and concepts ensures that the taxonomy reflects the realities of construction project management. This validation confirms the applicability and significance of the research findings to the project planning and control domain. The outcomes of this study furnish a structured framework for comprehending the diverse functionalities inherent in project planning and control systems. It encapsulates the complexities and underlying concepts of various planning and control methods, which enhances actionable insights for project managers and stakeholders.

The proposed taxonomy makes a substantial contribution to the field of project planning and control by mapping structured functionality concepts across different schedule levels against planning methods and control metrics. This facilitates project managers in selecting appropriate planning methods tailored to address specific project requirements, potentially leading to enhanced decision-making, superior project outcomes, and improved alignment between project objectives and execution strategies. The scientific implications of this research are profound, setting new processes for integrating quantitative and qualitative data analysis techniques in project management studies. The practical ramifications are equally significant, providing project managers with a deeper understanding of the multifaceted nature of project planning and control systems and enabling the use of this taxonomy to improve decision-making processes.

A notable limitation of this research was the absence of a domain-specific textual dataset,

which necessitated the use of a pre-trained SBERT model. While SBERT is proficient in processing and analyzing text, it was not originally optimized for semantic textual similarity analysis specifically within the construction domain. This limitation underscores the potential discrepancies in semantic understanding when applying generalized models to specialized fields.

Looking ahead, future research should focus on developing customized models that are directly trained on domain-specific datasets within the construction industry. Moreover, future endeavours may find value in utilizing the derived taxonomy and functional concepts outlined in this study as a foundation for assessing the efficacy of various planning methods and control metrics in supporting these functionality concepts. Such an approach could propose a multi-level planning and control system that accounts for the diverse functional requirements of project teams. Eventually, this study not only contributes to the academic literature but also offers tangible strategies for promoting project planning and control in the construction sector by bridging the gap between theoretical research and practical application.

Chapter 4. An Innovative Integrated Framework for Multi-level Production Planning and Control Systems in Construction

This chapter is a copy of the following paper:

- Sheikhkhoshkar, M., Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Sakikhales, M. (2024). "An Innovative Integrated Framework for Multi-level Production Planning and Control Systems in Construction." *Developments in the Built Environment*, 19, 100524, <https://doi.org/10.1016/j.dibe.2024.100524>.

This chapter addresses the third objective of this thesis: to propose a comprehensive, multi-level, and collaborative planning and control framework that tackles fragmented and ineffective planning and control methods. The aim is to develop 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 chapter 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.

4.1. 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; Roupé et al. 2020), inefficient workflow (Hamzeh 2009b), 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 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; Sakikhales 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; Sbiti 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; Hamzeh et al. 2019b; Sheikhhoshkar et al. 2024c). 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.

4.2. 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 Modeling (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. 4.1. 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.

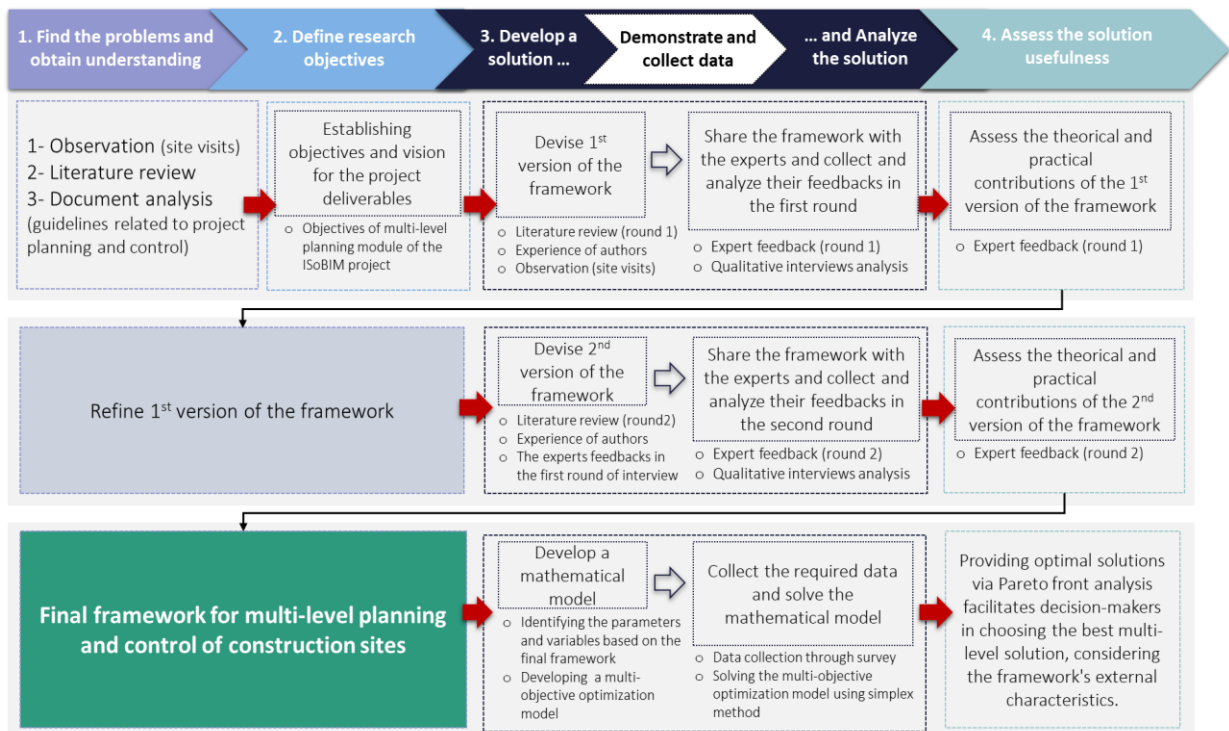


Fig. 4.1. Adopted methodological steps for applying DSR

4.2.1. 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 (Sheikhkhoshkar et al. 2023a; Sheikhkhoshkar et al. 2024c; Sheikhkhoshkar et al. 2023b) 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.

4.2.2. 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. 4.2, 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 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.

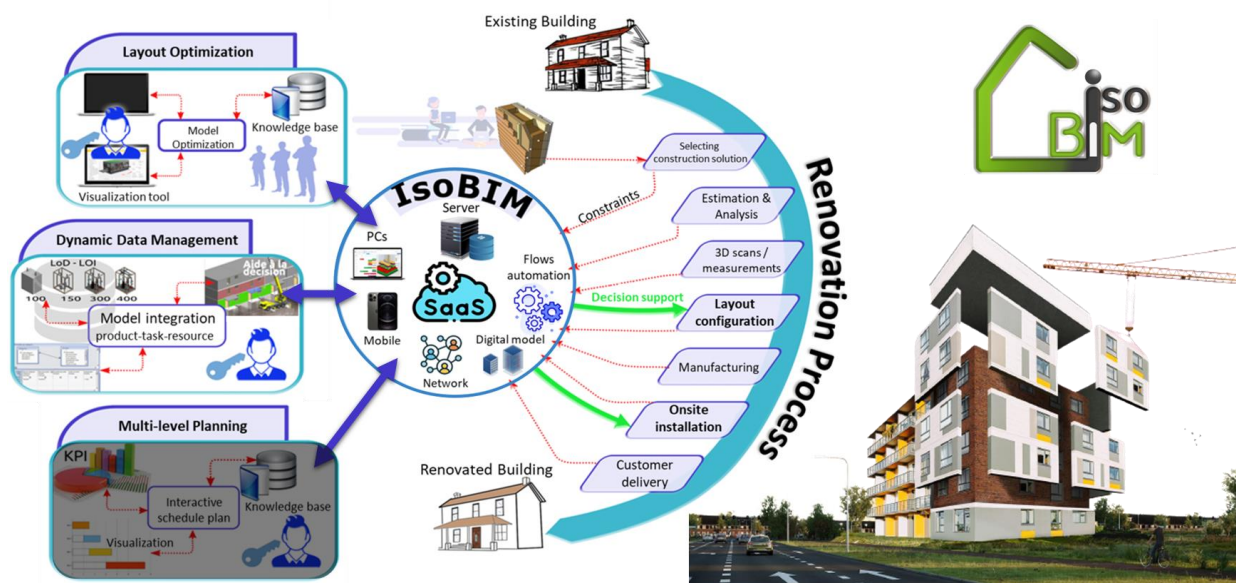


Fig. 4.2. IsoBIM project overview

4.2.3. 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. 4.3 illustrates the observed production system design for project planning and control at the visited project, which consists of multiple buildings within an approximately 51-hectare 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 4.1, 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 hours. 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 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 4.2.



Fig. 4.3. Observed production system for planning and control in the visited projects

Table 4.1. 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

Table 4.2. Some of the quotes from experts that caused important changes in the framework

Sample statements from the Experts	Derived insights for the framework
<i>"In the initial iteration of the conceptual framework, a key difficulty lies in connecting the three layers of diverse characteristics."</i>	
<i>"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."</i>	Played an important role in defining and incorporating functionality as a key concept within the framework for effectively integrating the three layers.
<i>"What specific planning and control principles should be put into action and applied at each level of schedule?"</i>	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

“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.”

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 .

“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.

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.

4.2.4. 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. 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 (Peppers 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 4.3 provides the details of the assessment criteria.

Table 4.3. 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

4.2.5. Develop a Multi-Objective Mathematical Model

A multi-objective mathematical model was formulated to clarify and 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 organisation, project, environment, and stakeholders. Essentially, the model furnishes a comprehensive and adaptable solution that aligns with the unique requirements of diverse project contexts.

4.3. 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. 4.4, 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.

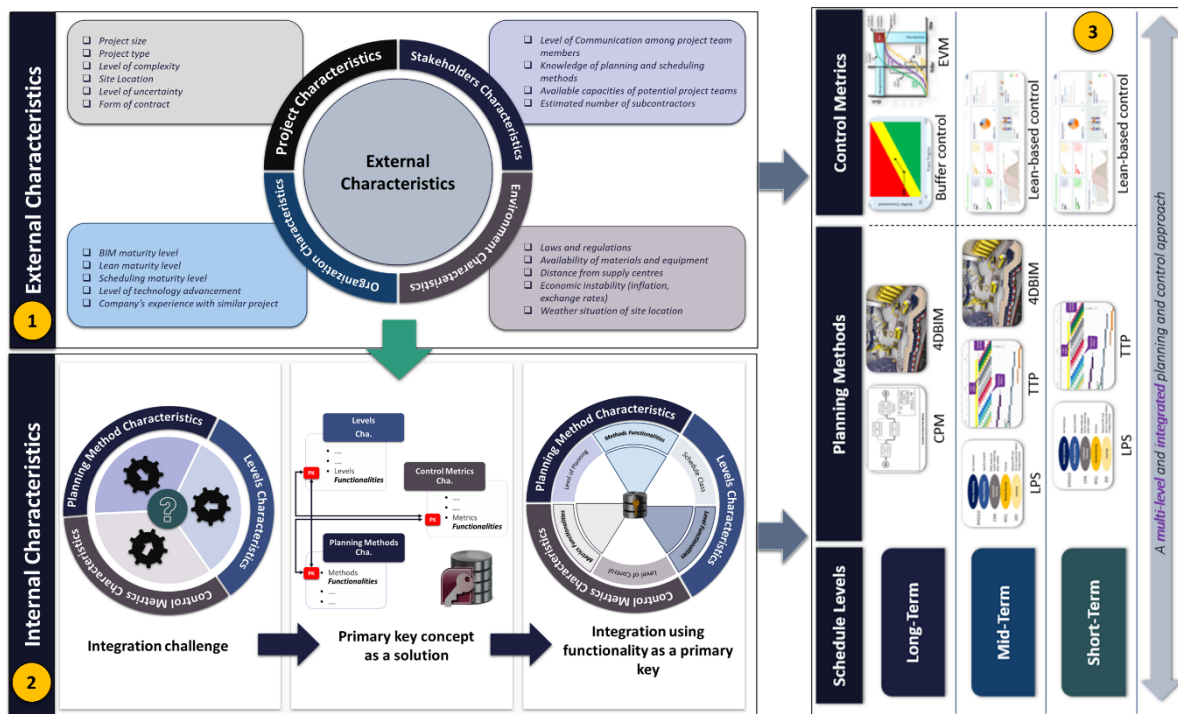


Fig. 4.4. Proposed multi-level and integrated framework for project planning and control

4.3.1. 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. 4.5.

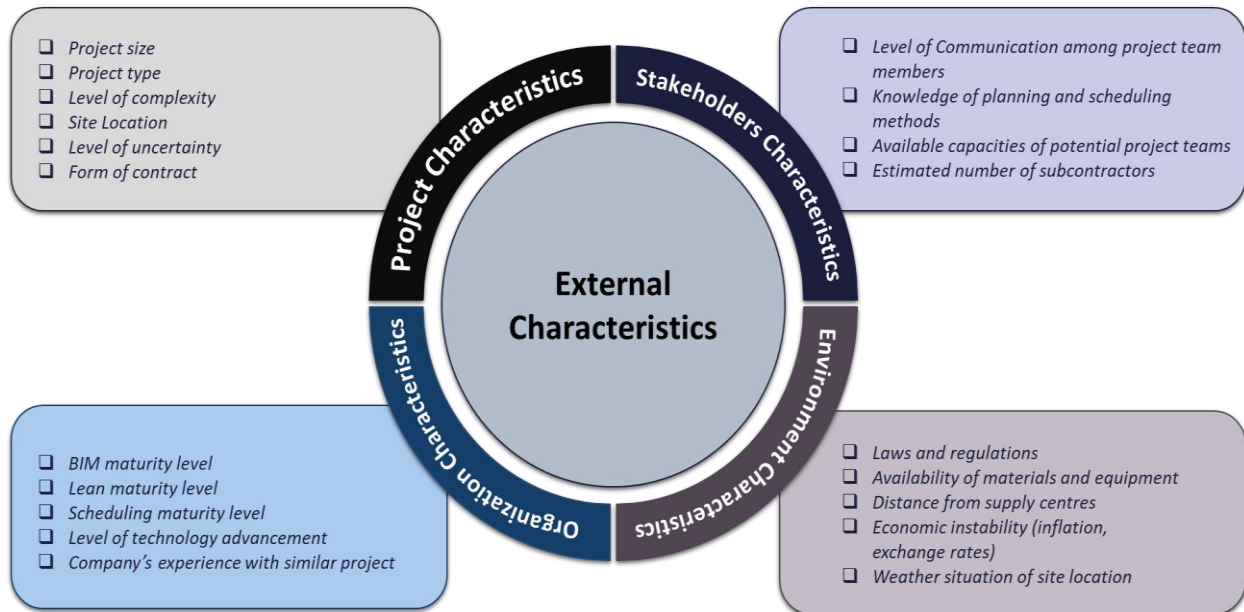


Fig. 4.5. Suggested external characteristics for the multi-level planning and control system

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.

4.3.2. 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) and Sheikhhoshkar et al. (2024c), where they extracted and analyzed the functionalities related to planning methods and control metrics. Fig. 4.6 depicts the components constituting the internal characteristics of the framework.

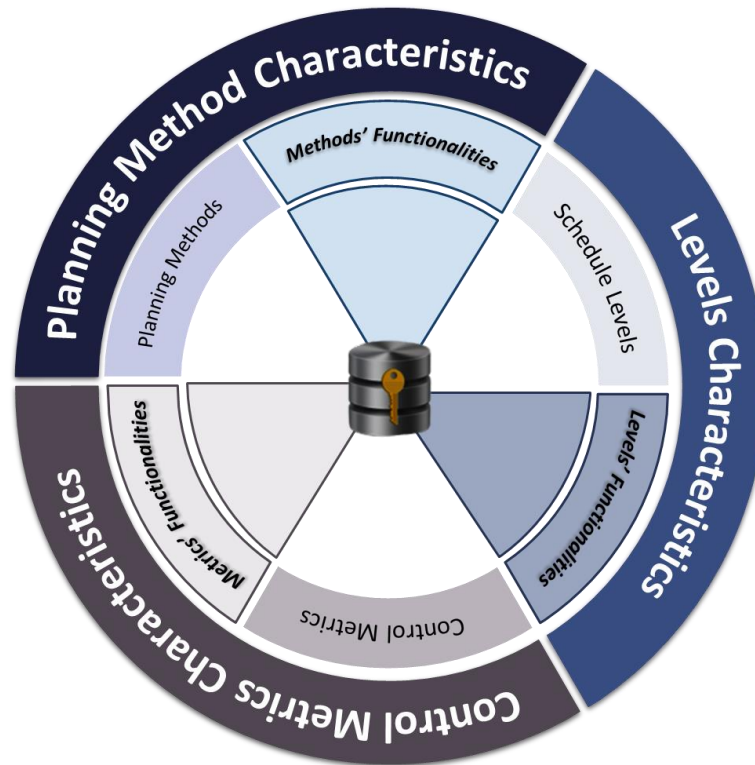


Fig. 4.6. Internal characteristics for the multi-level planning and control system

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?

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. 2024c), 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), Sheikhhoshkar et al. (2024c), and Sheikhhoshkar et al. (2024b) studies and considered (Table 4.4). Since the functionality concepts outlined in Table 4.4 are somewhat extended, their detailed definitions for this research are provided in Table A5 in the appendix.

Table 4.4. Functionalities considered in project planning and control systems

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

The relationship between the principal components is distinctly illustrated in Fig. 4.7. The first step involved collecting the necessary data to operationalize the mathematical model, guided by the connections shown in Fig. 4.7. 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. 2024c) 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).

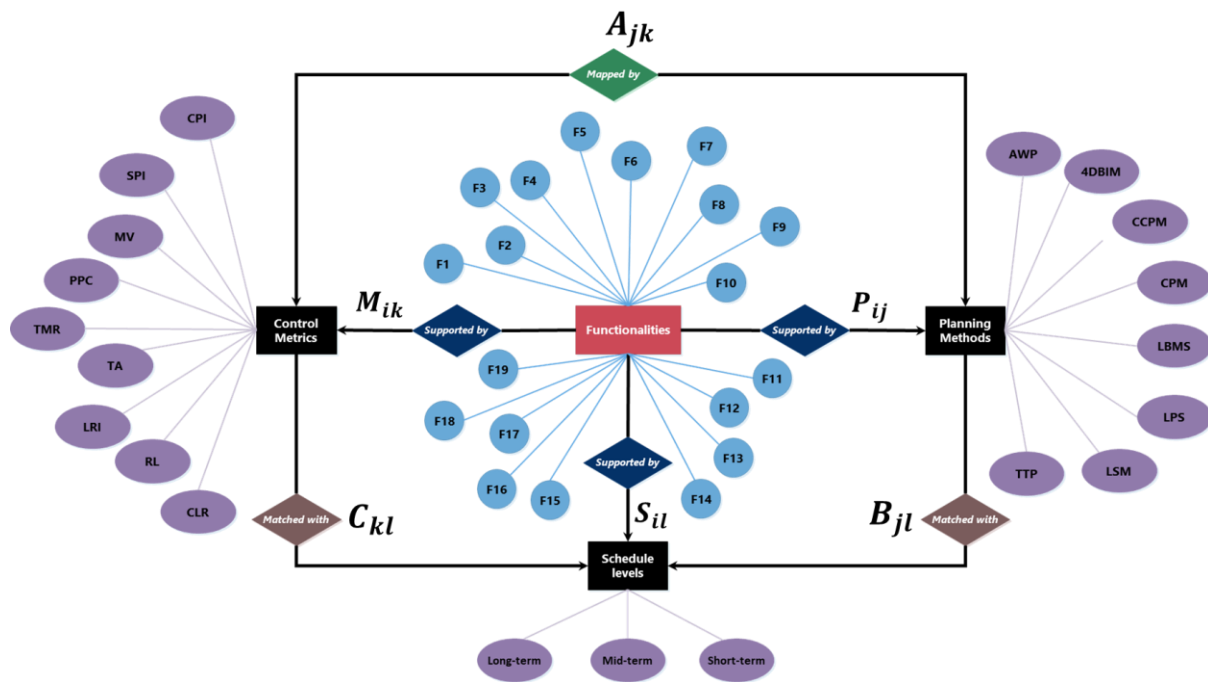


Fig. 4.7. Relational diagram of the main components of the multi-level framework for a case study

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.

4.4. 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:

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, $i \in [1..I]$

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

$$W_j = \sum_{i=1}^I P_{ij} \quad (4.1)$$

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

$$V_k = \sum_{i=1}^I M_{ik} \quad (4.2)$$

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

$$U_l = \sum_{i=1}^I S_{il} \quad (4.3)$$

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

Objective Functions:

$$Z_1 = \max \left(\sum_j W_j \cdot X_j + \sum_k V_k \cdot Y_k \right) \quad (4.4)$$

$$Z_2 = \min \left(\sum_j X_j \right) \quad (4.5)$$

$$Z_3 = \min \left(\sum_k Y_k \right) \quad (4.6)$$

Eq. (4.4), (4.5) and (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:

$$\forall k \in [1..K], \sum_{j=1}^J (A_{jk} \times X_j) - Y_k \geq 0 \quad (4.7)$$

Eq. (4.7) ensures that if a control metric is selected, then at least one planning method that supports this control metric must also be selected.

$$\forall l \in [1..L], \sum_{j=1}^J (B_{jl} \times X_j) \geq U_l \quad (4.8)$$

Eq. (4.8) demonstrates that deploying a particular schedule level requires the simultaneous deployment of at least one planning method corresponding to that level.

$$\forall l \in [1..L], \sum_{k=1}^K (C_{kl} \times Y_k) \geq U_l \quad (4.9)$$

Eq. (4.9) 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.

$$\forall j \in [1..J], \sum_{l=1}^L (B_{jl} \times U_l) \geq X_j \quad (4.10)$$

Eq. (4.10) enforces that if a scheduling level is active, at least one applicable planning method for that level must be chosen.

$$\forall k \in [1..K], \sum_{l=1}^L (C_{kl} \times U_l) \geq Y_k \quad (4.11)$$

Eq. (4.11) enforces that if a scheduling level is active, at least one applicable control metric for that level must be chosen.

$$\forall i \in [1..I], \sum_{j=1}^J (P_{ij} \times X_j) \geq R_i \quad (4.12)$$

Eq. (4.12) ensures that the selected planning methods meet the user requirements in terms of functionalities.

$$\forall i \in [1..I], \sum_{k=1}^K (M_{ik} \times Y_k) \geq R_i \quad (4.13)$$

Eq. (4.13) guarantees that the selected control metrics cover the user requirements in terms of functionalities.

4.5. 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. 4.8 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.

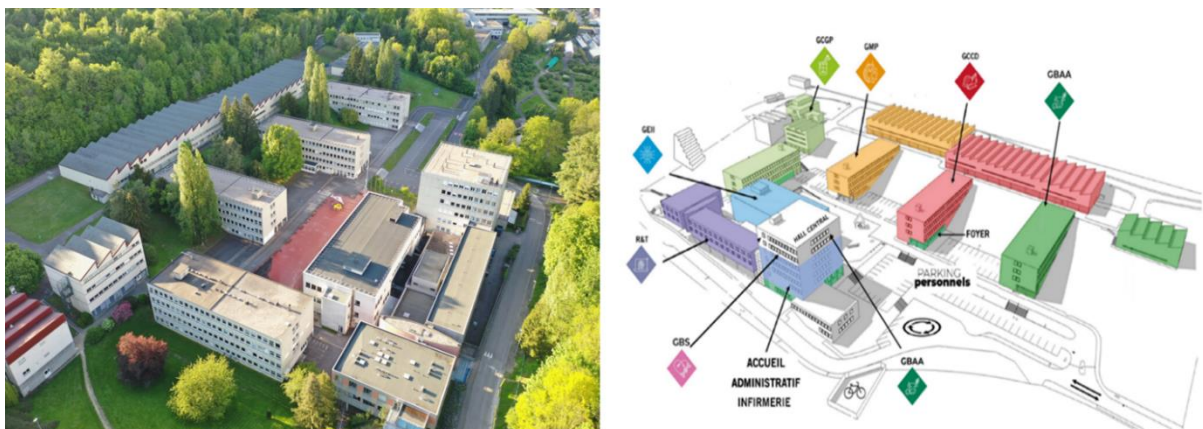


Fig. 4.8. An overview and layout of the renovation case study

4.6. 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 Filipič 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. 4.9 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.

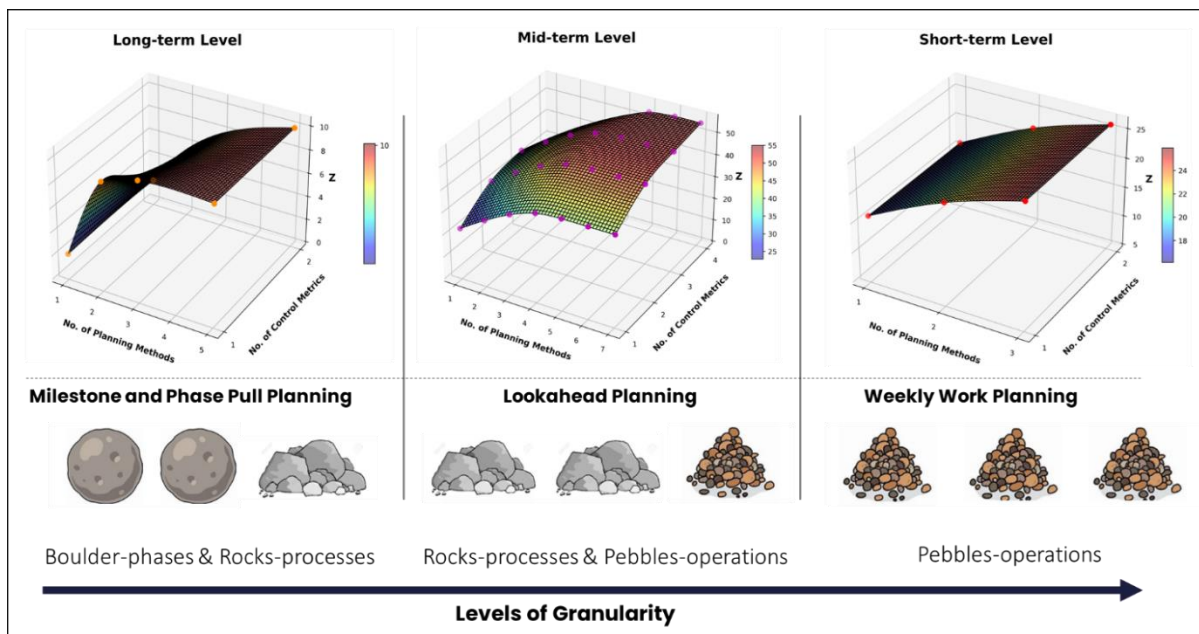


Fig. 4.9. Pareto front graphs for the results

In addition, Table 4.5 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. 4.9 and Table 4.5, 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 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 4.5 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).

Table 4.5. 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
<i>Long-term level</i>																			
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	0	0	0	0	0	0	0	0	0	0	0	1	0	0
10	5	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	1	0	0
10	5	2	1	1	1	1	0	1	0	0	0	0	1	0	0	0	1	0	0
<i>Mid-term level</i>																			
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	1	0	0	0	0	1	1
39	2	2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
42	2	3	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1
45	3	2	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
48	3	3	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1	1
50	5	2	1	1	0	0	1	0	1	1	1	0	0	0	0	0	0	1	1
52	4	3	1	0	0	0	1	0	1	1	1	0	1	0	0	0	0	1	1
53	5	3	1	1	0	0	1	0	1	1	1	0	1	0	0	0	0	1	1
54	5	4	1	0	0	1	1	1	0	1	1	0	1	0	0	0	1	1	1
<i>Short-term level</i>																			
16	1	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
16	1	2	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0
22	2	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
22	2	2	0	0	0	0	0	0	0	1	1	1	0	0	1	0	0	0	0
26	3	1	0	0	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0
26	3	2	0	0	0	0	1	0	1	1	1	1	0	0	1	0	0	0	0

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 look-ahead 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 (Sheikhkhoshkar 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. 2015b). 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. 4.10 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.

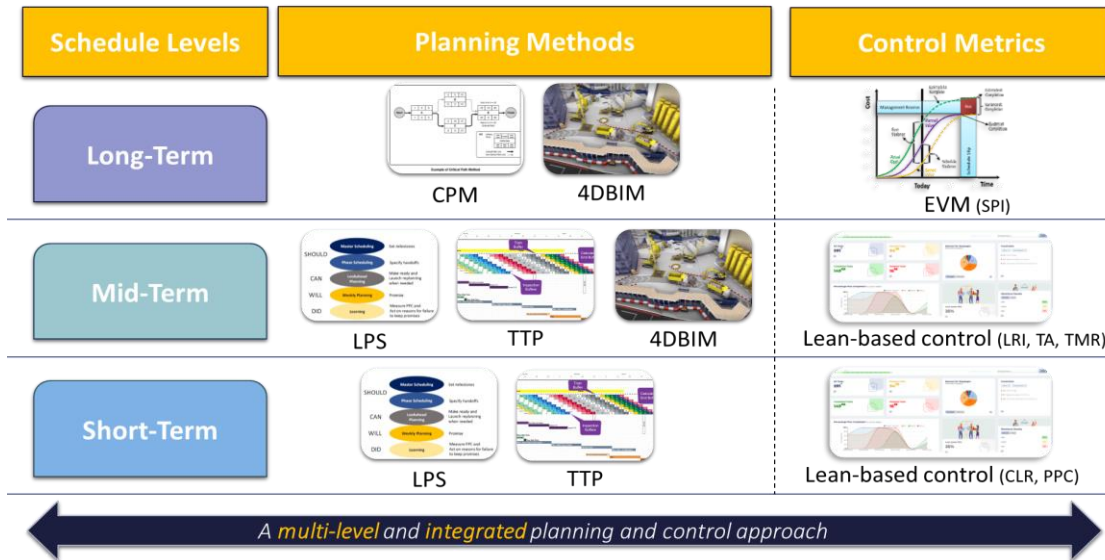


Fig. 4.10. Proposed production planning and control system for the renovation case study

4.7. 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 ten academic and industrial experts who participated in the six-month endeavor of conceptualizing, developing, and evaluating the framework. The profiles of these experts are presented in Table 4.1. 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. 4.11 presents the survey questions, respondents' answers, and the average response for each question.

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

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.

4.8. 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 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.

4.9. 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 4.6 presents a more detailed comparative analysis.

Table 4.6. 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.

4.10. 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.

4.11. 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 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.

Chapter 5. A Data-driven and Knowledge-based Decision Support System for Construction Planning and Control

This chapter is a copy of the following paper, which is under review:

- Sheikhhoshkar, M., Bril El-Haouzi, H., Aubry, A., Hamzeh, F., and Rahimian, F. (2024). " A Data-driven and Knowledge-based Decision Support System for Construction Planning and Control." *Automation in Construction, Under Review.*

This chapter addresses the fourth objective of this thesis: to design a decision support system (DSS) for implementing the multi-level and collaborative planning and control framework developed in the previous chapter, and to recommend the most suitable approach based on the needs of the project team. The aim is to create a data-driven and knowledge-based DSS that leverages a knowledge repository constructed from experts' experiences, and proposes multi-level, integrated systems for the planning and control of construction projects. To achieve this, a mixed-method approach was employed to collect data from industry professionals, develop a knowledge repository and a rule-based expert system based on rough set theory (RST), and integrate these insights into a DSS optimized by a mathematical model. The results demonstrated that the decision support system effectively captures and utilizes expert knowledge, facilitating enhanced decision-making in project planning and control. The system's application in a real-world renovation project highlights its practical utility and effectiveness. The research significantly impacts the construction industry by providing a tool that enhances systematic and data-driven decisions for planning and control systems based on expert knowledge. This provides a more efficient approach that aligns with the specific needs of the project team.

5.1. Introduction

Project planning and control stands as a fundamental element of construction project management. This multi-functional domain handles a broad spectrum of decision-making challenges. These functions not only ensure that all project activities are meticulously planned, sequenced, and resourced to promote a seamless operational flow but also deal with analysing deviations and delays, managing constraints and commitments, and fostering collaboration and communication among project team members (Pellerin and Perrier 2019; Sheikhhoshkar et al. 2023a). To tackle these decision-making challenges, a wide variety of methods, techniques, and tools have been devised over decades. The critical path method (CPM) represents one of the earliest methods conceived for project planning, scheduling and control (Kelley Jr and Walker 1959). While it's still widely used and often required by project

owners for scheduling needs, there are several concerns with this approach, including a tendency to create overly detailed schedules even when project details are uncertain, failure to encourage collaboration during the planning phase, oversight of non-critical tasks, and limitations in monitoring resource allocation (Olivieri et al. 2016). Given the complexity of construction projects and the engagement of numerous stakeholders, the Architecture, Engineering and Construction (AEC) industry has recognised the need for more effective project planning and control methods. In this regard, the introduction and adoption of lean-driven planning and control methods, such as the last planner system (LPS) (Ballard 2000; Hamzeh 2009a), location-based management system (LBMS) (Seppänen et al. 2010), and takt time planning (TTP) (Frandsen and Tommelein 2014), represented a significant paradigm shift in project planning and control domain. Emerging building information modelling (BIM) and its integration with industry 4.0 technologies was another significant advancement in project planning and control (Yilmaz et al. 2023). BIM provides a digital representation of the physical and functional characteristics of the project, which facilitates enhanced visualization and improved decision-making throughout the construction lifecycle (Akbari et al. 2024). Integration with Industry 4.0 technologies, including the Internet of Things (IoT), virtual reality (VR), augmented reality (AR), and artificial intelligence (AI), further augments the capabilities of BIM for project planning and control (Najafi et al. 2024). This synergy enables predictive analytics, real-time monitoring, better visualization and collaboration, and improved stakeholder engagement in the planning and control process (Rashidi et al. 2023). While these developments have notably improved the project planning and control field, the scholars identified certain shortcomings in the independent implementation of these methods (Dallasega et al. 2021). Standing alone, each system is strong in some functions but requires improvements in others (Olivieri et al. 2016). Therefore, several academics have attempted to integrate these planning methods, aiming to establish a comprehensive approach that effectively mitigates their limitations. In this context, Olivieri et al. (2016) synthesized CPM, LBMS, and LPS to enhance the modelling of workflow dynamics. This integrated approach was intended to facilitate managerial analysis and communication regarding delays, as well as to inform decision-making processes regarding the best strategies for the critical path. Rashidi et al. (2023) focused on employing a virtual reality (VR) environment to improve 4D-BIM-based construction planning. They uncovered the potential enhancements in construction planning, particularly in spatial understanding, spatial-temporal conflict resolution, stakeholder collaboration, training and education, and safety management, through integrating these innovative technologies. Liu et al. (2024) investigated a novel experimental tool developed to examine the social mechanisms of LPS implementation by utilizing immersive virtual reality (IVR) gaming technology. Additionally, it has been proposed to utilise the LPS along with Location-Based Planning (LBP) methods to better organize work sequences across different project locations, aiming to streamline workflows further (Ballard and Tommelein 2021).

These developments go beyond just improving planning methods. Endeavours have additionally been directed towards establishing and utilizing control metrics for the continual monitoring and analysis of project performance, efficiency, and other dynamic aspects, including the efficiency of resource allocation, quality of the construction flow, constraints removals, labour productivity, and quality of the commitments (Shehab et al. 2024; Sheikhhoshkar et al. 2024c). This guarantees that projects are not solely meticulously planned but are also regularly evaluated and updated based on ongoing actual data (Hamzeh et al. 2019b).

Despite the widespread implementation of these individual and integrated planning methods and control metrics globally, the choice to prefer one planning method over another, or to integrate multiple methods, was driven by the need to address their respective shortcomings and leverage their strengths (Dallasega et al. 2021). Selecting the most effective planning and control system based on the specific needs of the project team has often been overlooked in both literature and practice. Therefore, there is a need for a tool that can propose the planning and control approached based on project-specific requirements. To fill this academic and practical gap, this research aims to develop a data-driven and knowledge-based decision support system (DSS) that suggests multi-level and integrated project planning and control systems for construction projects. To achieve this aim, the research outlines the following objectives:

1. Capture and extract the knowledge and experiences of professionals in project planning and control to construct a knowledge repository
2. Develop a decision support system to use the knowledge database and suggest planning and control systems based on the project team's requirements
3. Develop and execute a mathematical model to optimize the proposed solutions by DSS

To achieve the objectives, this research captures and analyzes the knowledge and experiences of domain experts to build a knowledge repository for the DSS. An inference engine is then launched to recommend suitable planning and control systems, taking into account both the knowledge database and the project team's functional requirements. A mathematical model is subsequently developed to optimize the solutions proposed by the DSS. The practicality and usability of the system are evaluated through a case study and feedback from experts.

The paper is organized as follows: Section 2 provides the research methodology. Section 3 includes the analysis and outcomes derived from data collection efforts, extending to mathematical modelling and validation results. In section 4, the paper delves into research discussion and implications. Finally, section 5 highlights the conclusion, limitations, and avenues for future investigation.

5.2. Knowledge-based Systems in Construction Management

The rapid advancement of artificial intelligence (AI) and its diverse applications have significantly enhanced decision-making processes, particularly in construction management. Given that the construction sector heavily relies on expert experience, best practices, and lessons learned, knowledge-based systems play a crucial role in capturing and preserving tacit knowledge (Dikmen et al. 2022). This is especially important in mitigating the loss of critical insights due to the industry's high staff turnover. In this context, several studies have proposed knowledge-based systems to address various challenges in construction management. For instance, Dikmen et al. (2022) developed a rule-based decision support system for risk and complexity assessment in construction projects. Their mixed-method research approach involved semi-structured interviews with 18 senior project managers to explore the risk-complexity relationship and inform the knowledge framework underlying the DSS. Similarly, Okudan et al. (2021) introduced a case-based reasoning approach for a knowledge-driven risk management tool tailored to construction projects. Hwang et al. (2018) presented a knowledge-based DSS for prefabricated prefinished volumetric construction

which followed a comprehensive literature review, pilot interviews with industry experts, and structured questionnaires to collect the required data and build a knowledge database. Akbari et al. (2020a) employed a rough set-based fuzzy inference system to create a DSS for dynamically assessing the sustainable success of infrastructure projects.

Such advancements have also had a notable impact on construction planning and control, where systems have been developed for various functions such as schedule updating, schedule analysis, time prediction, activity duration estimation, cost estimation, and project network generation. For instance, Hendrickson et al. (1987) pioneered a knowledge-intensive expert system for generating project activity networks, cost estimates, and schedules, including defining activities, specifying precedences, selecting technologies, and estimating durations and costs. More recently, Jahr and Borrmann (2018) proposed a rule-based knowledge inference system that supports semi-automated site equipment planning using data from building information models and work schedules. Additionally, Hajdasz (2014) introduced an intelligent decision support tool for flexible site management in repetitive projects, while Mohamed (2001) offered a knowledge-based approach for analyzing factors that influence project duration, generating both normal and productivity-adjusted schedules.

Despite the extensive developments in decision support systems and knowledge management tools within construction management—especially in project planning and control—there remains a gap in capturing expert knowledge on the applicabilities and functionalities of various planning and control systems. Addressing this gap, the present study aims to develop a data-driven and knowledge-based DSS designed specifically for the preconstruction phase, which can recommend fit-for-purpose, multi-level, and integrated planning and control systems tailored to the unique needs of construction projects.

5.3. Adopted Research Methodology

This paper's objectives were achieved through a mixed-method approach, as demonstrated in Fig. 5.1. This methodology encompasses three primary phases: data collection and preprocessing, expert system development, and results optimization. During the data collection phase, semi-structured interviews and surveys were conducted by domain experts to gather the requisite data for further analysis. Subsequently, in the expert system development phase, a rule-based knowledge repository was constructed. Following this, an inference engine was launched using the forward chaining method and the Pyke which is a knowledge engine in Python, aimed at recommending the most suitable planning methods, control metrics, and schedule levels based on the project team's requirements. Finally, a multi-objective mathematical model was formulated to optimize the suggestions provided by the expert system and propose an enhanced multi-level planning and control system. The following subsections provide detailed explanations for each aspect of the research methodology.

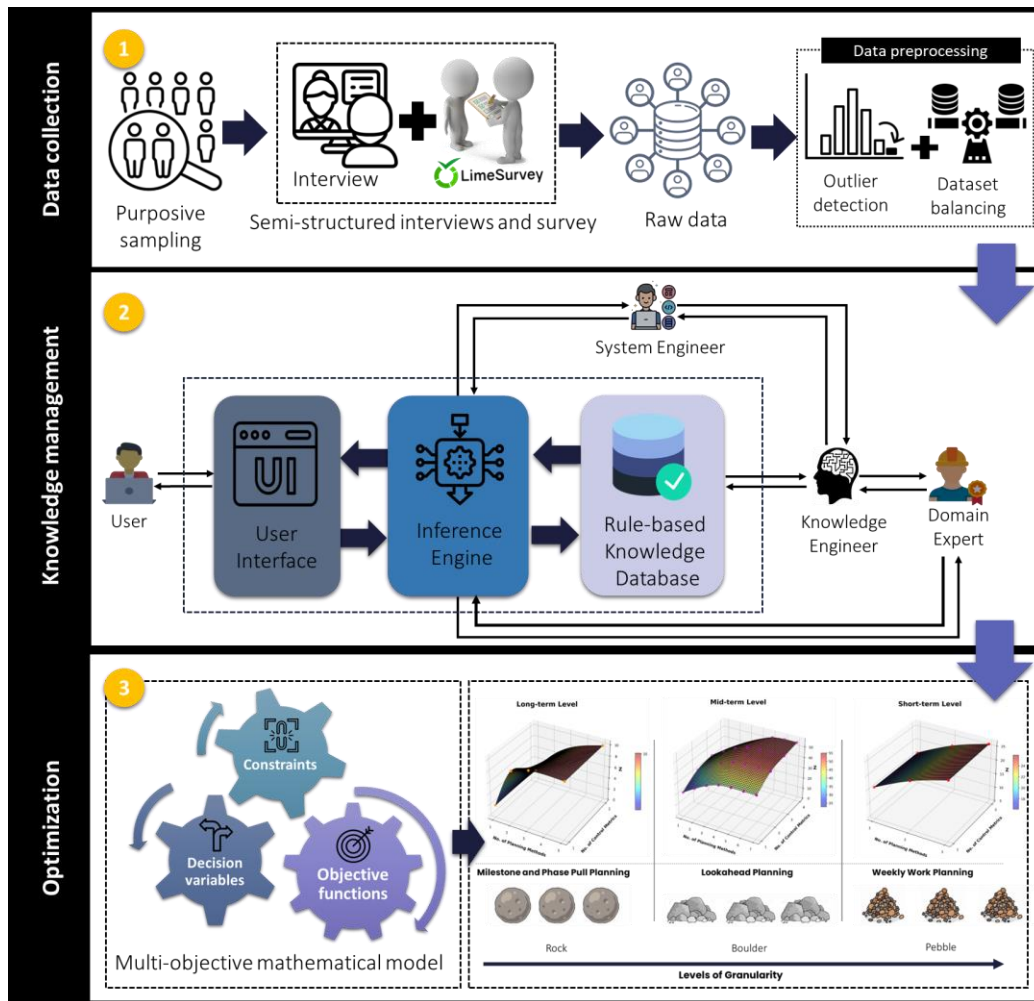


Fig. 5.1. Mixed-method adopted methodology

5.3.1. Data Collection and preprocessing

5.3.1.1. Sampling and Data Collection Approaches

This study used purposive sampling to select the population members to participate in the data collection process. Given the constrained availability of domain experts versed in various project planning and control systems, as well as the need to select a sample of individuals with diverse knowledge and experience in this domain, purposive sampling was deemed appropriate for the data collection process within the scope of this study. Suri (2011) and Hennink et al. (2017) clarified the method's validity by highlighting its ability to allow researchers to select participants who have specific expertise relevant to the study topic.

Regarding the data collection method, a semi-structured interview was chosen as the primary approach to collect the necessary data for building a knowledge repository for project planning and control systems. In addition, a survey was designed to provide a consistent structure in the interview process, standardize the topics discussed, as well as collect the required quantitative data for building a knowledge database.

5.3.1.2. Data Preprocessing

Following the data understanding, it was observed that the initial dataset exhibited an

imbalance due to variations in expertise among participants in different planning methods. For instance, while all participants responded to the last planner system inquiries, only 50% of participants responded to inquiries regarding the critical chain project management method. Additionally, certain responses displayed outliers, further challenging the integrity of the dataset. As a result, two preprocessing steps were deemed imperative to enhance data quality: outlier detection and addressing the imbalances inherent in the dataset.

The interquartile range (IQR) method was selected for managing the outliers. In addressing imbalanced datasets, given that this study employed purposive sampling for data collection, which inherently limits the dataset, adopting undersampling as a strategy was deemed suboptimal due to the potential data loss. Therefore, oversampling becomes the preferred approach. To do this, the Synthetic Minority Oversampling Technique (SMOTE) was employed to handle the imbalance dataset in this study. SMOTE is a powerful approach utilized for mitigating class imbalance in datasets and has demonstrated remarkable performance in a variety of applications (He and Garcia 2009). SMOTE enhances data representation by synthesizing samples from the minority class rather than just duplicating existing records. This technique operates by identifying the nearest neighbors of a minority instance and interpolating between them to create new synthetic samples (He and Garcia 2009). Such a procedure balances the dataset by increasing the diversity of the minority class, reducing the risk of overfitting, and enhancing model performance in scenarios where data imbalance would make accurate forecasting more difficult.

5.3.1.3. Reliability and Consistency of the Data

The consistency and reliability of the survey data were assessed using Cronbach's α coefficient method (Cronbach 1951). Cronbach's Alpha is a commonly used measure to assess internal consistency, which shows how effectively several survey questions evaluate the same concept. A higher Cronbach's Alpha value, typically above 0.7, indicates a higher level of reliability in the collected data. The formula for Cronbach's Alpha is:

$$\alpha = \frac{n}{n-1} \left(1 - \frac{\sum_{i=1}^n \sigma_i^2}{\sigma_T^2} \right) \quad (5.1)$$

where n is the number of survey items, σ_i^2 is the variance of each individual item, and σ_T^2 is the total variance of all items combined.

5.3.2. Knowledge Management and Expert System Development

An expert system is a kind of artificial intelligence program which leverages either a predetermined set of rules or a repository of human expertise, known as a knowledge base, to replicate the decision-making ability of a human expert (Abioye et al. 2021). These systems are designed to address complex problems by reasoning a knowledge repository, typically encoded in the conditional statements form (if-then rules), rather than relying on conventional procedural programming paradigms. The main components of an expert system include 1) a knowledge database, 2) an inference engine, and 3) a user interface (Adamczyk et al. 2020). The outline of the implemented steps to initialize the expert system is depicted in Fig. 5.2 and discussed in more detail in the following subsections.

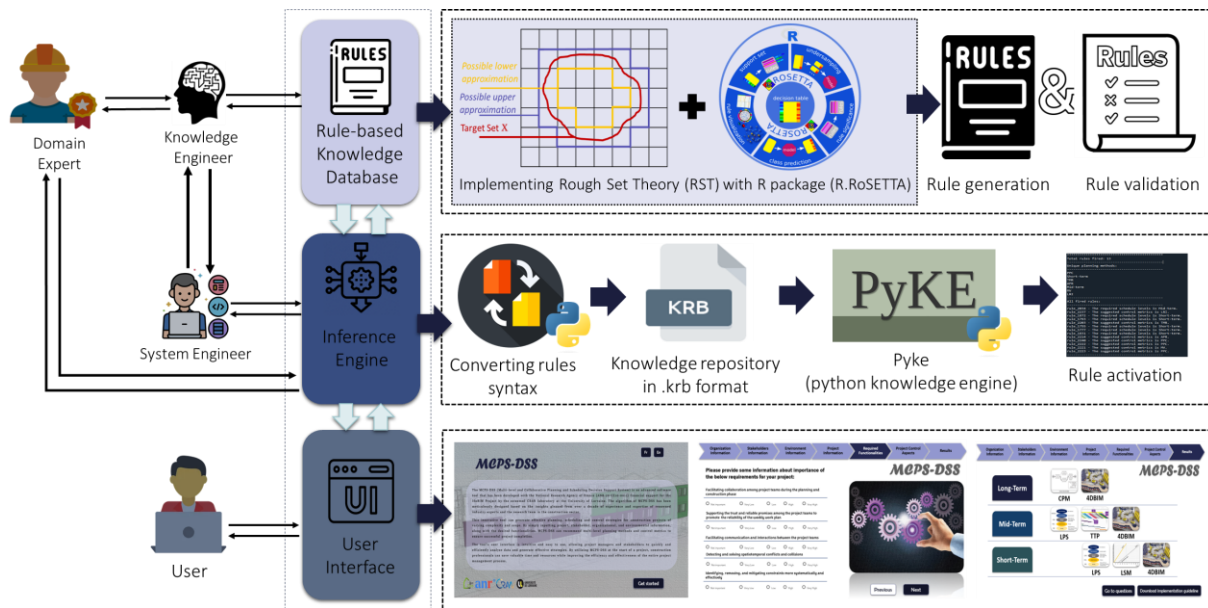


Fig. 5.2. An overview of the conducted steps to initialize the expert system

5.3.2.1. Building Knowledge Repository

A knowledge repository is a centralized system designed to collect, manage, and share valuable insights, best practices, and expert knowledge. It organizes and stores information in a structured manner, making it easily accessible for users who need it to make informed decisions (Fatfouta and Le-Cardinal 2021). This repository ensures knowledge continuity, preventing loss when team members leave, and fostering a culture of continuous learning and improvement. Within the construction sector, a knowledge repository holds significant value because the sector relies heavily on experience, best practices, and lessons learned. Such a repository enables project teams to quickly access essential information, reducing the chances of repeating past mistakes, streamlining workflows, and enhancing project outcomes. As expert insights often come with uncertainties due to subjective interpretation, incomplete data, and varying contexts, it's crucial to apply a method that effectively builds the knowledge database while addressing these uncertainties. Rough Set Theory (RST) effectively handles uncertainties by enabling data analysis with imprecise boundaries (Akbari et al. 2020b; Karimi et al. 2022). Thus, this method was selected to establish the knowledge database for the project planning and control system. The following subsections explore the details of the RST approach.

Rule Generation Using Rough Set Theory (RST)

Rough set theory, proposed by (Pawlak 1982), is a key component of interpretable machine learning. It plays a vital role in artificial intelligence research, particularly in the classification, knowledge discovery, data mining, and pattern recognition domains (Garbulowski et al. 2021). The core principles and implementation processes of RST are outlined below:

Concept 1: Information system

In RST, a dataset is structured within an information system table wherein each column represents an attribute, such as a variable, and each row corresponds to an object or case. Formally, a dataset comprises a pair denoted as $S = (U, A)$, where U is a finite set of objects and A is a finite set of attributes. The attribute sets are split into condition attributes (C) and

decision attributes (D). Thus, any information system structured as $S = (U, A = C \cup D)$ becomes a decision system, where $D = d$ and $d \notin C$ represent the decision attribute. Table 5.1 presents an example of an information system table that includes five functionalities of planning and control systems as condition attributes (F1 to F5), along with two planning methods, LPS and 4DBIM, as decision attributes. The table also incorporates ten objects (O1 to O10), representing expert opinions on the level of support of each functionality by the planning methods. For instance, O1 indicates Expert 1's view on the level of support provided by the 4DBIM for functionalities F1 to F5. The values 0 (without support) to 4 (very high support) illustrate a Likert scale for the level of support of each functionality by the planning methods.

Table 5.1. An example of an information system table

Objects	F1	F2	F3	F4	F5	Planning methods
O1	1	0	3	4	4	4DBIM
O2	3	2	4	1	3	LPS
O3	4	1	3	0	2	LPS
O4	0	1	4	3	3	4DBIM
O5	0	1	3	3	3	LPS
O6	3	1	4	1	4	LPS
O7	4	0	3	0	3	LPS
O8	1	0	3	4	4	4DBIM
O9	3	1	4	1	4	LPS
O10	0	1	3	3	3	4DBIM

Concept 2: Indiscernible relation

For any subset, $B \subseteq C$, an equivalence relation denoted as $IND(B)$ is defined in Eq. (5.2), known as the B-indiscernibility relation.

$$IND(B) = \{(x, x') \in U^2 : \forall a \in B, a(x) = a(x')\} \quad (5.2)$$

If $(x, x') \in IND(B)$, then x and x' are objects that are indiscernible based on the attributes in B .

In the information system presented in Table 5.1, objects O6 and O9 are indiscernible concerning the recorded attributes and therefore comprise an equivalence class. Similarly, objects O5 and O10 also constitute an equivalence class. However, these objects fall into different decision classes (LPS, 4DBIM). The information system can be summarised in terms of the following equivalence classes:

Table 5.2. Equivalence classes of the information system

Equivalence classes	F1	F2	F3	F4	F5	Planning methods
E1 = {O1, O8}	1	0	3	4	4	{4DBIM}
E2 = {O6, O9}	3	1	4	1	4	{LPS}
E3 = {O5, O10}	0	1	3	3	3	{LPS, 4DBIM}
E4 = {O2}	3	2	4	1	3	{LPS}
E5 = {O3}	4	1	3	0	2	{LPS}
E6 = {O4}	0	1	4	3	3	{4DBIM}
E7 = {O7}	4	0	3	0	3	{LPS}

Concept 3: Lower and upper approximation

Two crisp sets referred to as lower and upper approximations of a given set X concerning $IND(B)$ are defined in the approximation space.

$$\underline{B}X = \{x : IND(B) \subseteq X\} \tag{5.3}$$

$$\overline{B}X = \{x : IND(B) \cap X \neq \emptyset\} \tag{5.4}$$

$\underline{B}X$ and $\overline{B}X$ represent the B -lower and B -upper approximations of X , respectively. The B -lower approximation includes objects that are certain to be in X , whereas the B -upper approximation includes objects that may be in X . The difference is known as a boundary of X in U .

$$BN(X) = \overline{B}X - \underline{B}X \tag{5.5}$$

The set X is called rough if $BN(X) \neq \emptyset$ and crisp otherwise.

Considering the example, the decision classes of LPS and 4DBIM objects are rough sets because they cannot be precisely defined using a single set of equivalence classes. Instead, they are characterized by upper and lower approximations. For instance, the decision class LPS can be outlined through the equivalence classes in which all objects belong to the LPS decision class, which forms the lower approximation (i.e., equivalence classes E2, E4, E5, and E7). Alternatively, it can be described by the equivalence classes containing at least one object classified as LPS, constituting the upper approximation (i.e., E2, E3, E4, E5, and E7), as shown in Fig. 5.3.

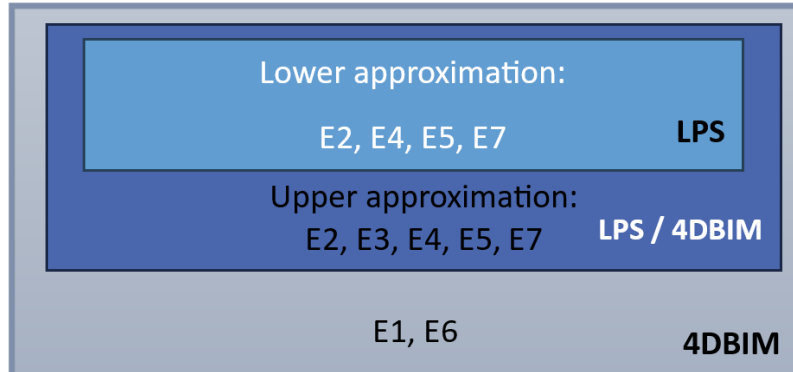


Fig. 5.3. Lower and upper approximation for the example

Concept 4: Core and reduct of attributes

If the number of equivalent classes formed by the attribute set A is the same as that formed by $A - a_i$, where $a \in A$, then a_i is redundant. Otherwise, a_i is indispensable in A . In Rough Set Theory (RST), the concept of a "reduct" is fundamental to feature engineering. A reduct refers to a minimal subset of attributes that preserves the same classification ability as the full attribute set. It is derived from the discernibility matrix using the discernibility function. By identifying and removing redundant or non-essential attributes, the reduct simplifies the dataset without compromising decision-making accuracy. This process not only streamlines the connection between input data and the conditions necessary for decisions but also enhances computational efficiency. As a feature selection technique, the reduct improves interpretability while reducing complexity. Finding a reduct, however, is an NP-hard problem,

making it computationally difficult to discover all minimal reducts. To address this, algorithms like genetic reducers and Johnson reducers can be used to approximate the optimal reduct by iteratively selecting attributes that maximize the dependency degree, which reflects the classification power of the feature set. In this study, the genetic reducer was employed to compute reducts (Anaraki and Eftekhari 2013; Garbulowski et al. 2021).

Another fundamental principle in RST is the concept of the "core" which is defined as the common portion of all reducts. For a given subset $B \subseteq A$, the core of B represents the set of attributes within B that are indispensable. The following equation embodies the connection between the core and reducts concepts.

$$Core(B) = \cap RED(B) \quad (5.6)$$

where $RED(B)$ is the set of all reducts of B.

Based on the equivalence class representation in Table 5.2, the discernibility function can be constructed by first developing a discernibility matrix that specifies the attributes of the different equivalence classes. The discernibility matrix for the example is shown in Table 5.3. It should be noted that the discernibility matrix is symmetric; for example, the entries for E1-E2 and E2-E1 are identical, so only one-half of the matrix needs to be considered. As shown in the highlighted column in Table 5.3, the entry for E2-E2 is empty (\emptyset) since, naturally, the equivalence class E2 cannot be distinguished from itself. The entry for E2-E3 involves a different decision and includes attributes F1, F3, F4, and F5, for which differing values are observed between equivalence classes E2 and E3; for instance, F1 is 3 for E2, while it is 0 for E3. The entry for E2-E4 is also empty because equivalence classes resulting in the same decision do not require further discernment. The rest of the matrix is constructed similarly.

Table 5.3. The discernibility matrix for the example

	E1	E2	E3	E4	E5	E6	E7
E1	\emptyset						
E2	F1, F2, F3, F4	\emptyset					
E3	F1, F2, F4, F5	F1, F3, F4, F5	\emptyset				
E4	F1, F2, F3, F4, F5	\emptyset	F1, F2, F3, F4	\emptyset			
E5	F1, F2, F4, F5	\emptyset	F1, F4, F5	\emptyset	\emptyset		
E6	\emptyset	F1, F4, F5	F3	F1, F2, F4	F1, F3, F4, F5	\emptyset	
E7	F1, F4, F5	\emptyset	F1, F2, F4	\emptyset	\emptyset	F1, F2, F3, F4	\emptyset

The minimal information required to discern E2 from all other objects with different decisions can now be expressed as a discernibility function:

$$f_{E2}(F1, F2, F3, F4, F5) = (F1 \text{ OR } F3 \text{ OR } F4 \text{ OR } F5) \text{ AND } (F1 \text{ OR } F4 \text{ OR } F5)$$

To satisfy the condition for this function to be true, it is essential that at least one attribute from each E2-related entry within the discernibility matrix is included. Consequently, the function can be simplified to:

$$f_{E2}(F1, F2, F3, F4, F5) = (F3 \text{ AND } F1) \text{ OR } (F3 \text{ AND } F4) \text{ OR } (F3 \text{ AND } F5)$$

which reflects the three *reducts*: $\{F3, F1\}$, $\{F3, F4\}$, and $\{F3, F5\}$.

It is important to note that identifying all reducts is an NP-complete problem (Skowron and Rauszer 1992). Nonetheless, several approximation algorithms, such as greedy algorithms (Johnson 1973) and genetic algorithms (Vinterbo and Øhrn 2000), have been developed to

facilitate the search for reducts. In this study, a genetic algorithm was employed to compute the reducts.

Concept 5: Decision rules

Rule generation is a crucial step derived from reduct computation in RST. Decision rules capture the knowledge extracted from the data and typically take the form: $r: IF C THEN D$, where the condition (C) is a conjunction of attribute-value pairs, like $a_1 = v_1 \wedge a_2 = v_2$, which specify the attribute values that define a particular condition. The decision (D) indicates the value associated with the decision attribute, such as $d = v_d$. These rules serve as a structured representation of knowledge, which facilitates decision-making by mapping conditions to specific outcomes.

Considering the reducts {F3, F1}, {F3, F4}, and {F3, F5} for discerning equivalence class E2 in the example, the resulting rules based on the attribute values would be:

- R1: **IF** F3 (4) **AND** F1 (3) **THEN** LPS
- R2: **IF** F3 (4) **AND** F4 (1) **THEN** LPS
- R3: **IF** F3 (4) **AND** F5 (4) **THEN** LPS

Rule evaluation

Rule evaluation is essential for assessing the accuracy, reliability, and usefulness of generated rules. It helps validate the rules to ensure they accurately reflect data relationships. By doing so, rule evaluation ensures that extracted knowledge is reliable and practical for informed decision-making. There are different measures for rule evaluation, including support, coverage, accuracy, and p-value. In this research, support, accuracy, and p-value were preferred as measures for rule evaluation. These three metrics offer comprehensive insights into the significance and applicability of rules, making coverage unnecessary as it doesn't add much beyond what others already reveal. Therefore, coverage was not included in the evaluation. Support measures how many instances meet the conditions of the rule. Left-hand side support (LHS support) counts the number of instances that satisfy the conditions in the IF part of the rule, while Right-hand side support (RHS support) measures the instances that meet the specified classes in the THEN part of the rule. The predictive efficacy of a rule is reflected in its accuracy, a metric determined through the computation of support values. More precisely, the following formula calculates a rule's accuracy:

$$accuracy(rule) = \frac{support(rule)_{RHS}}{support(rule)_{LHS}} \quad (5.7)$$

Moreover, the p-value is a measure that evaluates the statistical significance of the generated rules in the context of rule evaluation. Garbulowski et al. (2021) adopted the hypergeometric distribution to compute these p-values, a method that assesses the representation of rule support relative to the total number of objects. A p-value less than 0.05 is considered acceptable, indicating that the rule is statistically significant, which ensures that only meaningful rules are included in the model. Eq. (5.8) depicts the calculation of the p value.

$$P(X = r) = \frac{\binom{t_d}{r} \binom{t_0}{l-r}}{\binom{T}{l}} \quad (5.8)$$

where r is the RHS support of the rule, l is the LHS support of the rule. The total number of

objects that align with the rule's decision class d is denoted as t_d , while t_0 indicates the number of objects belonging to decision class(es) other than the one targeted by the rule. The total number of objects within the dataset is depicted by T .

Table 5.4 summarizes the evaluation metrics for the rules generated from the equivalence class E2 in the example.

Table 5.4. Rule assessment results for the generated rules in the example

ID	Rules	RHS support	LHS support	Accuracy	p-value
R1	IF F3 (4) AND F1 (3) THEN LPS	3	3	1.0 (3/3)	0.16
R2	IF F3 (4) AND F4 (1) THEN LPS	3	3	1.0 (3/3)	0.16
R3	IF F3 (4) AND F5 (4) THEN LPS	2	2	1.0 (2/2)	0.33

The first rule, R1, corresponds to the condition part of three objects in Table 5.1, resulting in a left-hand side support of 3. Additionally, R1 aligns with the decision part of these same three objects in Table 5.1, giving it a right-hand side support of 3.

Among the three objects that satisfy the IF-part of rule R1, all three also belong to the decision class specified in the THEN-part (i.e., the LPS decision class). Consequently, the rule's accuracy is 1.0. Furthermore, according to Equation (5.8), the calculated p-value for this rule is 0.16.

RST Implementation Using R.ROSETA

This study used the R.ROSETTA package in the R programming language to implement rough set theory. R.ROSETTA is an advanced toolkit designed to facilitate the entire spectrum of data mining and knowledge discovery processes (Garbulowski et al. 2021). It is an extension of the original ROSETTA system, augmenting its functionality, accessibility, and flexibility. Notably, R.ROSETTA specializes in developing and analyzing rule-based classification models, encompassing features such as data preprocessing, discretization, and reduct computation (Garbulowski et al. 2021). For reduct computation, a Genetic algorithm was utilized, which excels in identifying minimal attribute sets that retain essential information. R.ROSETTA's robust analytical capabilities enable the generation of effective decision rules and filters according to rigorous evaluation metrics, which offers a reliable platform for extracting insights from uncertain data.

5.3.2.2. Implementing the Inference Engine

The forward chaining approach was employed for implementing the inference engine and rule activation. Rule activation approaches include forward chaining and backward chaining (Al-Ajlan 2015). Forward chaining begins with available facts and applies inference rules to derive new facts until a conclusion is reached. In contrast, backward chaining starts with a goal and works backwards to identify the supporting facts. Forward chaining was chosen for this study due to its ability to derive conclusions iteratively by applying rules based on existing data (Al-Ajlan 2015). Pyke was selected for implementing the inference engine with the forward chaining approach. It is a Python knowledge engine that provides a logic programming framework and supports knowledge-based inference through rule-based programming. Users are empowered to define rules and facts, making it easier to create decision-making programs that rely on logical conditions (Frederiksen 2008). This made Pyke ideal for implementing forward chaining in this study, as it facilitated structured rule activation and data-driven reasoning processes. Pyke starts with a knowledge base, which

consists of a set of facts and rules. Facts in this research are the user requirements in terms of functionalities and will be collected through the system's interface, whereas rules are conditional statements that indicate what conclusions can be inferred from what facts.

To perform forward chaining, Pyke finds rules whose "*if*" clause matches its list of known facts. When a rule's conditions are met, It activates the rule, which adds the facts in the "*then*" clause of the rule to the existing list of known facts. These newly added facts can then trigger other rules with matching "*if*" clauses, continuing the chaining process to any depth. In this way, Pyke links the "*then*" clause of one rule to the "*if*" clause of the next, progressively drawing logical inferences from the data. Pyke effectively manages the flow of rule activation, ensuring that rules are fired in a logical sequence, which allows for efficient knowledge discovery and reasoning (Frederiksen 2008).

It is worth noting that although the implemented Pyke engine initiates forward chaining and typically activates rules in a logical succession, the activation process in this study is linear and straightforward as the generated rules follow a flat structure and each rule is processed independently in a linear sequence, without triggering or relying on other rules. Rules are evaluated one by one, simplifying execution without the need for cascading activations.

Following the deployment of the inference engine, a Python script was formulated to parse the outcomes of the inference process and construct a part of the input dataset for the mathematical model and optimization purposes, which will be explained in the next sections.

5.3.2.3. User Interface

A user interface plays a crucial role in bridging the gap between end users and technical systems, enhancing user experience by providing an intuitive platform for interaction. In this study, a user interface was designed to gather user requirements effectively and facilitate communication between users, system engineers, and knowledge engineers. One of its roles is to collect project team requirements for a planning and control system. Also, by reasoning through the inference engine and optimizing via a mathematical model, the interface visually displays the results of the suggested planning methods and control metrics across three schedule levels. Fig. 5.4 depicts the configuration of the interface designed for the Multi-level Planning and Control System Decision Support System (MPCS-DSS). Notably, the interface comprises four primary components. The initial page outlines the key objectives of the DSS and the requisite data. Subsequently, the second component endeavors to gather project-related information, while the third segment is dedicated to collecting functional requirements, based on Sheikhhoshkar et al. (2023a), Sheikhhoshkar et al. (2024c), and Sheikhhoshkar et al. (2024b), from the project team for a planning and control system, serving as the primary input data for the DSS. Finally, the last component demonstrates the outcomes proposed by the DSS.

MCPS-DSS Fr En

The MCPS-DSS (Multi-level and Collaborative Planning and Scheduling Decision Support System) is an advanced software tool that has been developed with the National Research Agency of France (ANR-20-CE10-0011) financial support for the ISO-BIM Project by the esteemed CRAN laboratory at the University of Lorraine. The algorithm of MCPS-DSS has been meticulously designed based on the insights gleaned from over a decade of experience and expertise of renowned industry experts and the research team in the construction sector.

This innovative tool can generate effective planning, scheduling and control strategies for construction projects of varying complexity and scope. By simply inputting project, stakeholder, organizational, and environmental information, along with the desired functionalities, MCPS-DSS can recommend multi-level planning methods and control metrics to ensure successful project completion.

The tool's user interface is intuitive and easy to use, allowing project managers and stakeholders to quickly and efficiently analyze data and generate effective strategies. By utilizing MCPS-DSS at the start of a project, construction professionals can save valuable time and resources while improving the efficiency and effectiveness of the entire project management process.

Get started 1

Organization Information Stakeholders Information Environment Information Project Information Required Functionalities Results

Please provide some information about your project: **MCPS-DSS**

Project Name
Project Type
Form of Contract
Level of Complexity
Level of Uncertainty
Location of Construction Site

Previous Next 2

Organization Information Stakeholders Information Environment Information Project Information Required Functionalities Results

Please provide some information about importance of the below requirements for your project: **MCPS-DSS**

Coordinating and integrating suppliers, materials, and construction site processes to optimize the flow of resources and information
Visualizing the schedules to enhance collaboration and communication with various stakeholders
Minimizing unnecessary delays and inefficiencies with a focus on reducing production cycle time
Using digital tools and technologies to enable real-time collaborative project planning and tracking on construction site

Not important Very Low Low High Very High

Previous Next 3

Organization Information Stakeholders Information Environment Information Project Information Required Functionalities Results

MCPS-DSS

Long term plan
Mid term plan
Short term plan

Go to questions Download implementation guideline 4

Fig. 5.4. Configuration of the designed interface for MPCSDSS

5.3.3. Mathematical Model for the Results' Optimization

This section introduces a multi-objective mathematical model developed to optimize the results of DSS and suggests a multi-level and integrated project planning and control system for construction projects. The objective is to minimize the number of planning methods and control metrics at each schedule level for more practical implementation while satisfying the maximum project team's requirements. The following subsection outlines the relevant sets, indicators, parameters, decision variables, objective functions, and constraints used in the mathematical model.

Sets and Indices:

i : index for the planning method, $i \in [1..I]$

j : index for the control metric, $j \in [1..J]$

l : index for the schedule level, $l \in [1..L]$

f : index for the functionalities, $f \in [1..F]$

Input parameters:

P = number of planning methods

C = number of control metric

L = number of schedule levels

F = number of functionalities

M_{fi} : level of support for functionality f in planning method i , $M_{fi} = [0,1,2,3,4]$

K_{fj} : level of support for functionality f in control metric j , $K_{fj} = [0,1,2,3,4]$

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

A_{ij} : connects planning method i to control metric j . $A_{ij} = 1$ means that the planning method i mapped by control metric j .

B_{il} : connects planning method i to schedule level l . $B_{il} = 1$ means that the planning method i matched with schedule level l .

C_{jl} : connects control metrics j to schedule level l . $C_{jl} = 1$ means that the control metric j matched with schedule level l .

W_i : A weight to evaluate the coverage of the suggested planning methods by DSS for user requirements in terms of functionalities.

$$W_i = \sum_{f=1}^F M_{fi} \quad (5.9)$$

V_j : A weight to evaluate the coverage of the suggested control metrics by DSS for user requirements in terms of functionalities.

$$V_j = \sum_{f=1}^F K_{fj} \quad (5.10)$$

U_l : A wight to evaluate the coverage of the suggested schedule levels by DSS for user requirements in terms of functionalities.

$$U_l = \sum_{f=1}^F S_{fl} \quad (5.11)$$

Output variables:

Binary decision variable X_i :

$X_i = 1$ If planning method i is decided to be deployed

$X_i = 0$ Otherwise

Binary decision variable Y_j :

$Y_j = 1$ If control metric j is decided to be deployed

$Y_j = 0$ Otherwise

Objective Functions:

$$Z_1 = \max \left(\sum_i W_i \cdot X_i + \sum_j V_j \cdot Y_j \right) \quad (5.12)$$

$$Z_2 = \min \left(\sum_i X_i \right) \quad (5.13)$$

$$Z_3 = \min \left(\sum_j Y_j \right) \quad (5.14)$$

Eq. (5.12), (5.13), and (5.14) 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.

Constraints:

$$\forall j \in [1..J], \sum_{i=1}^I (A_{ij} \times X_i) - Y_j \geq 0 \quad (5.15)$$

Eq. (5.15) ensures that if a control metric is selected, then at least one planning method that supports this control metric must also be selected.

$$\forall l \in [1..L], \sum_{i=1}^I (B_{il} \times X_i) \geq U_l \quad (5.16)$$

Eq. (5.16) demonstrates that deploying a particular schedule level requires the simultaneous deployment of at least one planning method corresponding to that level.

$$\forall l \in [1..L], \sum_{j=1}^J (C_{jl} \times Y_j) \geq U_l \quad (5.17)$$

Eq. (5.17) 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.

$$\forall i \in [1..I], \sum_{l=1}^L B_{il} \times U_l \geq X_i \quad (5.18)$$

Eq. (5.18) enforces that if a schedule level is active, at least one planning method that is applicable to this level must be selected.

$$\forall j \in [1..J], \sum_{l=1}^L C_{jl} \times U_l \geq Y_j \quad (5.19)$$

Eq. (5.19) enforces that if a schedule level is active, at least one control metric that is applicable to this level must be selected.

The selection of appropriate planning and control systems for projects is influenced by a range of external factors, including project type, scale, contract type, and the project team's expertise in planning and control systems. These variables contribute to the complexity of the decision-making process. To address this complexity, this study utilizes Pareto front plots to present the outcomes of the mathematical model. This approach offers project teams the flexibility to choose solutions that best meet the specific requirements of diverse project

conditions. A Pareto front chart is a graphical tool used in multi-objective optimization to display a set of feasible solutions. It identifies options where no single solution is superior in all aspects, highlighting the trade-offs between competing objectives. This helps decision-makers find a balance between conflicting goals by illustrating where improvements in one objective may require sacrifices in another.

The mathematical model was executed using Python 3.11, and the Gurobi linear solver, under academic licence.

5.3.4. Solution Evaluation and Case Project Application

In this study, two approaches were adopted to assess the validity, usefulness, and practicality of the solution. First, a case study was conducted within the IsoBIM project framework to showcase the practicality of the decision support system and mathematical model in proposing a multi-level planning and control system for a renovation project. Second, quantitative performance measures from satisfaction surveys, as recommended by Peffers et al. (2007) were used for a general evaluation. Accordingly, a team of five experts along with the research team evaluated the usability of the proposed solution and its integration into current project planning and control processes. Through semi-structured interviews, the participants shared their functional requirements for a planning and control system using the user interface. They then assessed the DSS using a Likert scale, considering the recommendations provided by the tool. To facilitate this process, five dimensions of evaluation were considered, including ease of use, interface quality, comprehensiveness, response time, and decision quality improvement. The specifics of the evaluation criteria are detailed in Table 5.5. Such end-user survey for evaluating a DSS or framework was also considered in the studies by Dikmen et al. (2022), Barkokebas et al. (2021), and Sheikhhoshkar et al. (2024d).

Table 5.5. Details of the evaluation criteria

Evaluation criteria	Objective
Ease of use	Assess how easy it is for new users to learn and for all users to operate the system
Comprehensiveness	Assess the extent to which the system includes all relevant data, variables, and functionalities necessary to support thorough and informed decision-making
Decision quality improvement	Determine whether and how much the DSS improves the quality of decisions compared to pre-implementation
Interface quality	Evaluate the intuitiveness, clarity, and aesthetic of the user interface.
Response time	Measure the time it takes for the system to provide outputs after inputs are given.

5.4. Results and Analysis

5.4.1. Data Collection Efforts

Using a purposive sampling approach, a targeted cohort of 45 individuals was identified for this study's data collection through a thorough review of LinkedIn profiles, peer-reviewed articles, and various online repositories. Following this identification, invitations to participate were sent via email and direct messaging channels. Of these, 23 individuals (51% of the identified sample) responded affirmatively. The respondents were subsequently scheduled

for interviews, which included participation from both industry and academic experts. These interview sessions collectively contributed approximately 23 hours of valuable insights.

To ensure data saturation and validate the sample size, numerous studies in construction management have advocated and utilized purposive sampling, typically selecting sample sizes varying from 5 to 25 (Jepson et al. 2020; Ugulu et al. 2020; Zulu et al. 2023). Moreover, the 23 interviews were conducted with experts possessing specialized knowledge in various planning methods and their applications. As the target population of these experts is relatively narrow worldwide, the 23 interviews provide a strong and representative sample of the targeted population. The details of the participants are provided in Table 5.6.

Table 5.6. Profile of Interviewees

ID	Type of Expert	Role	Organization Type	Years of Experience in Project Planning and Control
IE1	Industry experts	Department head	General contractor	11-15 years
IE2		National director of projects	General contractor	Over 15 years
IE3		Process manager	General contractor	1-5 years
IE4		Senior innovation engineer	General contractor	6-10 years
IE5		R&D manager	General contractor	11-15 years
IE6		Lean director	General contractor	Over 15 years
IE7		Scheduler	Client	Over 15 years
IE8		Project manager	Client	Over 15 years
IE9		Project manager	Client	Over 15 years
IE10		Project manager	Consultant	Over 15 years
IE11		Project manager	Consultant	Over 15 years
IE12		Superintendent	Consultant	Over 15 years
IE13		Project manager	Consultant	11-15 years
IE14		Manager - customer success	Software vendor	6-10 years
AE1	Academic experts	Professor	University	11-15 years
AE2		Professor	University	11-15 years
AE3		Professor	University	Over 15 years
AE4		Professor	University	6-10 years
AE5		Professor	University	11-15 years
AE6		Senior lecturer	University	6-10 years
AE7		Lecturer	University	6-10 years
AE8		Researcher (PhD student, post-doc)	University	6-10 years
AE9		Researcher (PhD student, post-doc)	University	6-10 years

This study employs a structure, depicted in Fig. 5.5, which synthesizes various planning methods and control metrics across different schedule levels to suggest multi-level and integrated project planning and control systems. The structure is underpinned by the functionality concept, which acts as a common principle among planning methods, control metrics, and scheduling levels to facilitate their harmonious integration. More information about defining, extracting and analyzing the functionalities is elaborated in (Sheikhhoshkar et al. 2023a; Sheikhhoshkar et al. 2024c).

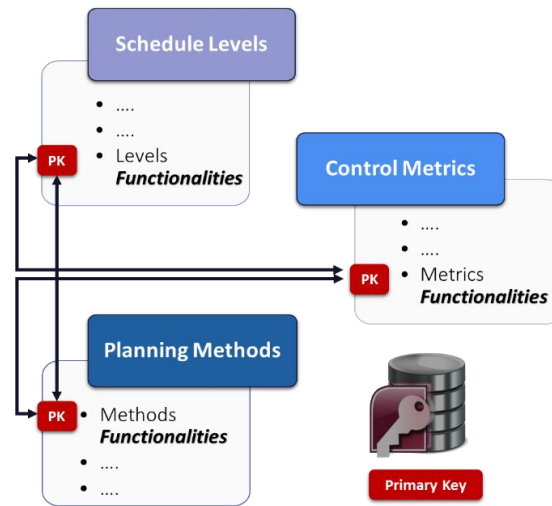


Fig. 5.5. The main elements of multi-level framework

To operationalize this structure, eight commonly used planning methods in construction for different project types (Sheikhhoshkar et al. 2023a) were examined, including advanced 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). Furthermore, the study considered nine control metrics frequently referenced in the academic literature and practical guidelines (Hamzeh et al. 2019b; Sheikhhoshkar et al. 2024c): 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). The framework also incorporates three schedule levels comprising short-term, mid-term, and long-term. Regarding the functionalities, 19 main concepts of functionalities were considered, drawing upon prior research conducted by Sheikhhoshkar et al. (2024a) illustrated in Table 5.7.

To enhance clarity and facilitate understanding for non-expert users, the extended functionality concepts presented in Table 5.7 are further elaborated in Table A5, located in the appendix. It should be noted that these detailed definitions of the functionalities were incorporated into the user interface, serving as the user requirements in terms of the functionalities for a planning and control system.

Utilizing these classifications, a relational diagram was developed, as shown Fig. 5.6 to guide data collection and serve as a foundational element of survey design for data-gathering purposes. The survey questions were formulated to gather data aimed at identifying potential connections between planning methods and control metrics, evaluating the alignment of planning methods and control metrics across various schedule levels, and assessing the degree of support offered by each planning method, control metric, and schedule level for different functionalities.

To cover all the necessary data for the connections between the components in Fig. 5.6, six groups of questions needed to be addressed, including:

1. How well did each planning method align with each schedule level?
2. Which schedule level is best suited for each control metric?

3. Which planning method does each control metric align with?
4. To what extent did each planning method support a specific functionality?
5. To what extent did each control metric support a specific functionality?
6. How much did each schedule level contribute to supporting a specific functionality?

During the interview process, experts' opinions were assessed using a Likert scale ranging from 0 (no support) to 4 (very high support).

Table 5.7. Incorporated functionality concepts in multi-level planning and control systems

ID	Functionalities
F1	Collaboration management
F2	Commitment planning
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 logistic management
F16	Supply chain management
F17	Visualization
F18	Waste management
F19	Real-time site monitoring

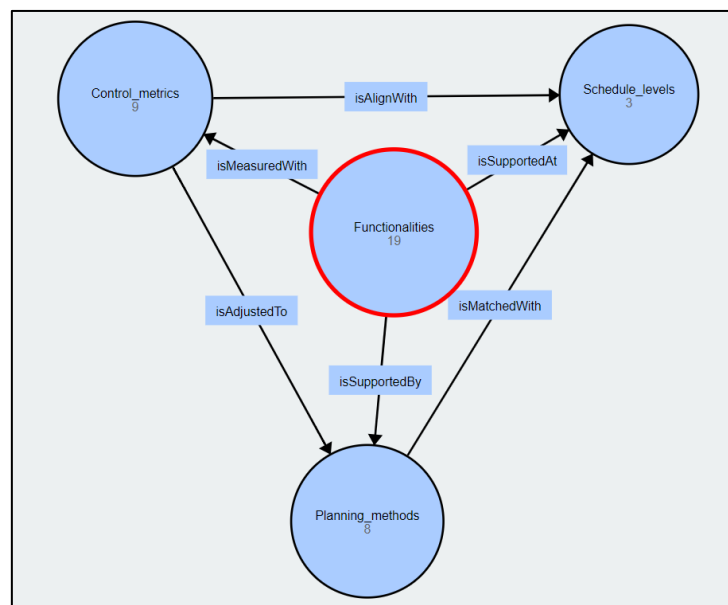


Fig. 5.6. The relational diagram of the main elements of the multi-level framework

5.4.2. Data Preprocessing Efforts

Following the application of the IQR method in the data preprocessing phase, the detected outliers were carefully investigated. Given that some outliers could potentially contain valuable information or represent errors, deliberate consideration was given to appropriately address genuine outliers and anomalies before determining whether to remove or replace them. Consequently, the real outliers were replaced with the average responses for that specific record in the whole dataset and for all classes. Fig. 5.7 indicates an example of detected outliers for the last planner system and long-term schedule level data.

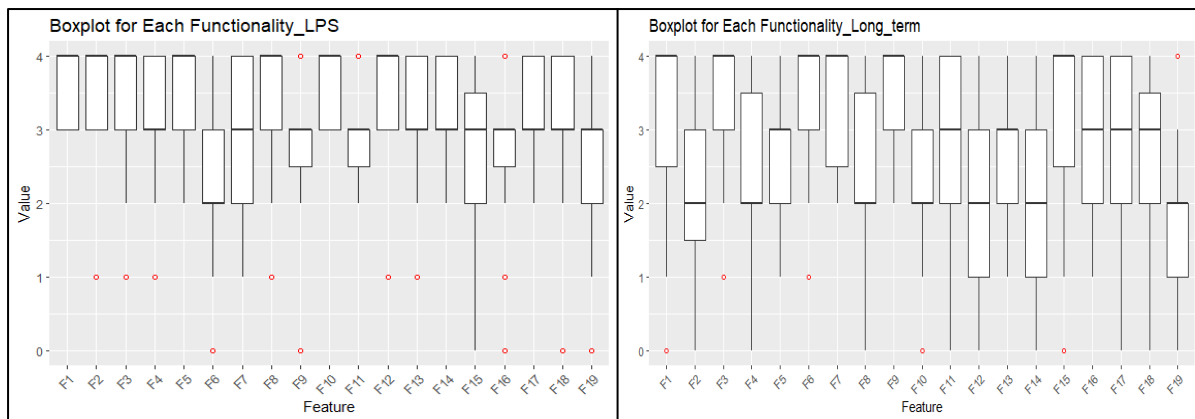


Fig. 5.7. Detected outliers for the last planner system (LPS) and long-term level of schedule data

After handling outliers, SMOTE was employed to address the challenge of imbalanced data. Fig. 5.8 depicts the class distribution of the imbalance dataset pre- and post-SMOTE augmentation.

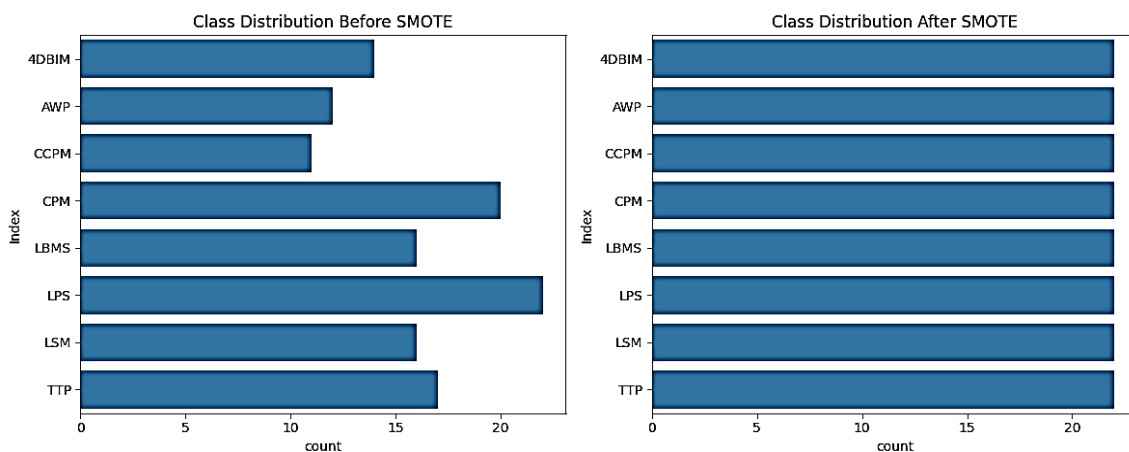


Fig. 5.8. Class distribution of the imbalance dataset before and after SMOTE implementation

To assess the reliability of the collected data, Cronbach's α coefficient was computed for all classes of the dataset, including eight classes for planning methods, nine classes for control metrics, and three classes for schedule levels. Table 5.8 displays the computation results. Cronbach's α coefficient for all classes is more than 0.7. Therefore, the data derived from the survey is considered reliable.

Table 5.8. Cronbach's alpha for collected data

Planning methods		Control metrics		Schedule levels	
Class	Cronbach's Alpha	Class	Cronbach's Alpha	Class	Cronbach's Alpha
4DBIM	0.838	CLR	0.726	Long-term	0.924
AWP	0.841	CPI	0.814	Mid-term	0.897
CCPM	0.970	LRI	0.815	Short-term	0.824
CPM	0.935	MV	0.715		
LBMS	0.953	PPC	0.921		
LPS	0.908	RL	0.774		
LSM	0.949	SPI	0.707		
TTP	0.929	TA	0.782		
		TMR	0.879		

5.4.3. Building the Knowledge Repository

The Genetic reducer is utilized for reduct computation in the rule generation process. A considerable number of outputs can be produced from Genetic heuristics in R.ROSETTA (Garbulowski et al. 2021), making it challenging to interpret such models. To deal with this challenge, defining precise thresholds was imperative to identify the most significant and valid rules derived from the rule generation process. To this end, multiple criteria were set, including a p-value threshold of less than 0.05, an accuracy greater than 0.7, a minimum RHS and LHS support of five, and a maximum rule length of eight. The outcomes of the rule generation process and the construction of a knowledge repository employing Rough Set Theory (RST) with R.ROSETTA are presented in Table 5.9. The table contains the total number of generated rules for each category, the number of rules that meet the thresholds, as well as the mean values of support, accuracy, and p-values associated with the generated rules.

Table 5.9. Performance evaluation of rules for the Genetic reduction method

Class	Planning Methods	Control Metrics	Schedule Levels
Total number of rules	39,977	463	12,962
Selected rules statistics			
Number of rules considering thresholds (P ≤ 0.05, accuracy ≥ 0.7, support (RHS & LHS) ≥ 5, length ≤ 8)	1753	80	447
Mean LHS support	10	12	13
Mean RHS support	9	11	12
Mean accuracy	0.895	0.962	0.935
Mean p-value	0.0065	0.00012	0.0306

Analysis of rule generation across planning methods, control metrics, and schedule levels reveals differentiated functionalities' support for each class and their implications for knowledge databases and decision-making. Planning methods, with a significant generation of 39,977 rules and 1,753 meeting rigorous selection criteria (P ≤ 0.05, accuracy ≥ 0.7, support ≥ 5, length ≤ 8), illustrate a multifunctional aspect, supporting a broad spectrum of functionalities within the system. In contrast, the control metrics class, generating only 463

rules with 80 meeting the thresholds, reflects its inherently focused functionality. The relatively low number of generated rules in this class is reasonable, as control metrics are designed to support specific and limited aspects of project control rather than multiple functionalities. Meanwhile, schedule levels, generating 12,962 rules with 447 qualifying the selection criteria, indicate a level of multifunctionality greater than control metrics.

The selected rules across all classes demonstrate high accuracy and validity, essential for integrating them into a knowledge repository and effective decision-making. Specifically, planning methods exhibit an accuracy of 0.895, control metrics show a remarkable accuracy of 0.962, and schedule levels maintain a strong accuracy of 0.935. These accuracy levels, coupled with very supportive p-values and substantial LHS and RHS support metrics, confirm the robustness and utility of the rules.

Table 5.10 depicts the rules information and distribution within the subclasses of the planning methods class, detailing the specific methods such as 4BIM, AWP, CCPM, CPM, LBMS, LPS, LSM, and TTP. Each subclass demonstrates a robust distribution of essential rules that effectively contribute to the knowledge repository, indicating a well-rounded approach to capturing diverse functional requirements. This distribution highlights that each subclass maintains a relatively consistent spread of rules that meet the selection criteria, underscoring all planning methods are included in the knowledge database.

Table 5.10. Rules information for the planning methods class

Class →	4BIM	AWP	CCPM	CPM	LBMS	LPS	LSM	TTP
Total number of rules	5786	3899	5307	6427	5776	5259	4102	3421
<i>Selected rules statistics</i>								
Number of rules considering thresholds (P ≤ 0.05, accuracy ≥ 0.7, support (RHS & LHS) ≥ 5, length ≤ 8)	120	143	197	378	249	208	285	173
Mean LHS support	10	10	9	13	9	10	9	9
Mean RHS support	9	8	8	11	8	9	8	8
Mean accuracy	0.893	0.865	0.943	0.852	0.911	0.887	0.916	0.893
Mean p-value	0.0062	0.010	0.0054	0.0013	0.0088	0.0052	0.0068	0.0083

The rule distribution is also relatively robust for subclasses of schedule levels, as shown in Table 5.11. This distribution indicates that the existing rules in each subclass hold a relatively compatible spread of rules, ensuring that the necessary aspects of schedule levels are effectively covered.

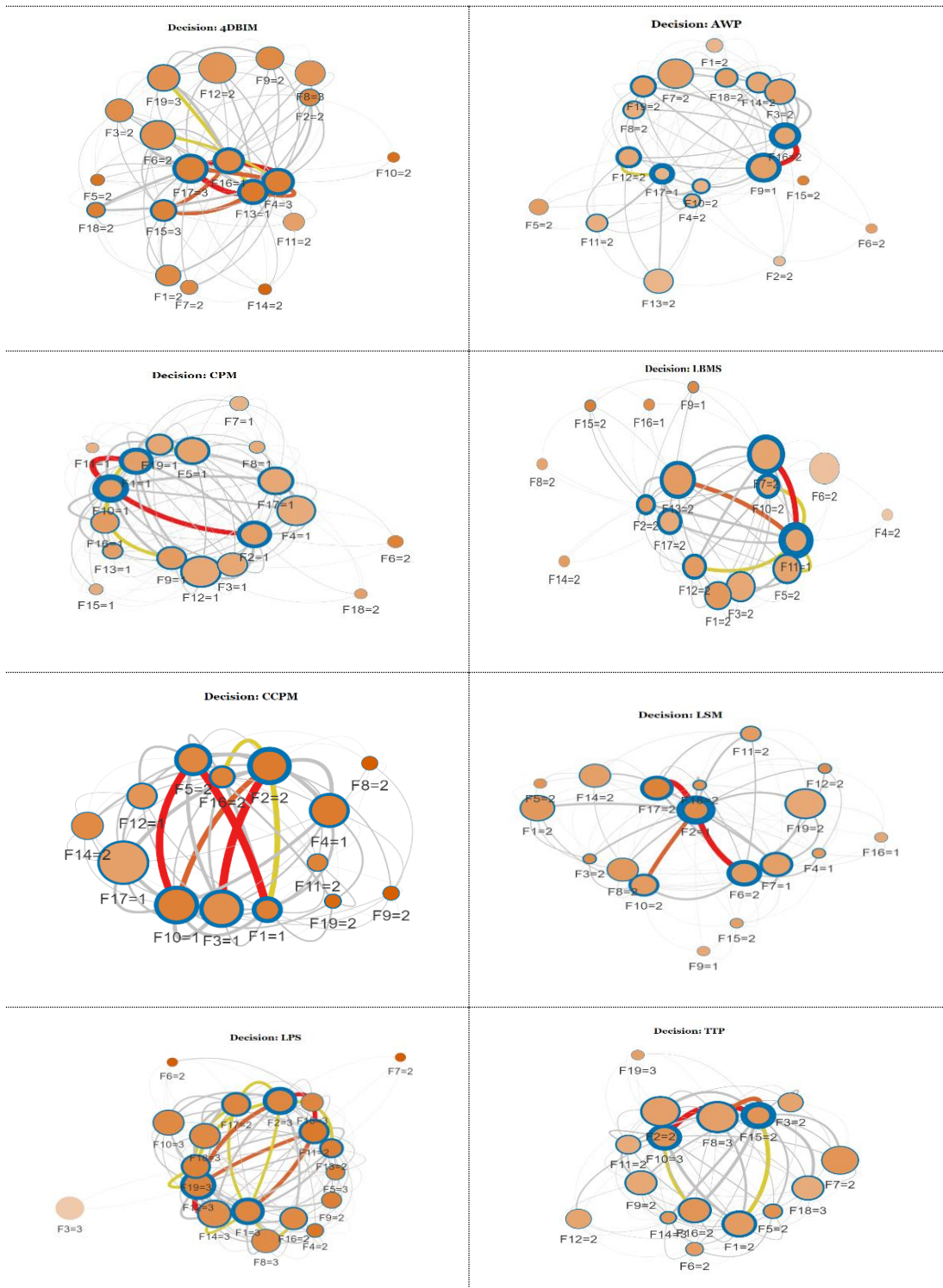
Table 5.11. Rules information for the schedule levels class

Class →	Long-term	Mid-term	Short-term
Total number of rules	4254	5341	3367
<i>Selected rules statistics</i>			
Number of rules, considering thresholds ($P \leq 0.05$, accuracy ≥ 0.7 , support (RHS & LHS) ≥ 5 , length ≤ 8)	107	99	241
Mean LHS support	13	12	15
Mean RHS support	12	11	13
Mean accuracy	0.939	0.944	0.921
Mean p-value	0.028	0.05	0.013

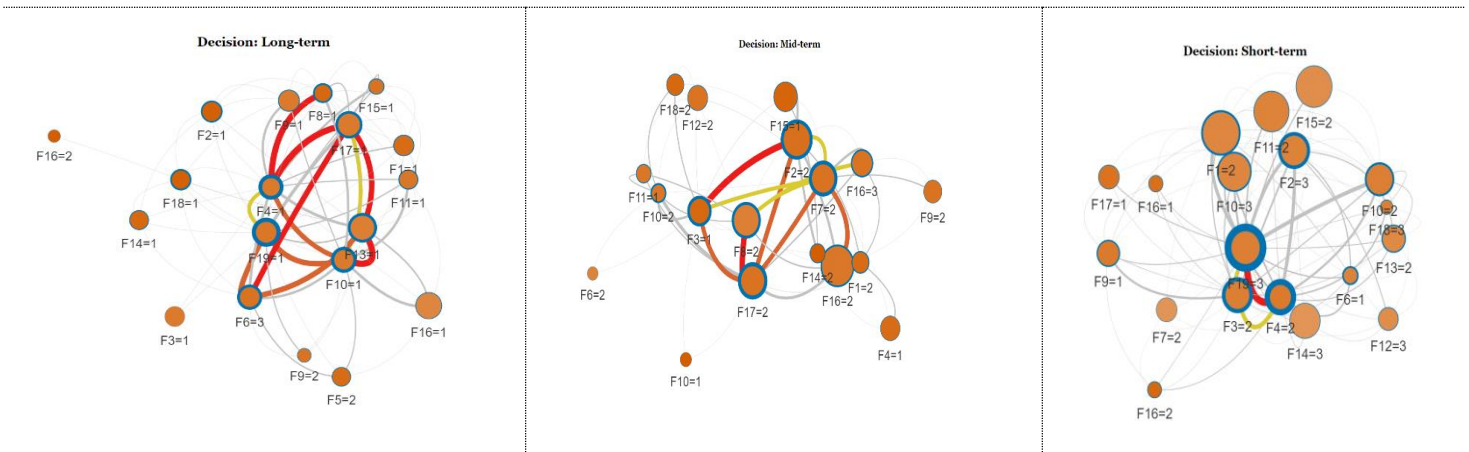
Conversely, the control metrics class displays fewer rules, as evidenced by the limited rules meeting the stringent criteria. This shortfall is consistent with the inherent nature of control metrics, which are typically not multifunctional and are designed to measure specific aspects of projects. The limited rule count in this class illustrates a gap in the coverage of control metrics, highlighting the need for further research and development in this area to ensure that essential aspects of project control are comprehensively addressed within the knowledge repository.

Fig. 5.9 illustrates a visual representation of the interactions among functionalities within each subclass of the knowledge database, depicted through R.ROSETTA's rule-based model visualization feature. This holistic approach displays the entire knowledge repository as an interaction network that organizes different subclasses and their respective functionalities. This kind of visualization not only highlights the integral network of interactions but can also be adjusted to emphasize the most relevant co-predictive functionalities and their intensity levels in each class. Importantly, these visual representations serve as a foundational step towards creating an ontology for the knowledge repository, facilitating deeper understanding and navigation of the underlying data structures. Additionally,

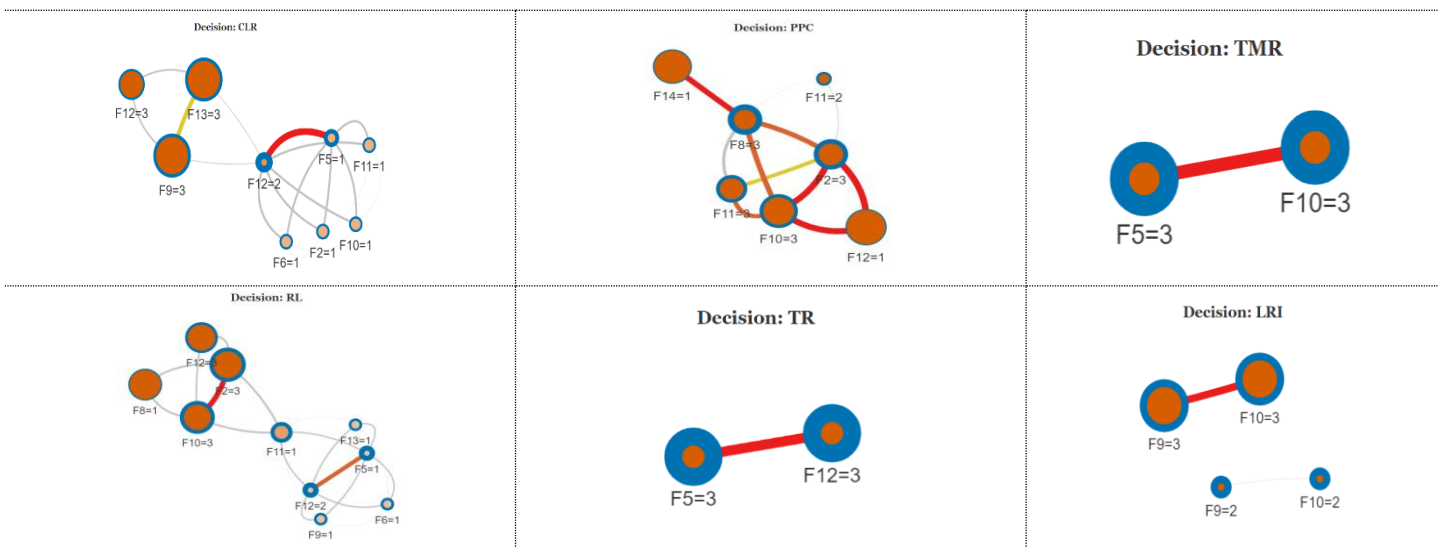
Fig. 5.9 further supports our claim regarding the low functionalities' support by the control metrics class. It clearly shows that, compared to the planning methods and schedule levels classes, the control metrics class supports only a limited number of functionalities. This contrast underscores the multifunctional nature of the other two classes, highlighting their broader applicational scope within the knowledge database.



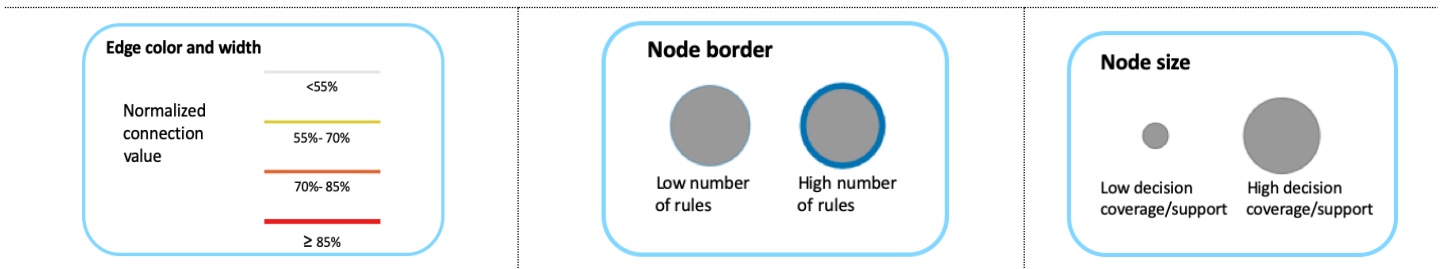
(a) Planning methods class



(b) Schedule levels class



(c) Control metrics class



(d) Rule visualization guide

Fig. 5.9. Visual representation of knowledge repository, (a) planning methods class, (b) schedule levels class, and (c) control metrics class, (d) rule visualization guide

Following the rule generation and validation process employing RST methodology, a set of 2280 rules was formulated. These rules are stated as individual statements or combinations of statements linked by "AND" or "OR" conditions, classified into three distinct categories: planning methods, control metrics, and schedule levels. The resulting database functions as a knowledge repository for project planning and control systems. Table 5.12 provides a sample of selected rules within each class.

Table 5.12. Filtered rules examples

Rule class	Rule	LHS support	RHS support	Accuracy	P-value
Planning methods	IF F1(1) AND F4(1) AND F5(1) AND F6(2) THEN CPM	14	10	0.714	0.00360
	IF F11(2) AND F12(3) AND F14(3) AND F19(3) THEN LPS	11	11	1	3.58E-07
	IF F4(3) AND F13(1) AND F19(3) THEN 4DBIM	12	10	0.913	0.000274
	IF F2(2) AND F8(3) AND F10(3) AND F15(2) THEN TTP	12	11	0.916	4.02E-06
	IF F2(2) AND F7(2) AND F11(1) AND F13(2) THEN LBMS	12	10	0.857	0.000274
	IF F7(2) AND F8(2) AND F9(1) AND F16(2) THEN AWP	16	13	0.813	7.05E-07
	IF F2(2) AND F3(1) AND F10(1) AND F17(1) THEN CCPM	12	12	1	2.48E-08
Control metrics	IF F2(3) AND F10(3) AND F12(1) THEN PPC	18	18	1	3.49E-28
	IF F6(3) AND F7(3) THEN MV	15	15	1	2.57E-22
	IF F5(3) AND F10(1) AND F12(1) THEN TA	13	13	1	1.14E-18
	IF F5(1) AND F10(1) AND F11(1) AND F12(2) THEN CLR	13	10	0.769	4.54E-11
Schedule levels	IF F5(3) AND F10(3) THEN TMR	20	20	1	1.79E-32
	IF F3(2) AND F19(3) THEN Short-term	21	19	0.905	4.44E-07
	IF F8(2) AND F16(3) AND F17(2) THEN Mid-term	14	13	0.929	0.00448
	IF F6(3) AND F17(1) AND F19(1) THEN Long-term	13	13	1	0.000383

To implement the inference engine using the Pyke engine, which requires a knowledge database in its specific syntax, the syntax of the generated rules had to be converted for compatibility with Pyke. A Python script was developed to handle this conversion efficiently. An example of the converted rule syntax is illustrated in Fig. 5.10, demonstrating how the rules were adapted for Pyke's framework.



Fig. 5.10. (a) Examples of the generated rules' syntax through applying rough set theory using R.ROSETTA, (b) examples of the converted rules' syntax through applying a Python script, readable in Pyke engine

The system's inference engine utilizes a forward chaining approach, which aligns with the flat rule structure observed in the knowledge base. Since the rules are designed to directly map conditions to decisions without engaging in complex inference chains, forward chaining efficiently linearly processes these rules. The inference engine evaluates the conditions and triggers the appropriate decisions immediately, consistent with a flat structure. This straightforward reasoning process is well-suited for the system's rule-based design.

5.4.4. Case Study and Inference Engine Results

A renovation project targeting the campuses of the University of Lorraine was considered as a case study to demonstrate the practicality of the decision support system and mathematical model for suggesting a multi-level planning and control system. This initiative is part of a

significant energy renovation project launched for the IUT Nancy-Brabois campus. Over two years, the project seeks to refurbish four departments and two workshops to enhance energy efficiency and foster a more conducive learning environment. This endeavor aligns with governmental initiatives aimed at reducing carbon emissions and upgrading public building infrastructure, thereby emphasizing a commitment to sustainability and the welfare of both students and staff, while concurrently advancing academic excellence. The layout and an overview of this case study are depicted in Fig. 5.11. It is worth noting that this case study was selected due to the inherent planning complexity associated with renovating educational campuses, where ongoing operations must be maintained throughout the renovation process. Also, effective stakeholder collaboration was required, given the involvement of numerous parties, which necessitates precise coordination to achieve project objectives. Furthermore, the project's scale, encompassing multiple buildings across the campus, demands a multi-level and collaborative planning approach to ensure efficient management.



Fig. 5.11. An outline and layout of the case study

Various discussions with the project team revealed the importance of adopting a systematic approach for planning and control of diverse aspects such as resources, workflows, logistical considerations, uncertainties, and promoting collaboration and coordination among subcontractors, among other relevant aspects. To systematically collect the functional requirements for the case study concerning a planning and control system, which will provide input data for the DSS, the project team was asked to outline their functional requirements (based on 19 functionalities) using a Likert scale ranging from 0 (not important) to 4 (very important) via the designed interface.

Following collecting the project team functional requirements as input data for the DSS and establishing the knowledge repository, the inference engine was initiated and fired the rules that their conditions were satisfied by the requirements, as illustrated in Fig. 5.12. Out of the 2,280 rules stored within the knowledge database, 59 rules specifically related to project planning methods, control metrics, and schedule levels were activated and fired. Based on the fired rules, 4DBIM, TTP and LPS are suggested for planning methods across all three schedule levels. Moreover, MV, PPC, RL, and CLR are proposed as the control metrics that align more with the project control requirements. This activation highlights the dynamic capability of the inference engine to selectively apply relevant rules based on the contextual demands of the project team. The following section presents a mathematical model developed to optimize the suggested solutions provided by the decision support system for a

specific case study. To do so, the data obtained from these fired rules and the data collected about the connections between planning methods and control metrics and the alignment of planning methods and control metrics across various schedule levels. This approach not only enhances the practical application of the knowledge repository but also underlines the system's efficiency in tailoring project management strategies to meet specific project needs.

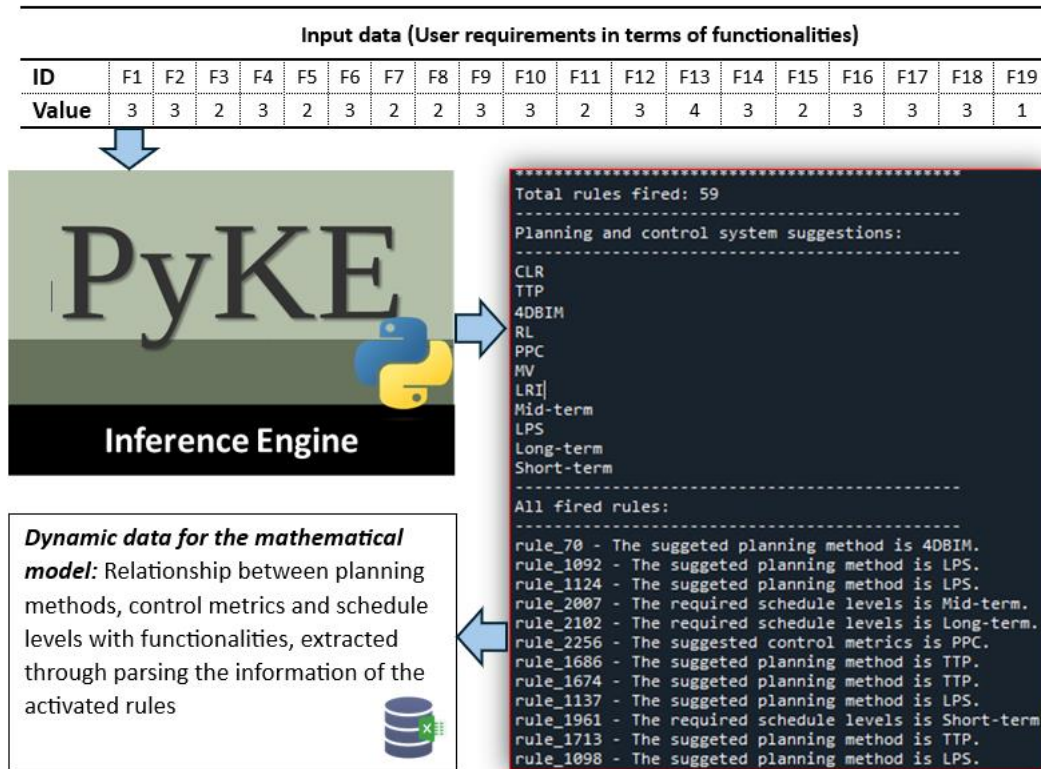


Fig. 5.12. Rule activation process through running the Pyke knowledge engine

The following section presents the results of the mathematical model to suggest the feasible and optimize solutions provided by the decision support system for the case study.

5.4.5. Mathematical Model Results

Based on the collected data and the functional requirements outlined by the project team in the case study, the mathematical model was employed to propose optimized solutions across various scheduling levels. Fig. 5.13 illustrates the input data feasible and best-fitted scenarios, highlighting potential planning strategies and corresponding control metrics across various schedule levels for the case study. Specifically, Fig. 5.13 (a) displays the input data derived from parsing the information of activated rules and expert knowledge. Fig. 5.13 (b) outlines multiple scenarios, showcasing possible planning strategies and their respective control metrics at different schedule levels. Lastly, Fig. 5.13 (c) presents feasible and optimal solutions via Pareto front charts, representing the findings for the case study graphically. As previously mentioned, the project team selects the most suitable solution for each scheduling level, taking into account both project-specific factors and relevant external conditions. The project team provides the following rationale for their selection:

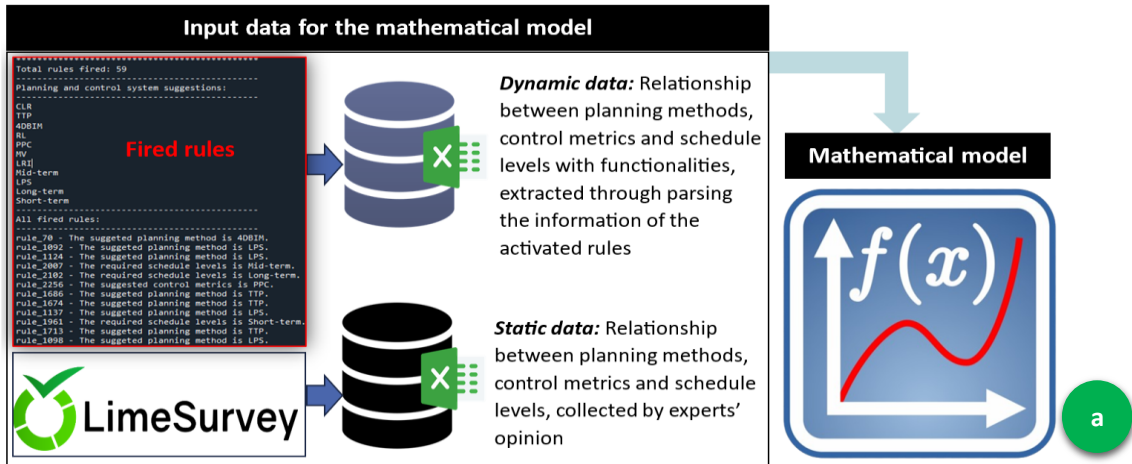
Scenario 1 with Z1=19 at the long-term level was chosen as the best fit for the case study, employing two planning methods: 4DBIM and takt time planning (TTP), along with a control metric: milestone variance (MV). This scenario was selected because it differed not much in terms of Z1 values from other scenarios while offering a more practical approach to

implementation due to its reduced number of planning methods and control metrics. The use of 4DBIM provides a comprehensive visualization of the project timeline, while Takt Time Planning ensures steady progress. MV offers precise tracking of schedule efficiency and critical milestones, which is required for long-term windows. The scenario's advantage is its ease of use and reduced complexity, making it ideal for long-term schemes where maintaining focus and adaptability over time is crucial.

In the mid-term schedule level, takt time planning (TTP) and last planner system (LPS) were selected for planning methods, while location risk index (LRI) and task made ready (TMR) were considered as control metrics based on the project circumstances and external factors. This integration enables a more thorough and practical approach to project planning and control. TTP enhances the predictability and synchronization of work across the project, standardizing the work rhythm and facilitating efficient resource management. Complementing this, LPS involves team members in the planning process, ensuring plans are realistic and achievable through its collaboration. This adaptability is vital for mid-term planning, where project conditions can change rapidly. LRI aids in early risk identification, allowing for strategic resource allocation and effective risk mitigation. Similarly, TMR guarantees that all prerequisites for upcoming tasks are complete, thus enhancing task execution and minimizing potential delays. Together, these methods and metrics create a robust framework that significantly improves the effectiveness of lookahead planning by ensuring consistent workflow, collaborative planning, meticulous risk management, and thorough preparation.

In short-term planning, takt time planning (TTP) and last planner system (LPS) were again selected as the planning methods, complemented by percent planned complete (PPC) and capacity to load ratio (CLR) as control metrics. By aligning the work sequences with the overall project schedule, TTP optimizes workflow efficiency, preventing delays between tasks in tightly coordinated renovation projects. This approach supports the weekly work plan by establishing a clear, consistent pace that all team members can follow, ensuring tasks are completed within designated time slots. LPS augments the functionality of TTP by promoting a collaborative environment where daily and weekly work plans are developed through consensus among all project stakeholders. This system facilitates daily coordination by enabling immediate adjustments to the plan based on real-time feedback from the ground, ensuring that the project responds adaptively to any challenges or changes. This level of coordination is vital in renovation projects, where unexpected issues often arise and require quick decision-making and flexibility.

Furthermore, PPC as a control metric provides immediate feedback on the progress against the weekly plans, promoting a cycle of continuous improvement in planning accuracy and execution. CLR, on the other hand, ensures that the capacity of resources matches the demand of the daily and weekly schedules, preventing overextension or underutilization of the workforce and materials. Together, TTP and LPS not only support the structuring of weekly work plans but also enhance daily coordination and operational efficiency, crucial for the dynamic and unpredictable nature of renovation projects.



Feasible scenarios and selected planning methods and control metrics at each schedule level for the case study

Max. Functionalities (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
<i>Long-term level</i>																			
19	2	1	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
29	3	1	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0
29	4	1	1	0	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0
29	5	1	1	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0
29	6	1	1	1	1	1	0	1	0	1	0	0	0	0	0	1	0	0	0
29	6	2	1	1	1	1	0	1	0	1	0	1	0	0	0	1	0	0	0
<i>Mid-term level</i>																			
26	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
45	2	2	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1
55	3	1	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0
55	4	2	1	0	0	1	0	0	1	1	0	1	1	0	0	0	0	0	0
55	5	2	1	0	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0
55	6	3	1	1	0	1	1	0	1	1	0	1	1	0	0	1	0	0	0
<i>Short-term level</i>																			
30	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
36	1	2	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0
49	2	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
55	2	2	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	0
49	3	1	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0
55	3	2	0	0	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0

Pareto front charts and optimize solutions for the case study

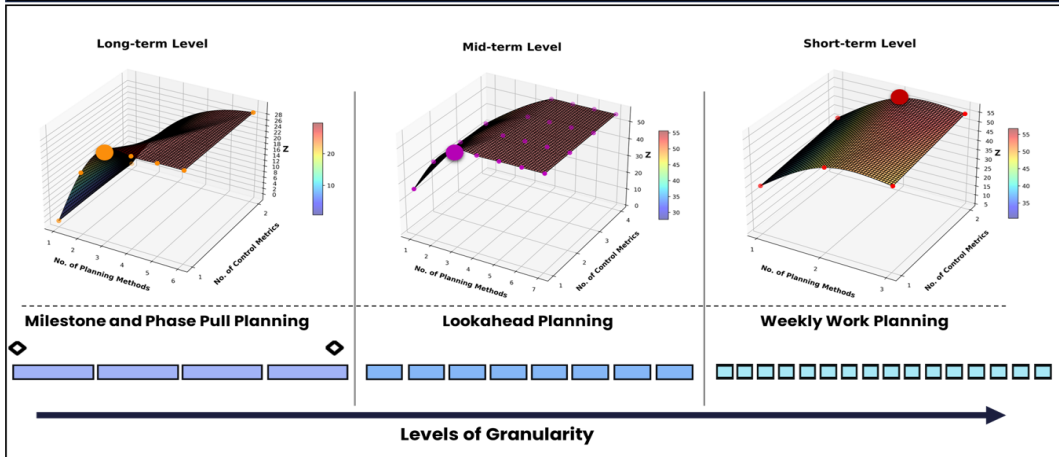


Fig. 5.13. (a) Input data for the mathematical model, (b) potential scenarios at each schedule level, (c) Pareto front plots of the findings

The overview of the optimized planning and control system for the case study, presented in Fig. 5.14, demonstrates a shift in perspective towards considering the project planning and control approach as a system. This study supports moving beyond conventional project planning methods to embrace a multi-functional system designed and implemented at various levels. By adopting this comprehensive approach, the study aims to revolutionize traditional thinking about project planning and control, emphasizing the need for a holistic and integrated system that addresses the complexities and dynamics of construction projects. This multi-level and integrated approach ensures more effective management and oversight, facilitating the achievement of project objectives through enhanced coordination and efficiency.

Regarding the engineering insights, this study adopts a data-driven and knowledge-based approach through a comprehensive and integrated process that leverages the mixed-method methodology to extract and utilize the expertise of construction professionals. By combining qualitative insights from industry experts with quantitative data analysis, the research develops a robust decision support system. This approach ensures that the practical experiences and knowledge of engineers are systematically captured and applied, leading to more accurate, reliable, and adaptive project management solutions.

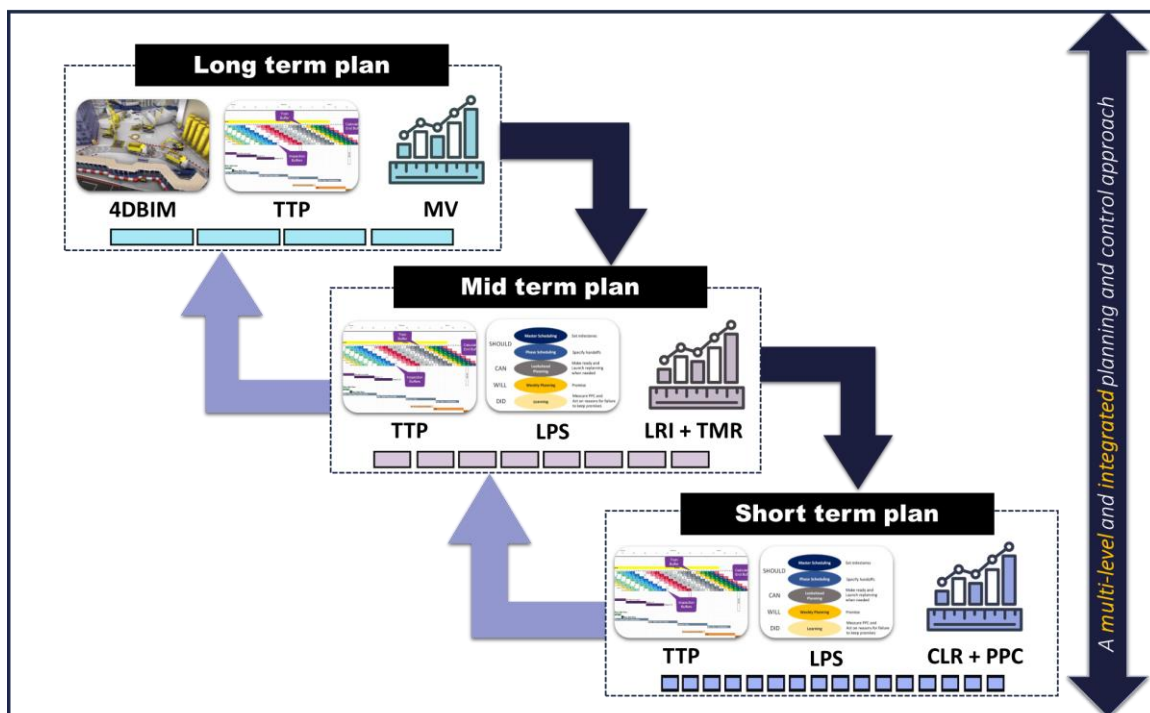


Fig. 5.14. Suggested multi-level and integrated solution for the case study

To successfully implement the suggested solutions, it is critical to meticulously plan the process and workflow for integrating the proposed methods at each scheduling level, identify the responsible parties, specify the necessary reference and exchange information, and detail the required steps and activities. These essential elements for the seamless adoption of the suggested system, fall outside the scope of this research. To provide a practical guide on implementing the proposed system by DSS in practice, a methodological guideline will be developed in a subsequent step. This guideline will aim to ensure that the theoretical strategies are effectively translated into actionable, efficient practices within project management environments.

5.5. General Assessment of the proposed DSS

Although the application of the DSS to the case study has indicated its applicability, for a more comprehensive and general assessment, the DSS's overall performance was evaluated by experts using a Likert scale. This evaluation focused on several criteria, including ease of use, comprehensiveness, decision quality improvement, interface quality, and response time. As depicted in Table 5.13, user satisfaction across all criteria ranged between 3 and 5 out of 5. Experts generally recognized the practicality and user-friendliness of the MPCS-DSS, highlighting its consistent outputs and its role in augmenting decision-making processes within project teams concerning the selection of planning and control systems. However, limitations have been raised about the knowledge database's comprehensiveness. The knowledge repository was constructed based on inputs from only 23 experts, indicating that expanding the data collection could lead to a more exhaustive approach. Furthermore, given the specific nature of control metrics, which cover a limited scope of functionalities, this segment of the knowledge repository contained merely 80 rules, which may have impacted its breadth. Despite these challenges, the satisfaction levels with the comprehensiveness of the DSS still surpassed the threshold of 3, which was deemed acceptable within the context of this study.

Table 5.13. Experts' evaluations in 5-point Likert-scale

Evaluation criteria	Likert scale					Average
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	
	1	2	3	4	5	
Ease of use						4.8
Comprehensiveness						3.4
Decision quality improvement						4
Interface quality						4.4
Response time						5

5.6. Research Discussion and Implications

This discussion tries to synthesize the key aspects and contributions of the paper, highlighting its significance, innovations, and implications within the field of project management. This study focuses on the development of a decision support system for multi-level and integrated project planning and control systems. This approach not only enhances project planning and control but also contributes to the existing body of knowledge by offering practical solutions that can be adopted in various construction projects. By bridging theoretical frameworks with practical applications, this study marks a pivotal step forward in storing and applying the experts' knowledge to propose planning and control systems for construction projects. To do so, the research methodology adopted a mixed-method approach, integrating data collection, expert system development, and result optimization. First, essential insights were gathered through semi-structured interviews and surveys conducted by domain experts. The expert system development phase involved building a rule-based knowledge repository using rough set theory (RST) and Pyke—a Python-based knowledge engine—to infer recommendations based on project requirements. The following phases involved launching an inference engine using forward chaining techniques as well as structuring and optimizing the suggestions by DSS through a mathematical model.

A key aspect of this research was the application of rough set theory (RST) to analyze the

collected data systematically. RST was a crucial component in discovering and extracting the essential knowledge from experts, effectively capturing the complexities inherent in construction project planning and control systems. By structuring the data within an information system and employing concepts such as indiscernibility relations, lower and upper approximations, and attribute reducts, RST facilitated data exploration and knowledge extraction. This method not only preserved the expert insights but also ensured that the resulting decision rules were both relevant and robust. To ensure the knowledge repository's robustness, stringent criteria were established for rule selection, including P-value thresholds, accuracy benchmarks, and support metrics. This meticulous selection process was pivotal in retaining only the most pertinent and reliable rules, which crucially mitigated the risk of overfitting and minimized noise within the decision-making process. Consequently, this enhanced the reliability and applicability of the DSS. The high accuracy and validity of the selected rules further warranted their effectiveness in accurately representing expert knowledge and facilitating informed decision-making. Furthermore, the system's practicality was demonstrated through a case study involving a renovation project. This practical application highlighted the DSS's effectiveness in navigating complex project requirements and adapting to varied planning and control needs.

Although the developed DSS suggests a combination of advanced planning methods and control metrics as a system for project planning and control, it asks very simple questions based on tangible functional requirements that even non-experts can understand. The final solution is not only an advanced system, but it is also tailored for those who might not have extensive information and knowledge about these methods. The DSS provides a suggested system as an input for methodological guidelines. Domain experts can then use these suggested systems to develop step-by-step methodological guidelines, explaining in detail how the proposed approach by the DSS can be implemented in projects. This ensures that even non-experts can effectively utilize the DSS and implement its recommendations in a practical and comprehensible manner.

While in this research a renovation project was selected as a case study to demonstrate the effectiveness of the developed DSS, this tool can be generalized for different project types, including infrastructure projects, new construction projects, and industrial projects. The developed knowledge repository is not dependent on project types but rather on planning and control systems. By importing the functional requirements of project teams for various project types, the DSS can provide the most appropriate results. This approach ensures the system's applicability and repeatability across diverse case study projects, allowing it to be used effectively in various project management scenarios. Eventually, the system's design and functionality were evaluated on multiple dimensions, including ease of use, comprehensiveness, decision quality improvement, interface quality, and response time. The evaluation revealed generally high user satisfaction, with scores ranging from 3 to 5 on a 5-point scale. These results underscore the practicality and user-friendliness of the MPCSS-DSS, particularly in its ability to deliver reliable outputs that enhance decision-making processes.

The originality of this study lies not only in developing a DSS for construction projects but also in proposing a replicable, integrated methodology for creating robust knowledge-based systems applicable across various domains. This mixed-method approach is particularly innovative in seamlessly integrating qualitative and quantitative techniques. By combining expert knowledge with advanced computational tools, the methodology establishes a tightly interconnected framework. The study's unique contribution stems from its ability to merge

traditional expert systems with forward-chaining inference engines, data-driven rough set theory, and mathematical optimization models. These interconnected layers of analysis ensure that the knowledge base is not only comprehensive but also adaptable, allowing the system to evolve and provide optimized context-specific recommendations. This holistic approach offers a scalable model that other fields can adapt to develop similar decision support frameworks, thereby advancing both the theory and practice of intelligent system development.

The processes of knowledge extraction and DSS development in this research significantly contribute to the academic environment by demonstrating how rough set theory can be effectively used to handle uncertain data, a characteristic inherent to the built environment, and to harness the expertise of industry professionals. This approach is crucial in construction, a sector that heavily relies on experience, best practices, and lessons learned. Moreover, the integration of mathematical models with DSS not only showcases how theoretical applications can provide practical solutions but also suggests an optimized approach for handling complex decision-making processes in construction management. This study not only bridges the gap between theoretical research and practical application but also advances the understanding of adaptive decision-making frameworks that can cater to the dynamic nature of construction projects.

Regarding the practical implications, as several studies have shown (AlNasseri and Aulin 2015; Salling et al. 2023), there is generally a low level of knowledge, understanding, and familiarity among project stakeholders regarding planning and control systems in construction. Addressing this challenge, the developed DSS simplifies the decision-making process by asking straightforward and sensible questions tailored to the project team's requirements, thus suggesting the best approach for project planning and control. This makes it a versatile tool that can be applied across various project types, from residential and commercial building projects to infrastructure and industrial projects, during the pre-construction phase to determine the most effective planning and control strategies based on team inputs. Furthermore, by presenting the results in a Pareto front plot, the DSS offers the project team multiple scenarios, providing them the flexibility to choose the most suitable option in light of specific project conditions and constraints. This adaptability enhances decision-making efficacy and promotes a more informed selection process, leading to optimized project outcomes and better alignment with strategic objectives.

While the developed DSS provides a valuable tool for project planning and control, several limitations must be acknowledged when considering its application in real-world engineering projects. Although the DSS offers multiple scenarios for integrating planning methods and control metrics at each scheduling level, the selection of the most appropriate solution is influenced by various factors, including the specific characteristics of the project, the maturity level of the organization and its stakeholders in planning and control systems, and external environmental conditions such as legal and regulatory frameworks. Due to the complexity of accounting for these variables, expert input may still be required to ensure the selection of the most suitable scenario. Additionally, implementing the multi-level and integrated system proposed by the DSS in actual construction projects would require a detailed, step-by-step methodological guideline, which falls outside the scope of this research. Future work could focus on developing such practical guidelines to facilitate the system's application. Additionally, the knowledge repository of the DSS is somewhat generalized due to the limited availability of experts with comprehensive knowledge of various planning and control systems

tailored to specific project types. As such, some functionalities or rules may not be fully relevant to specific project types and would need further customization for optimal applicability.

5.7. Conclusion, Limitations and Future Directions

This research successfully demonstrated the development and practical application of a data-driven and knowledge-based decision support system for multi-level planning and control in construction projects. The study utilized rough set theory integrated with a Python-based knowledge engine, Pyke, to develop a rule-based expert system that systematically addresses the uncertainties inherent in project data and leverages experts' knowledge and builds a knowledge database for the DSS. The development of the DSS involved formulating a multi-objective mathematical model designed to enhance decision-making by evaluating various feasible solutions simultaneously. This model leveraged the outputs from the DSS—primarily the recommended planning methods and control metrics—to generate a set of optimized solutions that balance competing project requirements. The optimization component of the DSS was implemented through Pareto front plots, which are critical in multi-criteria decision-making. These plots visually represent the trade-offs between different objectives, allowing decision-makers to understand the implications of various choices and select the most appropriate strategies based on specific project needs. The case study involving a renovation project at the University of Lorraine showcased the DSS's capability to suggest a multi-level planning and control system and adapt to the specific needs of the project.

This study has several limitations that should be acknowledged. First, the data collection was limited to 23 experts, which, while sufficient for this study's scope, might not fully represent the broader range of expertise available in the construction management field. Another significant limitation is that although the DSS and mathematical model suggest a multi-level planning and control system for construction projects, there is a need for a methodological guideline to assist the project team in implementing the suggested solutions by the DSS. This aspect falls outside the scope of this study, and future research could focus on developing these methodological guidelines, which are crucial for the practical application and operational success of the DSS results in real-world settings.

Considering the scope and successful application of the DSS in this study, future research could expand in several directions. Investigating the application of the DSS in different types of construction projects, including new construction and infrastructure projects, could validate the system's adaptability and effectiveness across various contexts. Additionally, exploring alternative methods for DSS development, such as case-based systems, could offer valuable perspectives on different approaches and their respective benefits. Another promising direction involves investigating optimization algorithms beyond the current methods. Exploring alternative algorithms like metaheuristic algorithms to identify the best fit could improve the robustness and effectiveness of the DSS results. Furthermore, extending the analysis to include Bayesian networks could introduce additional flexibility to the inferences produced by the system. Integrating insights from studies like Feng et al. (2014) could enrich the research and offer new avenues for enhancing the DSS's capabilities.

In conclusion, this study marks a significant step forward in the application of decision support systems within construction management. It offers a robust framework for enhancing project outcomes by proposing multi-level and integrated planning and control systems. The

implications of this research are far-reaching, promising to influence both current practices and future innovations in the construction industry. Furthermore, this framework can be applied to other case studies, demonstrating its scalability and potential for broader impact across various project management contexts.

Chapter 6. Multi-level and Integrated Production Planning and Control Guideline for Construction Sites

This chapter addresses the fifth objective of this thesis: to propose a methodological guideline for implementing the suggested approach by DSS for renovation projects. Based on the planning methods and control metrics for the multi-level and integrated system for a renovation project proposed in the previous chapter, a rigorous procedure involving multiple key steps was adopted to establish a methodological guideline for industry implementation of the suggested system. Firstly, a thorough review of existing guidelines was conducted to ensure that the framework was grounded in established practices, recommendations and guidelines. The information gathered from papers and guidelines was then systematically organized and analyzed using tabulated reviews, which helped to uncover important patterns and lessons learned. To further refine the approach, experts from the project planning and control field were consulted, and their collective knowledge and experience were leveraged to extract the essential components necessary for the guideline. This collaborative and systematic approach ensures that the final guideline is robust, practical, and tailored to meet the industry's needs. It should be mentioned that while this guideline is initially developed for large-scale building renovations, its comprehensive nature and detailed approach make it applicable to a wide range of projects.

6.1. MIPRI Framework Components For Methodological Guideline

Following the review and analysis of related guidelines, reports, and documents on the Last Planner System, Takt Time Planning, 4D BIM, and CPM, along with discussions with experts involved in this research and leveraging the experience of the supervisors and the author, four main components were identified as the fundamental elements of a methodological guideline. **Multi-level and Integrated method**, **Process (workflow)**, **Responsible roles**, and **required Information** were considered as MIPRI framework's components for the methodological guideline, shown in Fig. 6.1. These components of the guideline are covered in depth in the following subsections.



Fig. 6.1. MIPRI framework's components

6.2. Multi-level and Integrated Planning and Control System

Each planning and control system comes with its own set of strengths and weaknesses, making it challenging to address every potential shortcoming with a single approach (Sheikhhoshkar et al. 2023a). To effectively manage these limitations, this guideline introduces a comprehensive system that integrates multiple planning methods and control metrics across various scheduling levels. This integrated approach aims to leverage the advantages of different systems while mitigating their drawbacks, providing a more robust and adaptable framework for project management. Fig. 6.2 illustrates the structure and components of this integrated system, demonstrating how it harmonizes various methods to achieve optimal planning and control outcomes.

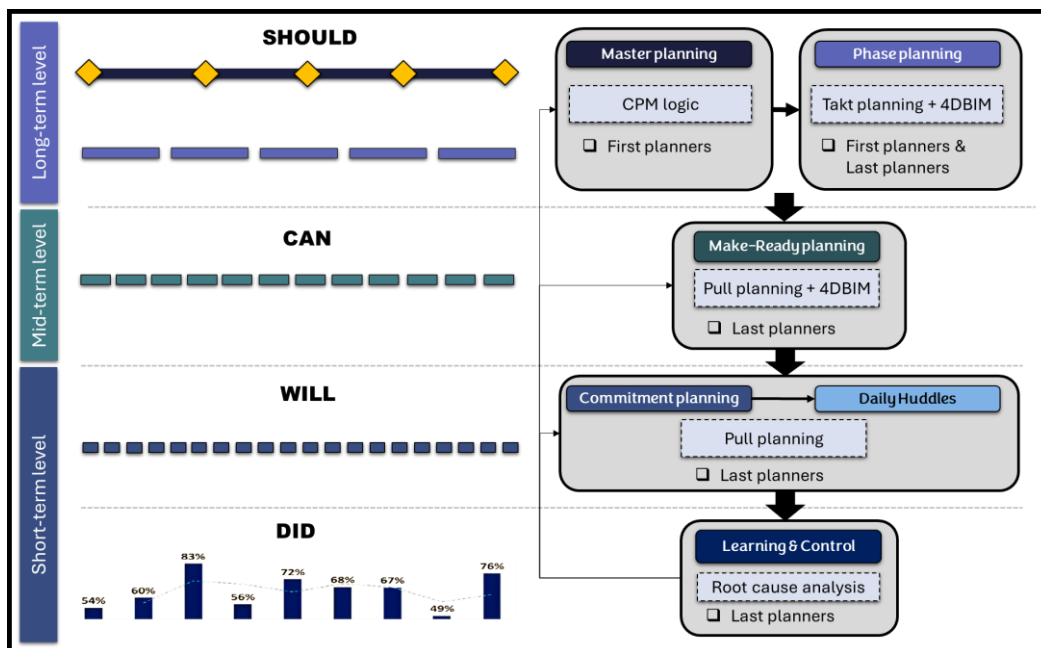


Fig. 6.2. Multi-level and integrated planning and control system

The Last Planner System (LPS) was adopted as the central framework and overarching structure in the proposed system. While LPS provides a robust foundation for collaborative planning and workflow management, it lacks specificity in defining how work should be structured. To address this limitation, planning methodologies such as the Critical Path Method (CPM), Takt Time Planning (TTP), and 4D Building Information Modeling (4DBIM) were integrated into the system. These methods complement LPS by offering detailed scheduling techniques, aligning work pace with production rates, and enhancing visualization and coordination through time-based 3D models, respectively. This integration ensures a comprehensive approach to project planning and control.

The suggested integrated system for planning and control in construction projects is organized into three hierarchical levels: long-term, mid-term, and short-term planning.

6.2.1. Long-term Level

Master Planning: This stage involves high-level scheduling of the entire project using the CPM logic. The responsibility for this phase lies with the primary planners, known as "First Planners". Master planning establishes the overall timeline and identifies key milestones, guiding the subsequent phases of planning.

Phase Planning: In this phase, Takt Time Planning (TTP) and 4DBIM are integrated to detail specific project phases. Both the first planners and last planners participate in this stage. TTP aligns the work pace with production rates, while 4DBIM enhances visualization by linking the schedule with 3D models.

6.2.2. Mid-term Level

Make-Ready Planning: At this level, pull planning and 4DBIM are employed to ensure that all preconditions for upcoming work are met. This phase focuses on the last planners, who ensure tasks are ready for execution as scheduled. The integration of 4DBIM helps visualize and coordinate the sequence of activities, thereby reducing potential delays.

6.2.3. Short-term Level

Commitment Planning: This stage involves daily and weekly planning sessions where tasks are committed to by the last planners. Pull planning ensures that the sequence of tasks is based on actual workflow requirements. This level includes daily huddles, where planners review and adjust commitments based on real-time conditions.

Learning & Control: This stage emphasizes continuous improvement through root cause analysis. Last planners identify and analyze issues that arise during project execution, allowing the team to learn from mistakes and implement corrective actions. This feedback loop enhances planning accuracy and improves project performance over time.

The following sections first introduce the methods considered, followed by a detailed explanation of how these methods are integrated at different scheduling levels.

6.2.4. Last Planner System

The Last Planner System (LPS) was developed in the 1990s by Glenn Ballard and Greg Howell as a collaborative planning approach to improve project management in the construction industry (Ballard 2000). It emphasizes the involvement of all participants, or "last planners,"

who are closest to the work being done, in the planning process to ensure more reliable and realistic commitments. The system is structured around several planning phases, as depicted in Fig. 6.3, to ensure that projects are executed efficiently and effectively. The system breaks down the planning process into five key stages, each addressing different aspects of project planning and execution.

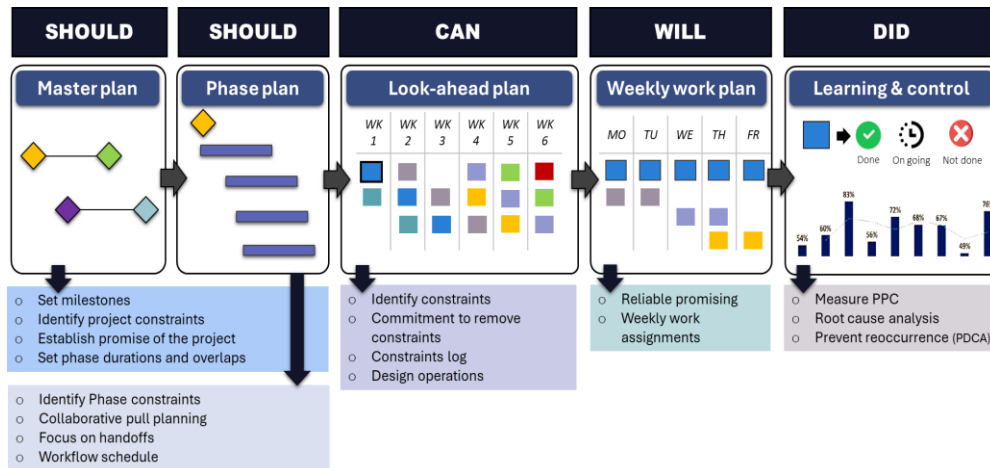


Fig. 6.3. The last planner system schematic

6.2.4.1. Master Plan (SHOULD):

Purpose: Establish the overall project milestones and identify constraints.

Activities:

- Set milestones for project deliverables.
- Identify gross constraints that could impact the project.
- Establish the promise of the project by defining key objectives and outcomes.
- Set durations and overlaps for different project phases.

6.2.4.2. Phase Plan (SHOULD):

Purpose: Develop detailed plans for specific phases of the project.

Activities:

- Identify constraints specific to each phase.
- Engage in collaborative pull planning to align team efforts.
- Focus on handoffs between tasks to ensure smooth transitions.
- Create a detailed workflow schedule for the phase.

6.2.4.3. Look-ahead Plan (CAN):

Purpose: Identify and remove constraints that could hinder progress in the upcoming weeks.

Activities:

- Identify constraints that could affect work in the near future (2-6 weeks).

- Commit to removing these constraints.
- Maintain a constraints log to track issues and resolutions.
- Design operations and plan activities for the upcoming weeks.

6.2.4.4. Weekly Work Plan (WILL):

Purpose: Ensure reliable task execution through weekly planning.

Activities:

- Make reliable promises by committing to specific tasks.
- Assign weekly work to team members, ensuring alignment with the overall plan.
- Review and adjust commitments based on real-time conditions through daily huddles

6.2.4.5. Learning & Control (DID):

Purpose: Monitor performance, learn from outcomes, and make necessary adjustments.

Activities:

- Measure Percent Plan Complete (PPC) and other control metrics to assess the efficiency of task completion and performance.
- Conduct root cause analysis to understand why tasks were not completed as planned.
- Implement corrective actions to prevent recurrence, following the Plan-Do-Check-Act (PDCA) cycle.

6.2.5. Takt Time Planning

Takt Time Planning (TTP), originally developed by Toyota as part of its Production System in the mid-20th century, has been adapted for use in the construction industry to improve efficiency and minimize waste. This lean construction methodology aims to synchronize the pace of work with the project's overall timeline, ensuring a smooth and continuous workflow. By dividing the project into manageable sections and assigning specific durations to each task, TTP helps maintain a consistent production rate, reducing downtime and enhancing coordination among project participants. The design process involves creating these zones, aiming to ensure that each activity within the sequence encompasses an equal amount of work in each zone. The system organizes the work structuring process into three key stages (Dlouhy et al. 2016), as shown in Fig. 6.4 and outlined below.

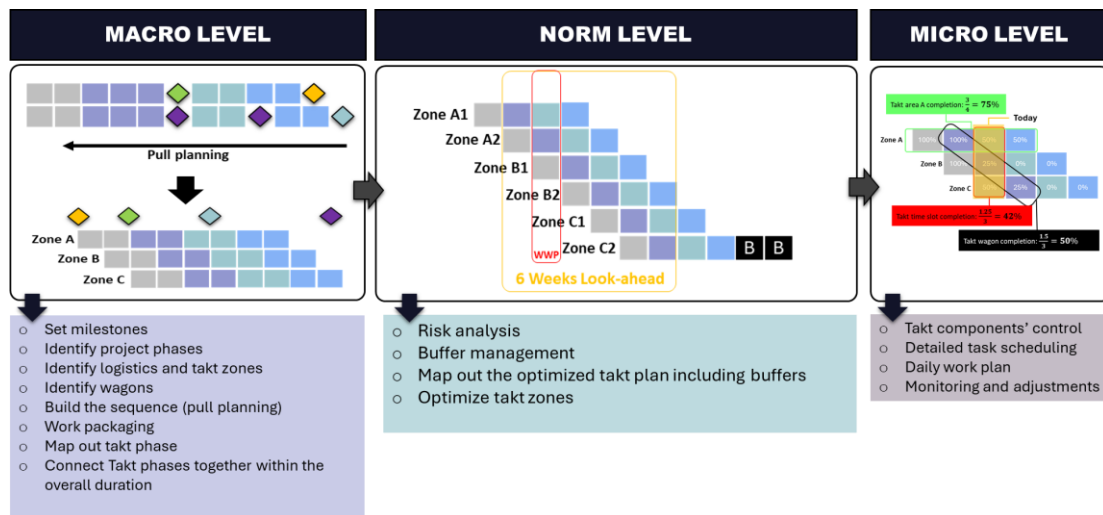


Fig. 6.4. The Takt planning system schematic

6.2.5.1. Macro Level: Project-wide Implementation

Purpose: At the macro level, the focus is on the overall structure and major milestones of the project. This stage involves high-level planning to set the foundation for detailed execution.

Activities:

- Set milestones: Identify key project deliverables and set major milestones.
- Identify project phases: Break down the project into distinct phases.
- Identify logistics and Takt zones: Determine the logistics required and divide the project into Takt zones.
- Identify wagons: Define work packages or "wagons" that move through the Takt zones.
- Build the sequence (pull planning): Use pull planning to sequence tasks based on dependencies and Takt time.
- Work packaging: Group tasks into manageable work packages.
- Map out Takt phase: Create a high-level plan for each Takt phase.
- Connect Takt phases: Ensure that Takt phases are seamlessly connected within the overall project duration.

6.2.5.2. Norm Level: Phase or Segment Planning

Purpose: The norm level involves detailed planning for specific project phases or segments, focusing on managing risks, buffers, and optimizing workflows within each phase.

Activities:

- Risk analysis: Identify and assess potential risks that could impact the project and phases.
- Buffer management: Plan for buffers to handle uncertainties and ensure continuity.
- Map out optimized Takt plan including buffers: Develop a detailed Takt plan for each

segment, incorporating necessary buffers.

- Optimize Takt zones: Refine and adjust Takt zones to ensure optimal flow and resource allocation.

6.2.5.3. Micro Level: Task-level Execution

Purpose: At the micro level, the emphasis is on the execution of individual tasks, ensuring they align with the established Takt time to maintain a consistent workflow.

Activities:

- Takt components' control: Monitor and control the progress of individual Takt components.
- Detailed task scheduling: Schedule tasks to align with the Takt time, ensuring timely completion.
- Daily work plan: Develop daily work plans that specify the tasks to be completed each day.
- Task-level resource allocation: Ensure the right resources are available for each task at the required time.
- Monitoring and adjustments: Continuously monitor task progress against the Takt time, making adjustments as needed.

6.2.6. Critical Path Method (CPM)

The Critical Path Method (CPM) is a project management technique used to plan and control a project's schedule. It involves identifying the longest sequence of dependent tasks (the critical path) that determine the project's minimum completion time. By focusing on these critical tasks, project managers can ensure that delays are minimized and deadlines are met. Despite its traditional approach, CPM can be adapted and integrated into modern project management practices. It can serve as a foundational system to create simple waterfall schedules at the master scheduling level, helping to meet contract obligations. However, for optimal efficiency and flexibility, CPM must be governed by Takt planning and the last planner system. These systems enhance workflow predictability and collaboration, ensuring that the project not only meets contractual deadlines but also adheres to lean construction principles.

6.2.7. 4D Building Information Modeling (4D BIM)

4D BIM is a powerful visualization tool used in the construction industry to enhance stakeholders' understanding and awareness, coordination, and collaboration between project teams among others. 4D BIM integrates the 3D models of a project with its schedule, providing a time-based simulation of construction activities, as illustrated in Fig. 6.5. This visual representation allows project teams to see the sequence of tasks and their progression over time, facilitating better decision-making and communication.

CPM is often used as a foundation for 4D BIM, but this approach has limitations and may not always be appropriate. To maximize the benefits of 4D BIM, it should be governed by more advanced planning methods such as the Last Planner® System (LPS) and Takt Time Planning (TTP). These systems provide a more structured and collaborative framework, ensuring that

the project schedule aligns more accurately with the dynamic nature of construction work. 4D BIM can be used as a crucial tool in phase planning and look-ahead planning to better identify constraints, spatial clashes, and other potential issues. By visualizing the construction sequence, teams can proactively identify and resolve conflicts before they impact the project, leading to smoother execution and fewer delays. This proactive detection and resolution capability further enhances the effectiveness of the planning process, contributing to the successful delivery of construction projects.

A common challenge with 4D BIM is the mismatch in the level of detail between the schedule plan, which is activity-based, and the 3D model, which is component-based. This discrepancy can hinder the effectiveness of 4D BIM. To address this, a location-based 4D approach can be more effective. In this approach, even if a specific task in the schedule is not directly associated with an object in the 3D model, the activity or task can be linked to its relevant location. This ensures a more coherent and practical integration of the schedule with the 3D model, improving the overall utility and impact of 4D BIM in project management.

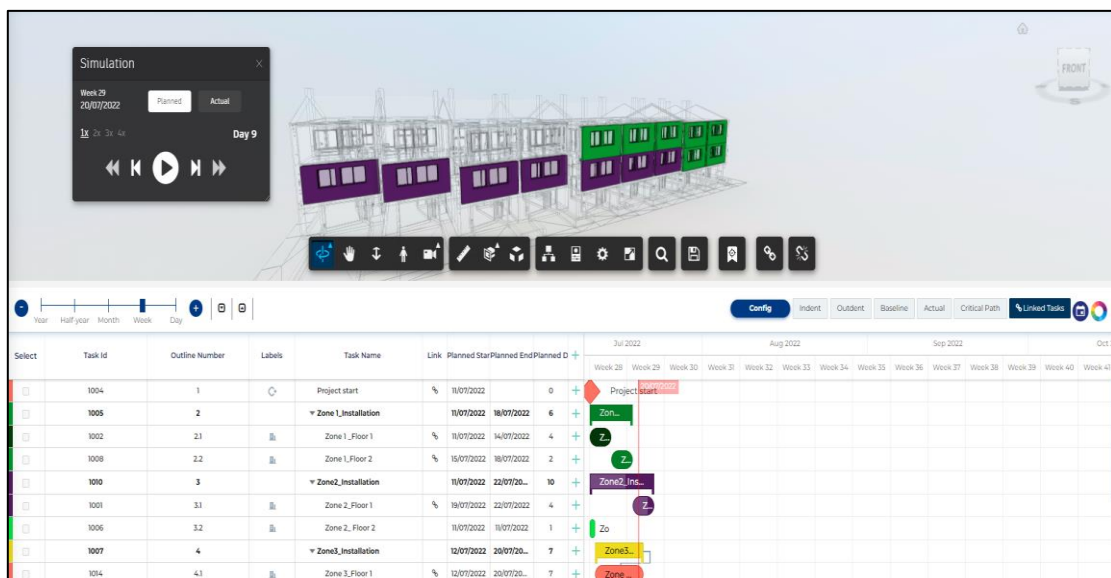


Fig. 6.5. An illustration of 4DBIM








6.3. Required Processes for implementing the Integrated system

In the following section, the other components of the MIPRI framework necessary for the integrated system's implementation guidelines are detailed. This includes the required processes and activities, the roles responsible for each component, and the information. Before delving into these details, it is essential to define the symbols used for process map representation to ensure clarity and consistency throughout the documentation.

6.3.1. Symbols Used for Process Map Representation

The preferred notation for process mapping development is the Business Process Modeling Notation (BPMN). One of the key elements of BPMN is the visual appearance of the process map in terms of the symbols and markers used. These should serve as the shapes defined in the BPMN specification. To develop a process map for the system's levels, the following symbols are used:

Table 6.1. Process mapping notation for integrated planning and control system process maps

Element	Description	Notation
<i>Event</i>	Represented by circles, these indicate the start and end points of a process.	
<i>Activities</i>	Depicted as rounded rectangles, these show the tasks or work performed in the process.	
<i>Gateways</i>	Diamond-shaped symbols are used to depict decision points where the flow can diverge or converge.	
<i>Sequence Flows</i>	Arrows that indicate the direction and sequence of activities.	
<i>Associations</i>	Used to tie required and output information as well as data objects with the steps and activities of the process.	
<i>Pools</i>	Act as graphical containers for partitioning a set of activities from other pools. For each process, three pools—Process, Information, and Stakeholders—are considered.	
<i>Artifacts</i>	Additional information or data associated with the process, such as data objects and annotations.	

6.3.2. The Multi-level and Integrated Production Planning and Control System

This section offers a comprehensive overview of each of the four multi-level and integrated system processes. For optimal performance, these processes must be implemented harmoniously, with compatible schedules, active involvement of project stakeholders, accommodation of dynamic changes and updates, and leveraging insights from past planning failures to drive continuous improvement.

6.3.2.1. Master Scheduling

Master scheduling is the initial process in front-end planning, translating the owner's value proposition into a comprehensive master schedule that outlines the work for the entire project duration. This process focuses on project-level activities related to contract documents. As depicted in Fig. 6.6, master scheduling begins by converting the owner's values and objectives, as stated in the contract documents, into work plans and execution strategies reflected in project-level activities. This dialogue between the owner's values and work strategies establishes the foundation for setting project milestones. After identifying key milestone dates, Critical Path Method (CPM) logic is applied to determine the overall project duration. CPM logic can be represented in various forms, such as Gantt charts and line-of-balance diagrams. The calculated project duration and milestone timings are then compared with the owner's expectations and contract specifications. If the schedule is found unsatisfactory, adjustments to the duration, sequence, or scope are made, and re-planning is conducted until a satisfactory schedule is achieved. This finalized schedule is known as the master schedule (Hamzeh 2009b). Throughout this process, key stakeholders, including the project manager, superintendent, and project planner, play pivotal roles in setting milestones, incorporating CPM logic, determining the project duration, and ensuring the schedule's adequacy. This iterative approach ensures a comprehensive and realistic master schedule, aligning with project goals and logistical considerations.

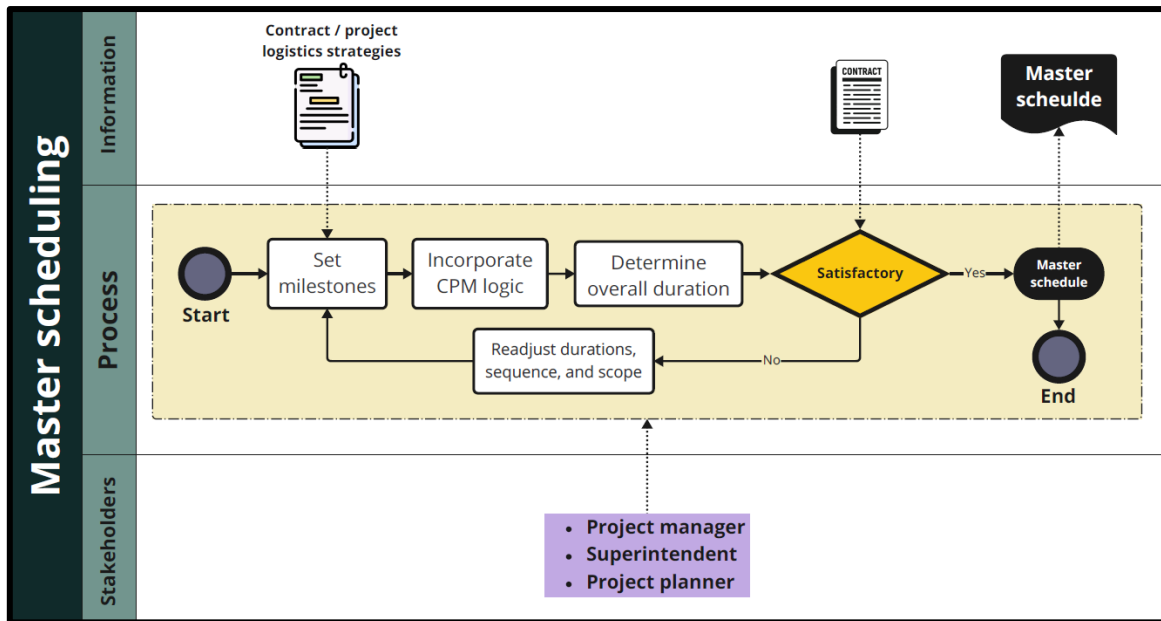


Fig. 6.6. The master scheduling process in the multi-level and integrated system

6.3.2.2. Phase Scheduling

Phase scheduling aims to break down the master schedule into detailed, manageable phases, ensuring efficient and coordinated execution of project activities. As this schedule level in the last planner system is not specific on how exactly work is to be structured (Ballard and Tommelein 2021), Takt time planning and 4D BIM are incorporated to create a more structured and precise phase schedule. The integration process involves several steps, various sources of information and involving key stakeholders as shown in Fig. 6.7 and are explained in depth below.

As Takt Time Planning plays a significant role in the phase schedule level of the suggested system, it is essential to delve into the process of Takt plan development. Takt Time Planning involves organizing work to align with a set rhythm, or "takt," ensuring continuous and balanced workflow throughout the project (Binninger et al. 2017). A Takt Plan is typically represented on a single page, making it highly visible and easy to understand. In the Takt plan format, as shown in Fig. 6.8, columns represent time durations, rows represent Takt areas, and colored boxes represent scopes of work, trades, or packages of scopes and trades. Each cell visualizes the intersection of time and space, creating a clear, visual schedule.

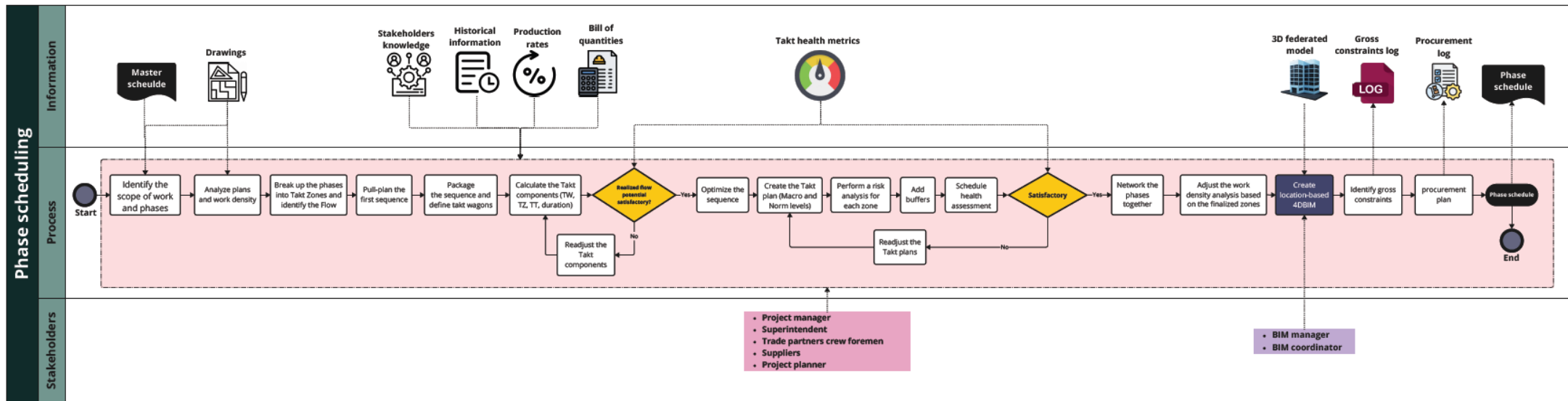


Fig. 6.7. The phase scheduling process in the multi-level and integrated system

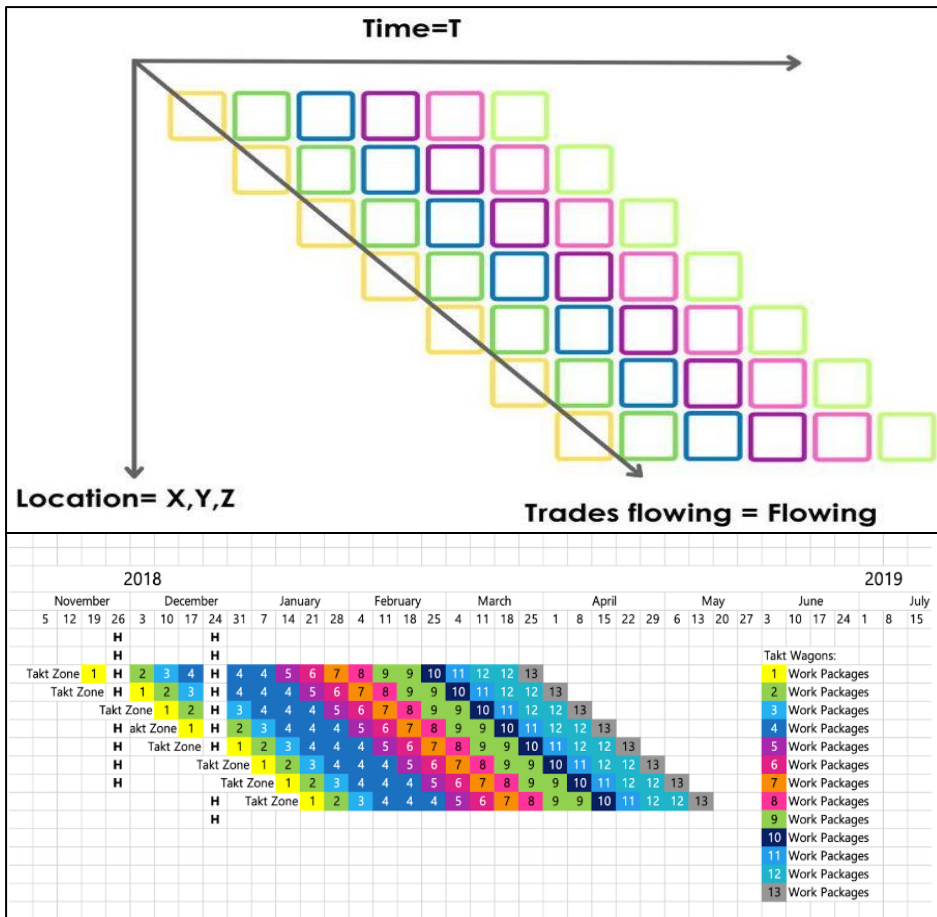


Fig. 6.8. A visual representation of Takt plan format (Schroeder and Easton 2022b)

The Takt Plan also captures three essential types of flow: workflow, trade flow, and logistical flow. Workflow represents the continuous flow of work within an area. Trade flow tracks the movement of trades from one area to another, ensuring sequential progress. Logistical flow outlines the ordered sequence of tasks across areas, including design, coordination, procurement, buyout, and permissions (Schroeder and Easton 2022b). By visualizing these flows, the Takt plan provides a comprehensive overview of the project's progress. A visualization of Takt plan flows is illustrated in Fig. 6.9.

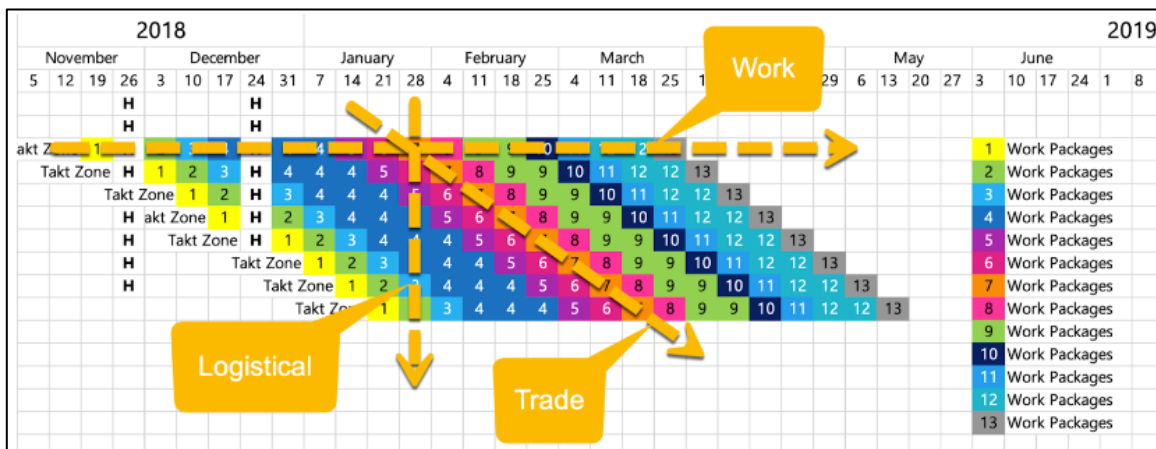


Fig. 6.9. A visualization of Takt plan flows (Schroeder and Easton 2022b)

Fig. 6.10 highlights key elements of the Takt plan. The **Takt Time** is the rate at which work needs to be completed to meet project deadlines. The **Takt Train** represents the sequence and flow of work packages, ensuring that tasks progress smoothly. The **Takt Zone** divides the project into specific areas, allowing for clear responsibility and progress tracking. The **Takt Phase** outlines different stages of work within each zone, from structure and interiors to exterior tasks. **Work Packages** are detailed tasks within each Takt Zone, color-coded for clarity. **Interdependency Ties** highlight dependencies between phases, ensuring logical and efficient sequencing. **Takt Wagons** are units of work moving through zones at a steady pace, ensuring a continuous flow of activities. By incorporating these elements, the Takt Time Planning process ensures a detailed and precise phase schedule, optimizing workflow and enhancing project efficiency.

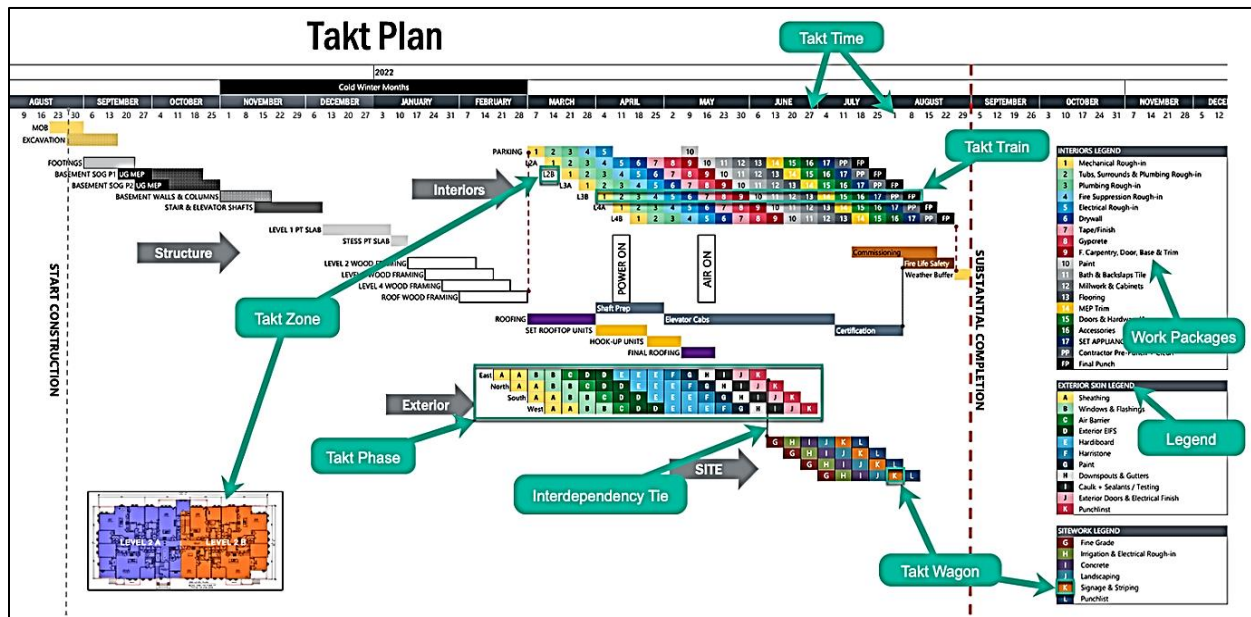


Fig. 6.10. Key elements of a Takt plan (Schroeder et al. 2023)

The phase scheduling process begins with the master schedule, which provides an overarching framework for the project timeline. The initial step involves defining the scope of work and breaking down the project into distinct phases. This includes identifying all major tasks and deliverables required for each phase. Phases are composed of groups of zones, with multiple trains of trades moving through these zones. Each phase features a start milestone, a pace-setting line of balance, a sequence, a buffer, and a finish milestone (Schroeder et al. 2023), serving as the first classification in breaking down the project into manageable parts. A project typically comprises multiple phases that can run concurrently on the schedule, as illustrated in Fig. 6.11. It is essential to note that each phase includes both macro and norm takt plans. The development of these phases is a collaborative process involving the project manager, superintendent, trade partners' crew foremen, suppliers, and project planner, ensuring a comprehensive and coordinated approach.

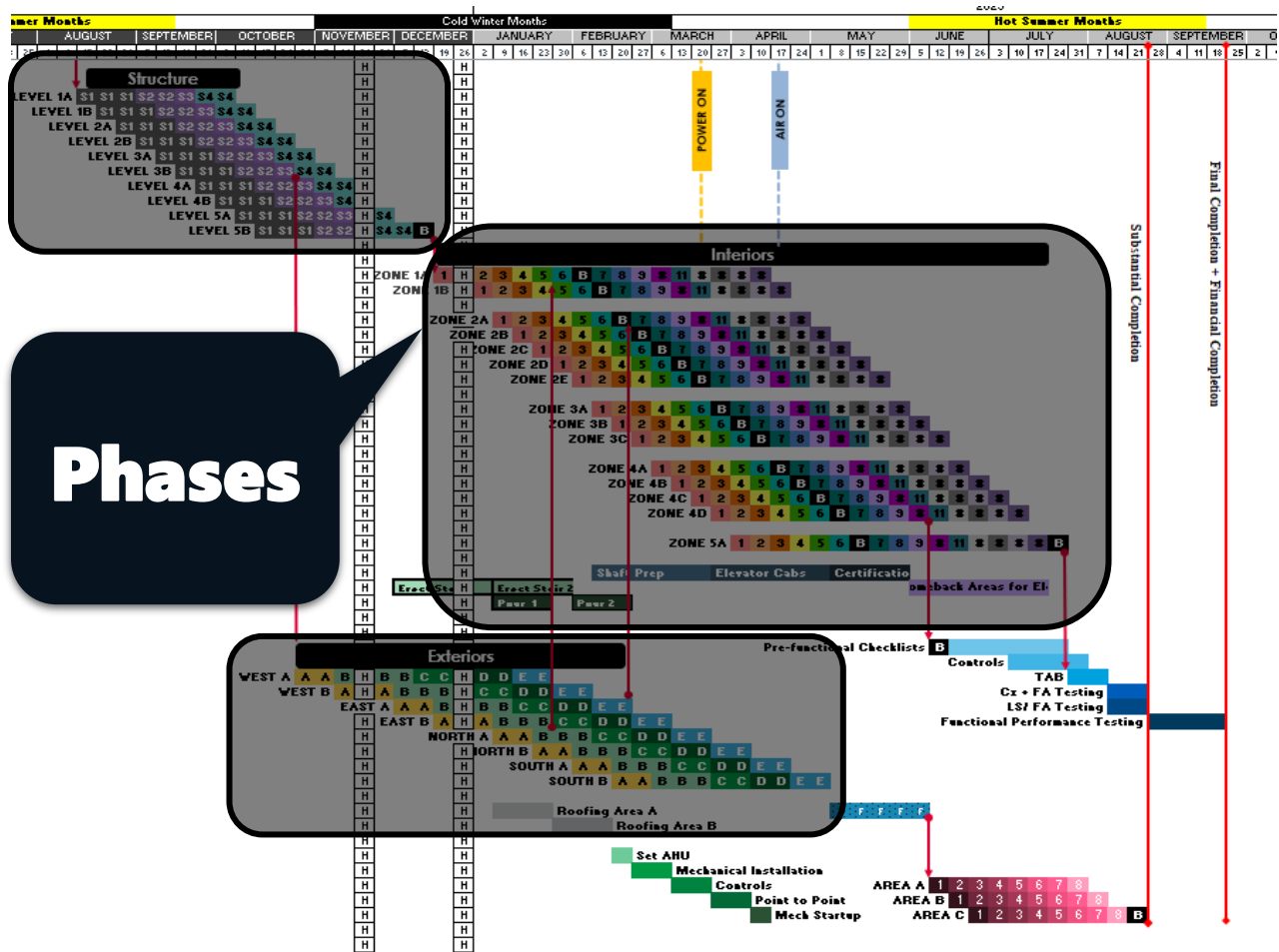


Fig. 6.11. Phase scheduling in a Takt plan (Schroeder 2024)

The most effective method for identifying project phases is to thoroughly examine the project scope and meticulously review the drawings. This approach allows for the identification of general phases and the natural flow of work. By analyzing these elements, one can delineate distinct phases that encompass specific zones and work sequences. This comprehensive review ensures that the phases align with the overall project objectives and logistical requirements, facilitating a smooth and organized progression of activities.

Once the project phases are identified, the next step is to break down the work within each phase into specific location zones. Creating well-balanced zones is essential for an effective takt plan. By carefully dividing the project into balanced zones, more consistent and predictable timelines can be achieved. When balancing zones, it is important to consider that different locations and areas of the project require varying efforts. Therefore, it is crucial to level the zones by work density rather than by area (Tommelein 2022).

Work density refers to the amount of work required in a given area or zone of the project. It is a measure of the intensity and complexity of the tasks that need to be completed in that specific location. High work-density areas might involve more intricate tasks, require more labor, or need more time to complete compared to low work-density areas. In recent studies, efforts have been put into making work density analysis more accurate. For more information, we refer to the

studies of Singh and Tommelein (2023) and Tommelein (2022). However, in this guideline, a simple multi-step approach is provided for work density analysis.

To calculate work density, the following steps should be followed using the project's drawings:

1. **Analyze Drawings and Identify Preliminary Takt Zones:** The project's drawings should be used to map out where each discipline's work will take place. The drawings, such as a floor plan, should be broken into grid segments. The specific locations and areas on the drawings should be identified. An example is depicted in Fig. 6.12.

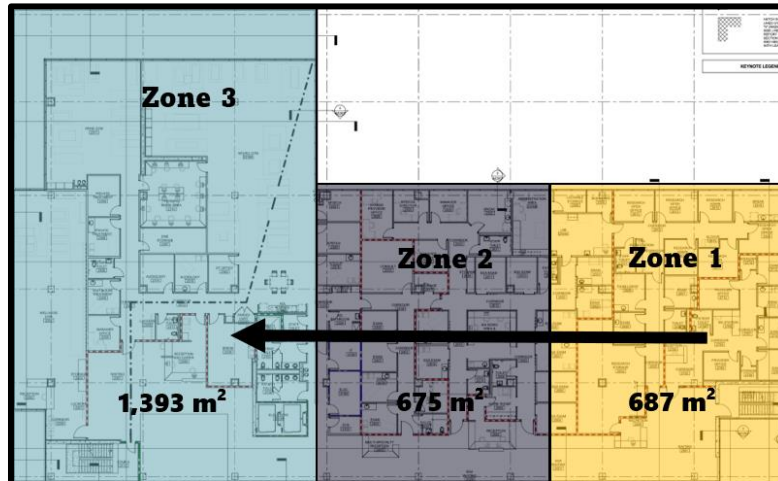


Fig. 6.12. An example of analyzing drawings and identifying preliminary zones

2. **Identify All Disciplines:** All work that needs to be completed in each zone should be listed, focusing on disciplines or phases like structural, architectural, mechanical, electrical, framing, and so on.
3. **Work Density Analysis:** For each discipline at each zone considering grid segments, the amount of effort required should be estimated. This step should be done collaboratively by involving the last planners. A density scale could be considered to determine the amount of time and effort that each trade will take to complete their assigned task in that zone. For example, a scale from 1 to 10 can be used, where 1 indicates little work, and 10 represents the highest effort. An example of work density analysis for a discipline is shown in Fig. 6.13.



Fig. 6.13. An example of work density analysis


4. **Aggregate Your Scores:** The scores from the density scale for each zone should be aggregated. This aggregation will give a total work density score for each zone, reflecting the combined effort required across all disciplines.
5. **Adjust Zones:** Based on the aggregated work density scores, the boundaries of the zones should be adjusted to ensure they are balanced. Zones with similar work densities should be aimed to achieve consistent and predictable durations across the project.

By focusing on work density, it can be ensured that each zone is appropriately balanced, leading to a more efficient and well-coordinated project execution.

To determine if the preliminary zones have the correct number and are optimized, the following formula provided by Nezval et al. (1960) and acquired from Binninger et al. (2018) should be considered (Schroeder et al. 2023).

$$(Takt\ wagons + Takt\ zones - 1) \times Takt\ time = Duration$$

To compute it, a rough estimate of the required Takt wagons is needed. To estimate Takt wagons, a list of activities and their duration considering the available crew size, should be identified using pull planning, collaboratively by involving the last planners. To estimate this information, stakeholders' knowledge, historical information, production rates, and the bill of quantities should be considered. A table like the one in Fig. 6.14 can be used as a template for collecting information.



DURATION PER ZONE

ID	Activity list	Duration per floor (Days)	No. of zones	Crew size	Duration per zone	Duration / Zone (Days)
1	Install wall and casework fixtures	10	3	2	3.33	3
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

Fig. 6.14. A template for preparing a list of activities and their information

Pull planning is a collaborative scheduling technique used in Lean construction to improve workflow and productivity. It involves working backwards from a target completion date to determine the sequence of tasks and their duration. The process encourages team involvement, as it requires input from all stakeholders, particularly the last planners, who are the individuals responsible for executing the work (Hamzeh 2009b).

The steps in Pull Planning are as follows:

1. **Select a Milestone in the Master Schedule:** Identify a key project milestone from the master schedule to serve as a starting point and work backwards from this date.
2. **List Activities:** Collaboratively identify all necessary activities, and their duration considering the available crew size, to achieve each milestone.
3. **Sequence Activities:** Determine the order in which the activities should be performed.
4. **Assign Durations:** Estimate the time required for each activity, considering stakeholders' knowledge, historical information, production rates, and the bill of quantities.
5. **Create the Schedule:** Develop a visual representation of the schedule, often using sticky notes or a digital tool to map out the tasks and their dependencies. To improve communication between the project team, it is suggested to use different colors for trades as well as a formatted sticky note like those provided in Fig. 6.15.

realized flow potential between 35% and 50% is desirable. For a norm-level Takt plan, this range is between 50% and 100% (Schroeder et al. 2023).

Optimize the Takt Phase		Takt Wagons	Takt Zones	Takt Time	Duration	Trade Time Gained	Area per Zone	Takt Level	Realized Flow Potential	Efficiency Parametric	Value Parametric				
Takt Inputs		Takt Wagons	20		168	1	14,828	Bad	20%	10.00	20.00				
		Takt Zones	3		110	0	9,885	Macro	31%	6.67	10.00				
		Takt Time	5		92	1	7,414	Macro	37%	5.00	6.67				
		Duration		110		72	0	5,931	Macro	47%	4.00	5.00			
		Area Inputs (m ² , sqft)		Area / Zone	9,885		75	3	4,943	Macro	45%	3.33	4.00		
				Min Zone Size	1,000		78	6	4,236	Macro	44%	2.86	3.33		
				Max Zone Size	10,000		54	1	3,707	Norm	63%	2.50	2.86		
				Total SQFT of Phase	29,655		56	3	3,295	Norm	61%	2.22	2.50		
				Shortest Durations		Best # Zones	Takt Time	Duration		5	2,966	Norm	59%	2.00	2.22
						15	1	34		60	7	2,696	Norm	57%	1.82
8	2					54		62	9	2,471	Norm	55%	1.67	1.82	
5	3					72		64	11	2,281	Norm	53%	1.54	1.67	
4	4					92		66	13	2,118	Norm	52%	1.43	1.54	
3	5					110		34	0	1,977	Norm	100%	1.33	1.43	
3	6	132				35	1	1,853	Norm	97%	1.25	1.33			
2	8	168				36	2	1,744	Norm	94%	1.18	1.25			
2	9	189				37	3	1,648	Norm	92%	1.11	1.18			
2	10	210				38	4	1,561	Norm	89%	1.05	1.11			
Shortest Durations		Best # Zones	Takt Time	Duration		5	1,483	Norm	87%	1.00	1.05				
		15	1	34		6	1,412	Norm	85%	0.95	1.00				
		8	2	54		7	1,348	Norm	83%	0.91	0.95				
		5	3	72		8	1,289	Norm	81%	0.87	0.91				
		4	4	92		9	1,236	Norm	79%	0.83	0.87				
		3	5	110		10	1,186	Norm	77%	0.80	0.83				
		3	6	132		11	1,141	Norm	76%	0.77	0.80				
		2	8	168		12	1,098	Norm	74%	0.74	0.77				
		2	9	189		13	1,059	Norm	72%	0.71	0.74				
		2	10	210		14	1,023	Norm	71%	0.69	0.71				
Shortest Durations		Best # Zones	Takt Time	Duration		15	989	Norm	69%	0.67	0.69				
		8	2	54		16	957	Norm	68%	0.65	0.67				
		5	3	72		17	927	Norm	67%	0.63	0.65				
		4	4	92		18	899	Norm	65%	0.61	0.63				
		3	5	110		19	872	Norm	64%	0.59	0.61				
		3	6	132		20	847	Norm	63%	0.57	0.59				
		2	8	168		21	824	Norm	62%	0.56	0.57				
		2	9	189		22	801	Norm	61%	0.54	0.56				
		2	10	210											

Fig. 6.17. Takt calculator's initial results (Schroeder 2024)

Considering the initial Takt components for the example, the realized flow potential is below the 35%-50% range for the macro level, necessitating adjustments. As illustrated in Fig. 6.17, an option with 5 Takt zones could be more aligned, as it has a realized flow potential of 47%. Given the Takt components of this scenario, it is essential to re-package the identified activities using pull planning and last planners into 5 zones. Consequently, there will be, for example, 15 Takt wagons. Thus, the finalized Takt components for a macro Takt level are as follows:

- Takt zones: 5
- Takt wagons: 15
- Takt time: 5

Fig. 6.18 illustrates the macro Takt plan for a phase of the example.

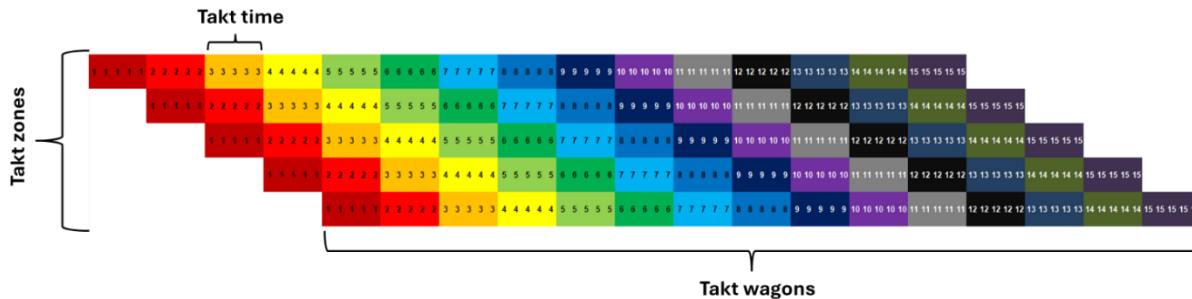


Fig. 6.18. An example of macro Takt plan for a phase

After adjusting the correct Takt components for the macro level, it is time to determine the new zone count and Takt time for the norm level. As shown in Fig. 6.19, the adjusted calculations of Takt components suggest that the strategy for the norm level could consist of 11 zones. Even though this is a solid plan, the team still has the option to use 9 or 13 zones as backup strategies if needed. Thus, the finalized Takt components for a norm Takt level of an example phase are as follows:

- Takt zones: 11
- Takt wagons: 15
- Takt time: 3

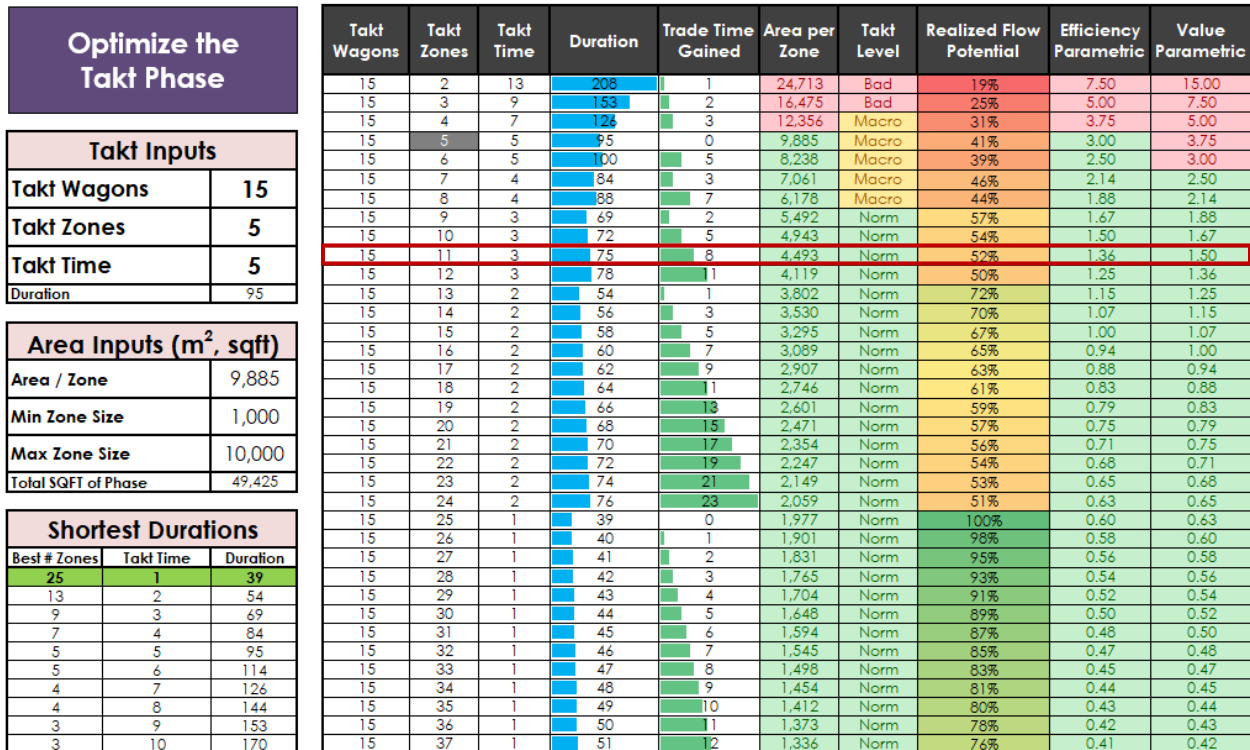


Fig. 6.19. Adjusted calculations for macro and norm Takt levels (Schroeder 2024)

Fig. 6.20 indicates the norm Takt plan for a phase.

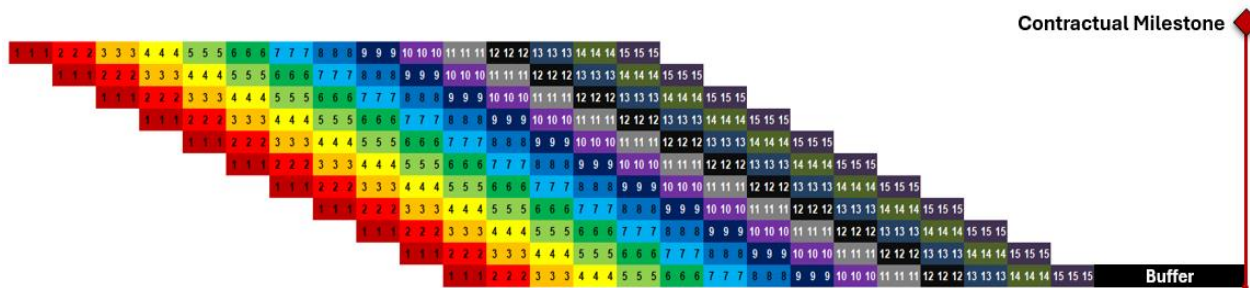


Fig. 6.20. An example of norm Takt plan for a phase

The difference between these two zoning strategies for the same phase is presented above. The

first plan, the macro level, displays the committed end date as specified in the contract and promised to the owner. The second plan, the optimized norm strategy, incorporates gained buffers. Essentially, they represent the same plan executed at two different speeds. The distinction lies in the zoning: the macro level is the commitment made to the owner, whereas the norm level represents the internal target.

It is suggested to consider specific color palettes for each phase and provide legends that include work packages and color palettes for each phase. This approach ensures clear visual communication and helps stakeholders easily identify and differentiate between phases and their respective work packages. By using distinct color coding, project plans become more intuitive and easier to follow, enhancing overall project management and coordination. Fig. 6.21 illustrates an example of a legend for an interior phase with 22 Takt wagons.

INTERIORS LEGEND	
1	Wall Layout + Top Track
2	Fire Sprinkler + Priority Walls
3	OH Ductwork
4	OH Branch Conduits and Lighting
5	OH Mechanical Piping
6	OH Electrical
7	Wall Framing
8	In wall Rough-in
9	Soffits + Ceilings
10	Soffit & Ceiling Rough
11	Drywall
12	Taping
13	Prime + First Coat
14	Data Cabling
15	Ceiling Grid
16	Casework + Doors
17	MEP Trim / Light and Devices
18	Flooring + Baseboards
19	Final Paint
20	Final Accessories
21	Pre-Punch & Clean
22	Punchlist

Fig. 6.21. An example of a provided legend for a phase (Schroeder 2024)

Once the macro and norm levels are completed, it's time to perform a risk analysis for each zone. To do risk analysis:

1. **Identify Risks:** List all possible risks for each zone collaboratively.
2. **Assess Impact:** Determine how each risk could affect the project.
3. **Evaluate Likelihood:** Estimate the probability of each risk happening.
4. **Prioritize Risks:** Rank the risks based on their impact and likelihood.
5. **Plan Mitigation:** Develop strategies to reduce or manage the most significant risks.
6. **Monitor and Review:** Continuously monitor the risks and adjust plans as necessary.

A table similar to the one in Fig. 6.22 can serve as an easy-to-use template for identifying and analyzing risks.


 RISK IDENTIFICATION AND ANALYSIS											
Project information		Risk Identification					Risk Analysis and Response				Comment
Project:	Project manager:	Phase	Zone	Affected activity	Responsible trade partner(s)	Date added	Likelihood (%)	Impact (days)	Priority (Likelihood * Impact)	Mitigation strategy	
Location:	Produced by:										
Date:	Produced at:										
ID	Identified risk										
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											

Fig. 6.22. A template for risk management

Risk analysis results can be effectively translated into buffers and applied to both macro and norm Takt plans. By identifying potential risks and their impacts, appropriate buffer times can be incorporated to mitigate these risks. In a macro Takt plan, these buffers help absorb variations and uncertainties at a broader project level, ensuring smoother overall progress. For a norm Takt plan, buffers can be fine-tuned to address more specific, localized risks, thereby maintaining the flow of individual tasks. This integration of risk analysis into buffer planning enhances the resilience and reliability of both Takt plan levels, promoting more efficient and predictable project execution (Dlouhy et al. 2019). After analyzing the risks for each phase, the largest identified risk becomes the buffer count. To allocate buffers effectively, 50%-75% of the buffer is assigned to the end of the phase, known as the end buffer, while 25%-50% is distributed within the phase itself. Another type of buffer is the Takt time buffer, which can pause the work of the entire train in a phase, accommodating interruptions such as holidays, weather days, and project closures. The third type is the Takt wagon buffer, a small buffer included within the wagons of the sequence. Packaging these accumulated buffers into a standard sequence is advisable, ensuring they make up between 5%-20% of the overall sequence duration (Schroeder et al. 2023). Fig. 6.23 depicts an example of a macro-level Takt plan for the interior phase, including buffers.

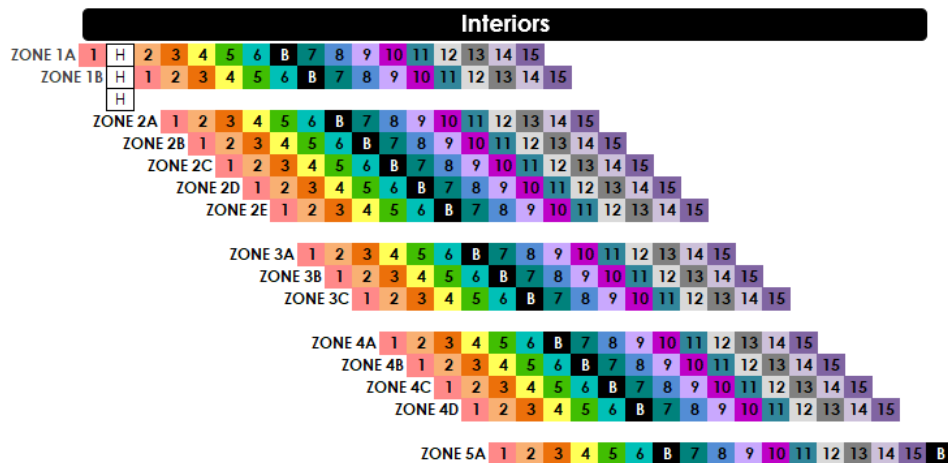


Fig. 6.23. A buffer included macro-level Takt plan (Schroeder 2024)

After incorporating buffers into the Takt plans, it's crucial to assess their health. To do this, the following metrics provided by Schroeder et al. (2023) can be used. If these metrics are not met, the Takt plans need to be readjusted:

1. **Value Parametric:** This metric divides the utilized Takts by the empty Takts in a Takt plan. It tracks the value provided in the workflow, ideally ranging from 0.5 to 2.5. Maintaining this range ensures the Takt plan is structured to maximize value.

$$VP = \frac{Takt\ wagons}{Takt\ zones - 1}$$

2. **Efficiency Parametric:** This metric compares the number of Takt wagons to Takt sequences, aiming for a ratio of 0.3 to 3.0. It ensures that Takt sequences are optimally structured for efficiency.

$$EP = \frac{Takt\ wagons}{Takt\ zones}$$

3. **Stability Parametric:** This metric measures the ratio of train buffers to end buffers, with an ideal range of 0.5 to 2.0. It ensures the Takt plan remains stable with a proper buffer ratio.

$$SP = \frac{Train\ buffers}{End\ buffers}$$

If the Takt plan fails to meet these metrics, adjustments are necessary to ensure the plan is balanced, efficient and maximizes value.

The next step in building the Takt plan is to network the phases together. These phases are designed to accommodate distinct flows of work within the project, such as site work, structural work, exteriors, interiors, finishes, and more. Each phase includes its own unique set of zones, takt periods, and tasks. Once each phase is constructed, it is essential to establish logical connections between them to create a cohesive project plan. This ensures a smooth transition from one phase to the next. For instance, in Fig. 6.24, multiple phases are interconnected with logical ties, demonstrating how integrated planning supports seamless project progress.

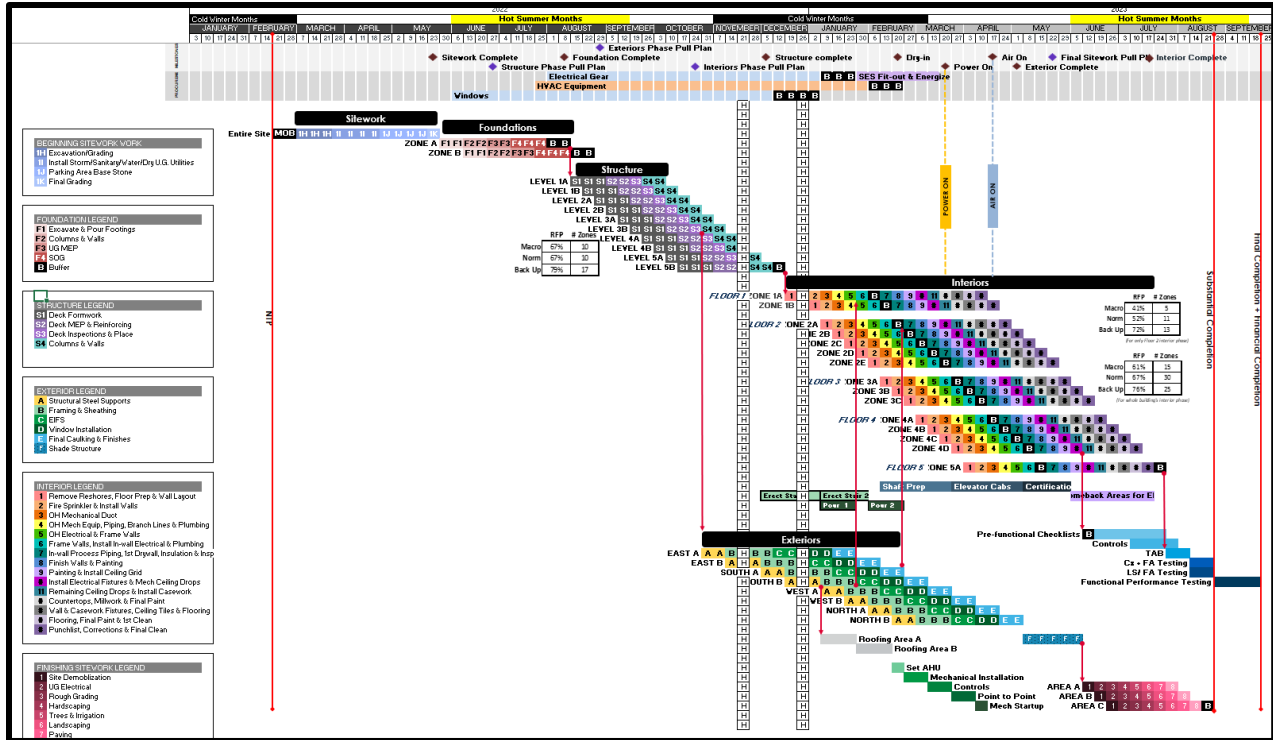


Fig. 6.24. An example of a full macro-level Takt plan (Schroeder 2024)

Since the norm-level Takt plan is the production target, it's time to adjust the overall flow and work density analysis, considering the Takt zones determined by the final calculated Takt components for this level. In the given example, there are 11 zones to implement the norm-level Takt plan. With this number of zones, it is essential to finalize the work density analysis to ensure that each zone has a balanced workload. To achieve this, the zone boundaries need to be adjusted to create 11 balanced zones, as shown in Fig. 6.25. By doing so, the crews will encounter a consistent amount of work in each zone, promoting efficiency and smooth operation throughout the project.

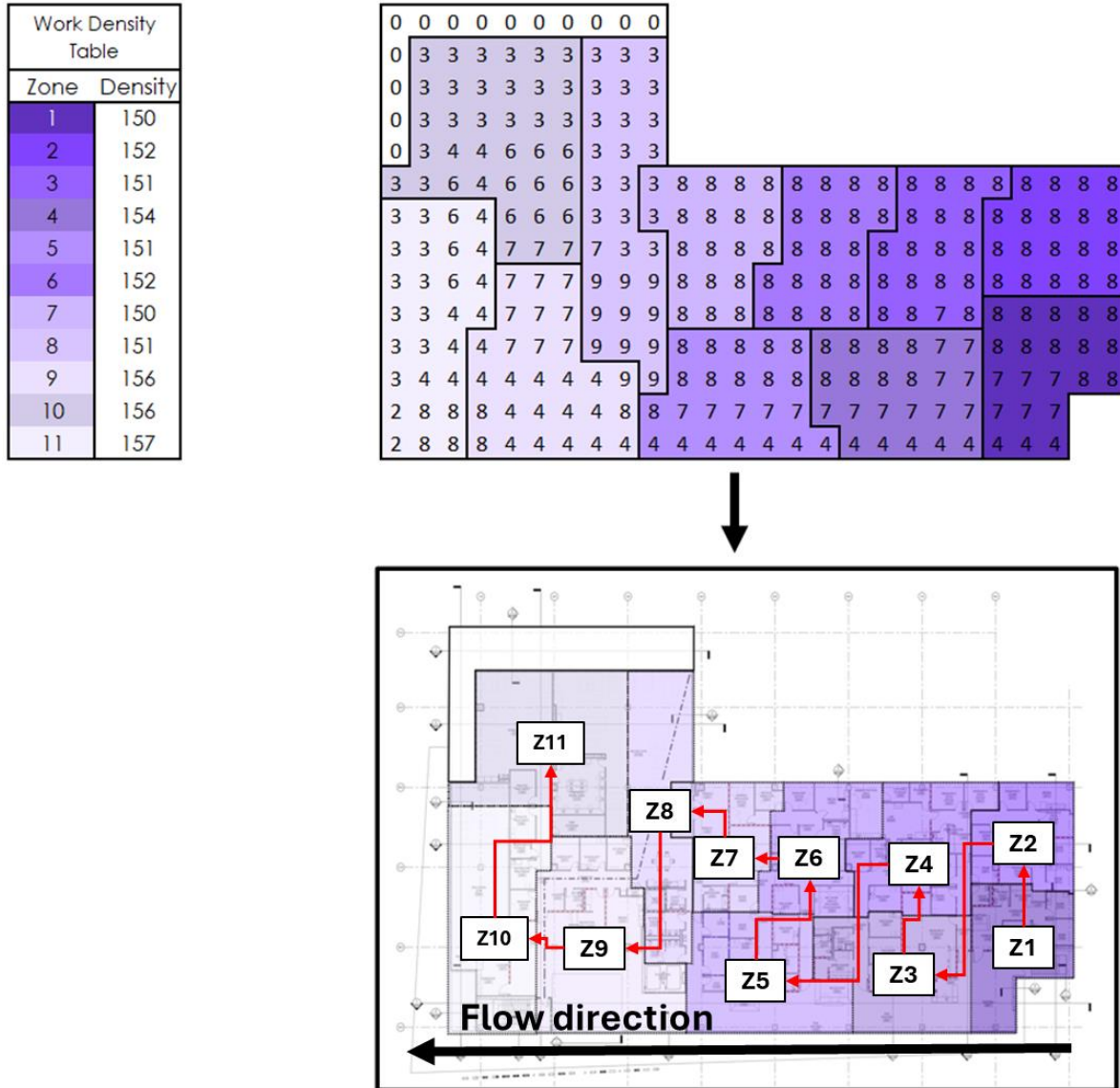


Fig. 6.25. Adjusted work density analysis based on 11 zones (Schroeder 2024)

By visualizing the schedule plan through 4D BIM, stakeholders can better understand it and analyze constraints. The next step is to create a location-based 4D BIM. For this phase, it's recommended to use locations based on macro Takt zones to group the elements of the 3D model. At this stage, a federated 3D model integrating models from all disciplines with a Level of Development (LOD) 300 can be utilized. All necessary information for creating the 4D model should be taken from the BIM Execution Plan (BEP) during the development of 3D models and the preparation of Takt wagons for linking to the 3D model.

A common challenge with 4D BIM is the mismatch in detail between the activity-based schedule plan and the component-based 3D model. To address this, if a specific task in the schedule is not directly associated with an object in the 3D model, the activity or task can be linked to its relevant location or zone. This approach ensures a more coherent and practical integration of the schedule with the 3D model, enhancing the overall utility and impact of 4D BIM in project management.

Rather than having the BIM manager or coordinator and the project planner independently create the 4D BIM model using standalone software solutions, it is advisable to utilize a touch-based wall or table screen to facilitate the collaborative creation of the 4D BIM model by involving the last planners in the process (Sheikhkhoshkar et al. 2024b). By collaborating during the 4D BIM model's development, bottlenecks, constraints, and issues can be identified more effectively. Fig. 6.26 shows the process of creating a 4D phase schedule model in detail.

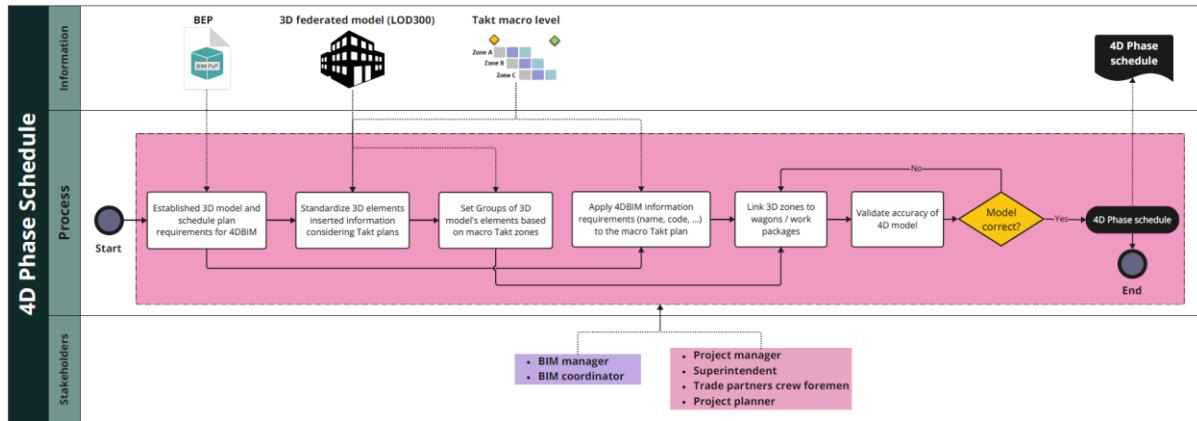


Fig. 6.26. The 4DBIM developing process for phase scheduling

Considering the norm and macro Takt plans, as well as the 4D BIM phase schedule model, it is essential to identify and document the overarching constraints for each zone at this stage by involving both the last planners and the first planners. To facilitate this process, a sample format for constraint logs has been provided and illustrated in Fig. 6.27.


Project information		Roadblock Tracking and Removal Log													
Project:															
Location:															
Date:															
No.	Roadblock / constraint	Trade partner	Zone	Date added	Affected activity	Date resolved	Process time	Constraint Log Categories							Necessary actions
								Previous activities	Materials	Crew	Equipment	Information	Space	External conditions	
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															

Fig. 6.27. A template for constraints logs

In the context of phase scheduling, developing a procurement plan could be crucial. At this phase, a well-crafted procurement plan ensures that all necessary materials and resources are readily identifiable in the look-ahead plan and available when needed, thereby preventing delays and disruptions. This proactive strategy facilitates the early detection of potential supply chain issues and the implementation of mitigation strategies. By synchronizing the procurement schedule with the phase schedule, the project can sustain a consistent workflow, optimize resource allocation, and adhere to the overall project timeline. Therefore, it is beneficial to involve all stakeholders, particularly potential suppliers, in the preparation of the procurement plan during

this phase. To aid in this process, a template for procurement logs, as illustrated in Fig. 6.28, provides clarity and documents the necessary steps. This template will assist in tracking items and analyzing related constraints within the look-ahead plan more efficiently.


Project information					Procurement Tracking																	
Project:		Project manager:																				
Location:		Produced by:																				
Date:		Produced at:																				
ub. No	Description	Affected activity	Scope of work	Takt zone	Trade partner	Material Submittal Date		Material Approval Date		Purchase Order Issued		Supplier Name	Delivery Period	Manufacture Started		Shipment Date		Clearance		Delivery to Site / Store		Remarks
						Required	Forecast/ Actual	Required	Forecast/ Actual	Required	Forecast/ Actual			Required	Forecast/ Actual	Required	Forecast/ Actual	Required	Forecast/ Actual	Required	Forecast/ Actual	
1																						
2																						
3																						
4																						
5																						
6																						
7																						
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9																						
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15																						

Fig. 6.28. A template for procurement logs

6.3.2.3. Look-ahead Planning

Lookahead planning serves as the first step in production planning, creating a vital connection between the overall project schedule and short-term commitments (Hamzeh 2009b). This process begins by developing a lookahead perspective, typically spanning 4-8 weeks, with a stronger emphasis on a 6-week timeframe, as most references suggest. In the integrated planning and control system outlined in this guideline, it is recommended to generate a 6-week look-ahead view from the norm Takt plan developed during phase scheduling. This view then progresses into the detailed planning of weekly work tasks.

The creation of a look-ahead plan entails multiple steps, incorporates various information sources, and engages key stakeholders, as shown in Fig. 6.29 and elaborated upon in the following sections.

After generating a 6-week look-ahead plan from the phase schedule, tasks should be broken down to the process and operation levels. Anticipate and further decompose tasks as needed using pull planning, involving both the first and last planners in the process. Fig. 6.30 displays a six-week lookahead process, detailing its progression from six weeks before execution up to the week of execution (Hamzeh et al. 2008).

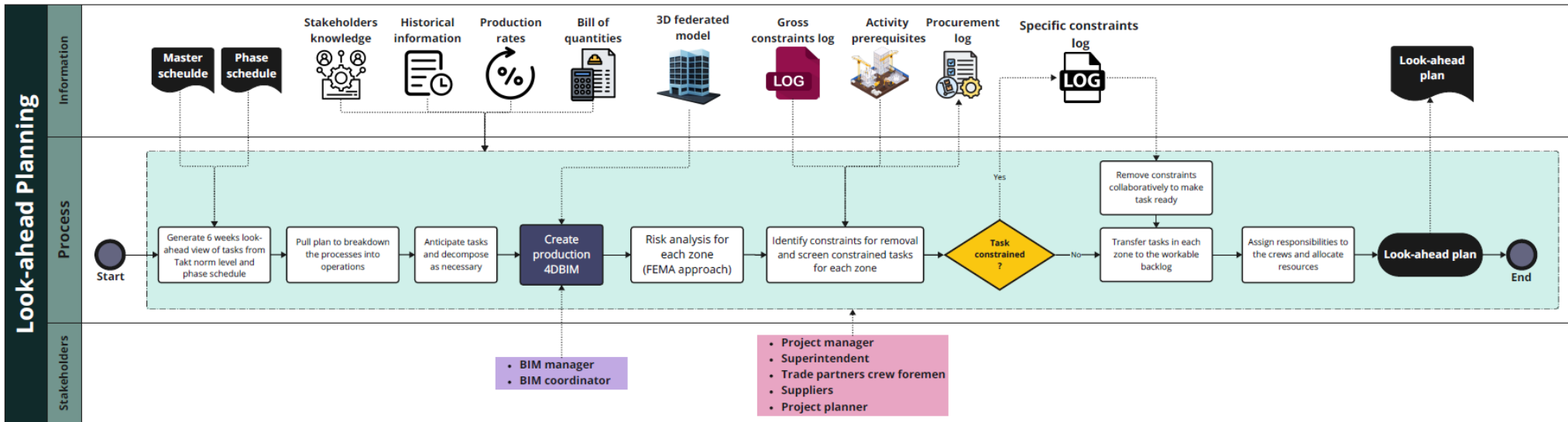


Fig. 6.29. The look-ahead planning process in the multi-level and integrated system

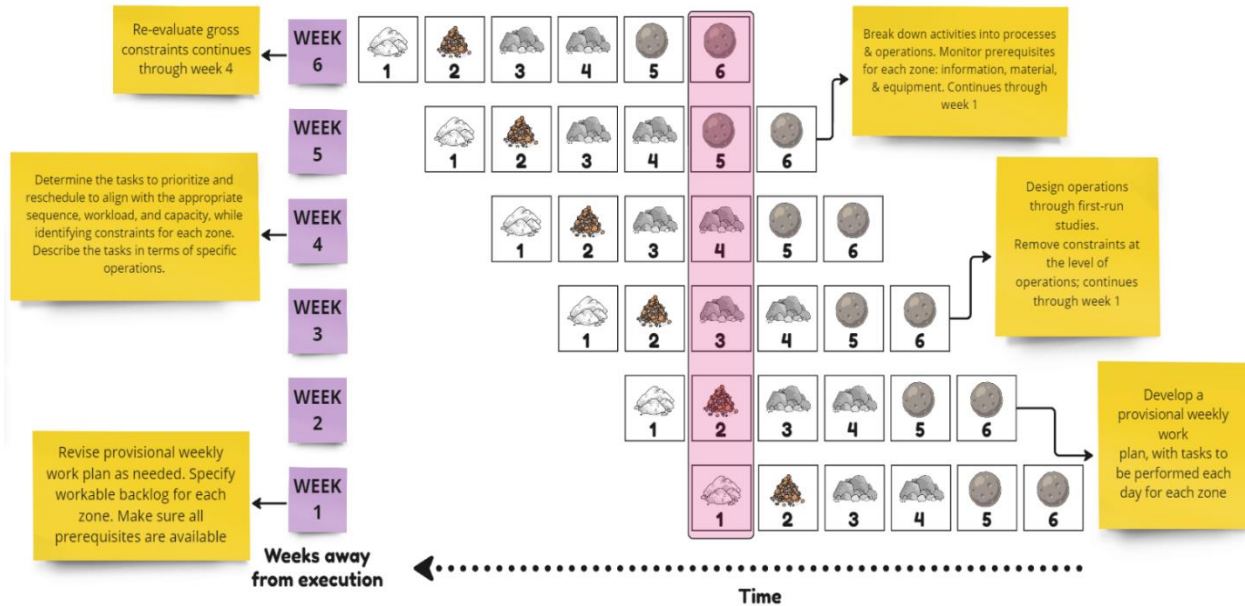


Fig. 6.30. Six-week lookahead planning process (Hamzeh et al. 2008)

Lookahead planning begins by filtering a schedule that projects several weeks into the future, typically spanning six weeks. The details of the six-week look-ahead planning process are as follows (Hamzeh 2009b; Hamzeh et al. 2008):

Six Weeks Ahead of Execution: At this stage, tasks enter the six-week lookahead plan from the phase schedule. The primary focus is on identifying and devising plans to remove gross constraints, which affect all instances of phase-level tasks and processes. For example, in construction, typical gross constraints include materials and design information. Removing these constraints should ideally occur two to three weeks before task execution.

Five to Four Weeks Ahead of Execution: During this period, tasks are broken down into their elemental components, moving from broader processes to specific operations. This involves defining operations, sequencing work optimally, coordinating tasks among stakeholders, allocating resources, matching load to capacity, and ensuring that prerequisite inputs such as materials and labor are ready.

Three Weeks Ahead of Execution: Operations are designed through first-run studies, which involve operating for the first time to study and improve the execution method. Detailed plans for work execution are developed, and tasks that cannot be made ready in time are screened out. This stage is crucial for refining plans and establishing standardized work for new, critical, or repetitive operations.

Two Weeks Ahead of Execution: As tasks move closer to execution, they are broken down and detailed to match the level required for production at the weekly work plan level. This involves planning at finer time intervals, such as daily or hourly planning for specific operations. Constraint-free tasks join the workable backlog and may be selected for the weekly work plan if they meet quality criteria.

One Week Ahead of Execution: A provisional weekly work plan is prepared, evaluating tasks

against criteria of definition, soundness, sequence, size, and learning. Tasks that are critical, ready or can be made ready in the upcoming week are incorporated into the weekly work plan. Tasks that are made ready but not critical are placed on the fallback or follow-on work list to be performed if extra capacity is available.

It should be noted that, since the norm level Takt plan is incorporated into the look-ahead plan in this guideline, all the processes and activities necessary for formulating the look-ahead plan must be carried out within each norm Takt plan's designated zone.

Incorporating 4DBIM in Look-ahead Process

Developing a production 4D BIM that incorporates a look-ahead view will significantly aid the project team in identifying and eliminating constraints more efficiently. Achieving this requires a federated 3D model with a high Level of Detail (LOD), specifically between LOD 300 and 350, to meet the scheduling requirements. Additionally, the 3D model elements should be grouped according to the zones defined by the norm Takt level. The process, required information and stakeholders for creating a 4D look-ahead plan is depicted in Fig. 6.31. Similar to the 4D phase schedule, it is recommended to employ a touch-based wall or table screen to enhance the collaborative development of the 4D look-ahead model, involving the last planners in the process.

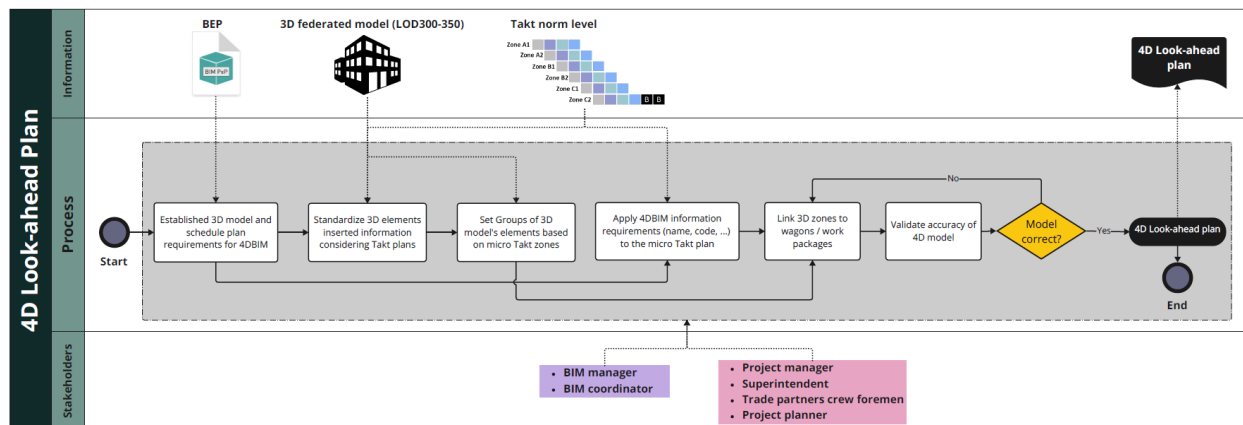


Fig. 6.31. The process of building 4D look-ahead plan

The primary goal of the look-ahead plan is to ensure that tasks are ready for execution as scheduled and to avoid committing to tasks that cannot be made ready. Achieving this requires identifying and addressing the constraints and risks associated with each task (Ballard and Tommelein 2021). As a result, in the next step, it is crucial to perform a thorough constraint and risk analysis collaboratively.

Risk Analysis

Failure Mode and Effects Analysis (FMEA) could be a highly effective approach for risk analysis in construction activities. FMEA is a systematic method designed to identify potential failure modes within a process, evaluate the effects of these failures, and prioritize actions to mitigate associated risks.

To apply FMEA in construction risk analysis, follow these steps:

1. **Identify Failure Modes:** Determine all the possible ways in which construction activities might fail, such as delays, safety hazards, or quality issues.
2. **Evaluate Effects:** Analyze the consequences of each failure mode on the construction project, considering impacts on schedule, cost, safety, and quality.
3. **Assess Causes:** Identify the root causes of each failure mode, such as resource shortages, design flaws, or environmental factors.
4. **Prioritize Risks:** Assign a risk priority number (RPN) to each failure mode. The RPN is calculated as the product of the severity, likelihood of occurrence, and ability to detect the issue before it causes problems.

($RPN = Severity \times Likelihood\ of\ Occurrence \times Ability\ to\ Detect$).
5. **Develop Action Plans:** Create and implement strategies to reduce or eliminate the most critical risks, focusing on those with the highest RPNs.
6. **Review and Update:** Continuously review and update the FMEA to ensure it remains relevant and effective as construction activities progress and new risks emerge.

For more detailed information on integrating this method into the look-ahead plan, refer to the study conducted by Wehbe and Hamzeh (2013).

Constraint Analysis

Constraint analysis during look-ahead planning involves identifying and addressing limitations or restrictions that prevent activities from being executed as planned. These constraints are either removed by securing commitments from team members or documented in a constraint log until they are addressed. Fig. 6.27 provides a template for documenting, managing and tracking these constraints.

A constraint is any limitation or prerequisite that must be met before or during an activity's execution. As illustrated in Fig. 6.32, constraints can include prerequisites such as prior work, necessary information, equipment, materials, human resources, funding, and conditions (e.g., weather and safety). Additionally, procurement and gross constraint logs from phase scheduling should be reviewed to identify and address specific constraints at the look-ahead planning level. To manage these constraints, make-ready actions are assigned to team members responsible for removing them. These actions are then incorporated into the current or future weekly work plans. A constraint remains in the log until a team member commits to resolving it. Once a team member commits to the make-ready task, they are assigned the necessary actions to remove the constraint, ensuring that activities can proceed as scheduled.

6.3.2.4. Weekly Work and Daily Planning

In the last planner system (LPS), weekly work planning extends lookahead planning into the immediate execution week. This phase represents the most detailed and actionable level of planning within LPS, directly guiding production activities. At this stage, promises and commitments are made by team members to complete specific tasks (Ballard and Tommelein 2021). The procedure involved in formulating weekly work and daily plans is revealed in Fig. 6.34. This process encompasses various stages, and information sources, and involves crucial stakeholders. The subsequent section provides a detailed exploration of these aspects.

As shown in Fig. 6.34, weekly work planning begins by advancing tasks that are already constraint-free and those that can be made ready within the week, ensuring that necessary predecessors are completed to avoid work delays. Tasks are prioritized based on capacity and readiness, with priority given to constraint-free critical tasks, followed by critical tasks that can be made ready during the week. Critical tasks that cannot be made ready are screened out to prevent executing unready tasks and will be re-evaluated in upcoming weeks for constraint removal. Non-critical tasks that are not ready are also screened out, while constraint-free critical tasks are placed on the fallback list to be executed when extra capacity is available. Only tasks that meet quality assignment criteria are advanced. These criteria include:

1. **Definition:** The task must have a clear and precise scope and desired outcomes, ensuring that everyone involved understands what is required.
2. **Soundness:** The planned tasks should be free from constraints or have constraints that can be removed during the plan period.
3. **Sequence:** Tasks must be arranged in the proper order to avoid out-of-sequence work, ensuring logical and efficient workflow.
4. **Size:** The workload must match the capacity of individuals, sub-teams, or work groups to prevent overloading and ensure efficient use of resources.
5. **Learning:** There must be mechanisms for continuous improvement through root cause analysis and the Plan-Do-Check-Act (PDCA) cycle, allowing the team to learn from past experiences and improve future performance.

The weekly work plan is discussed, coordinated, and finalized during a collaborative meeting involving all project stakeholders. Last planners, responsible for production teams, discuss constrained tasks, request the removal of constraints, and ensure tasks are ready by resolving any issues, and making quality commitments to the next week's tasks. Daily planning further breaks down the weekly plan into detailed daily schedules, ensuring alignment with the planned sequence and efficient task execution, reflecting progress, and adjusting for any unexpected issues or delays to keep production on track and meet quality criteria (Hamzeh 2009b).

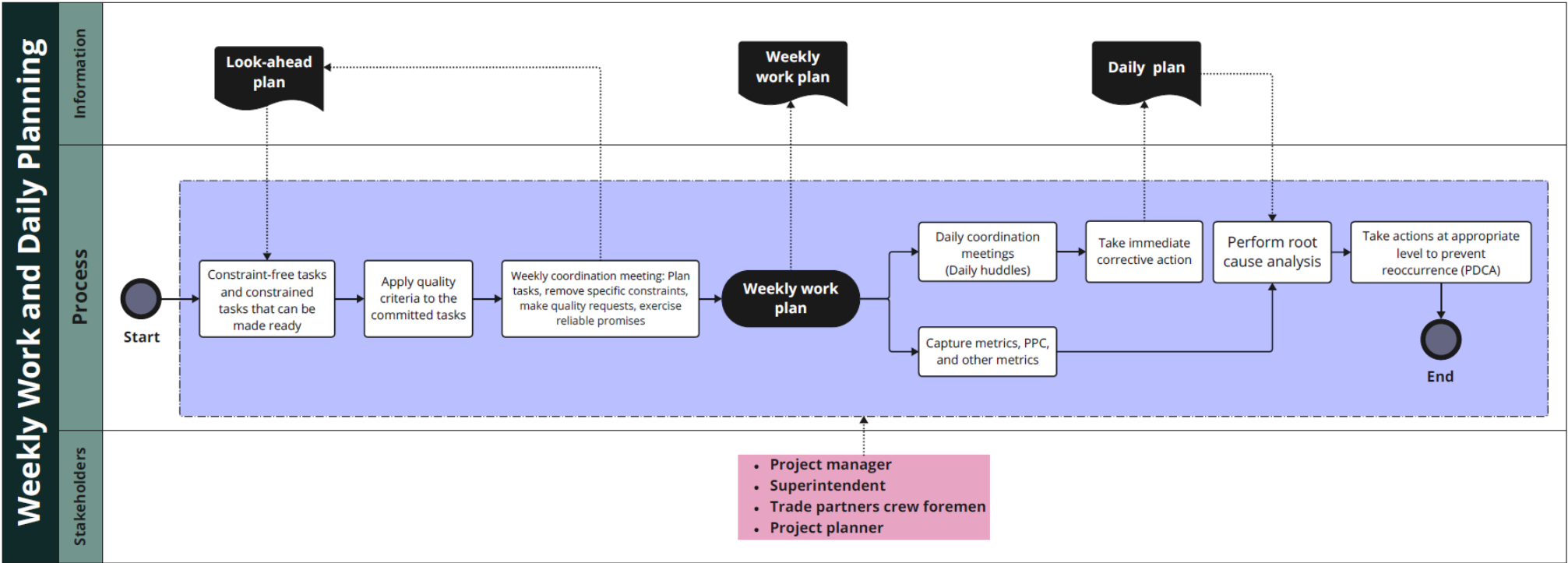


Fig. 6.34. The weekly work and daily planning process in the multi-level and integrated system

Percent Plan Complete (PPC) serves as a metric for evaluating the effectiveness of weekly work planning and the reliability of commitments made. Weekly, PPC is determined by comparing the number of completed assignments to those planned. Instances where tasks are not completed prompt an analysis of the reasons for plan deviations, which in turn serves as a foundation for learning and continuous improvement.

The daily planning procedure, as depicted in Fig. 6.34, begins with the formulation of a daily plan considering the Weekly Work Plan (WWP). This plan is discussed during daily coordination meetings, also known as daily huddles, where team members review the day's tasks and address any immediate issues. If any problems arise, immediate corrective action is taken to ensure work proceeds smoothly. Following daily plan issues and PPC assessment, a root cause analysis is performed to understand the underlying reasons for any issues encountered. This analysis helps in developing strategies to prevent recurrence. Actions are then taken at the appropriate level to implement these strategies, adhering to the Plan-Do-Check-Act (PDCA) cycle for continuous improvement. This iterative process ensures that daily activities are aligned with overall project goals and are continuously optimized for efficiency and quality. For more clarification, the weekly work planning cycle is revealed in Fig. 6.35.

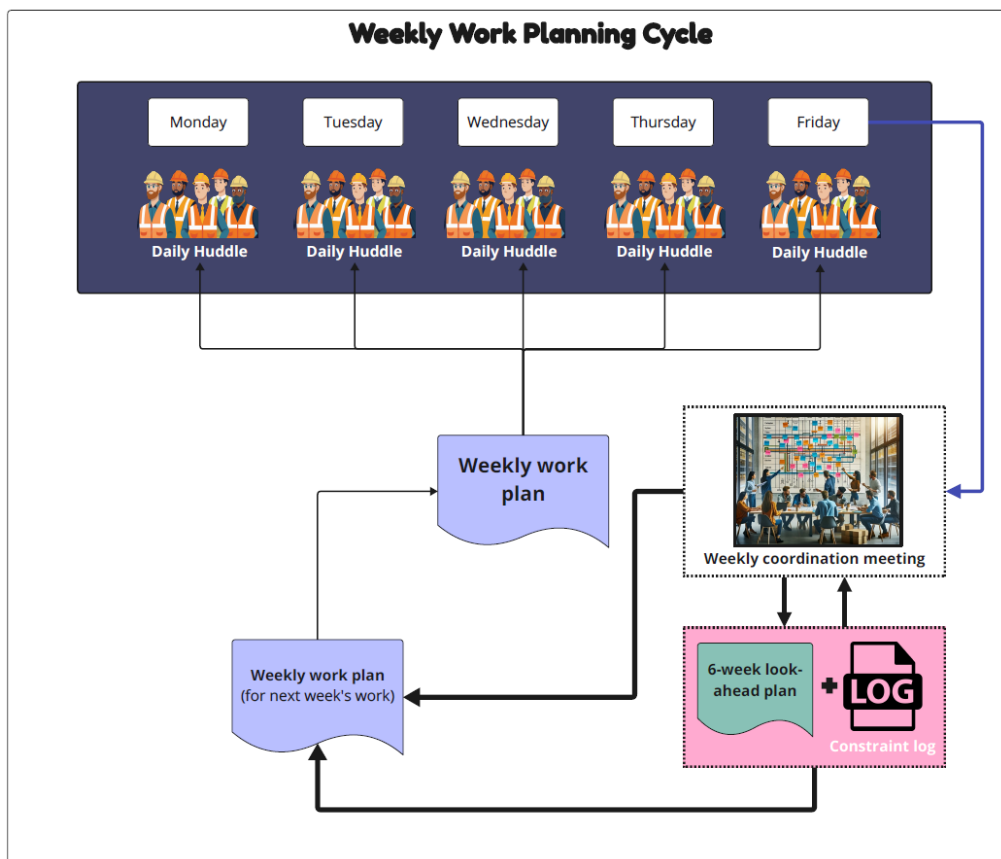


Fig. 6.35. Weekly work planning cycle

Daily Huddles:

A daily huddle is a tool used by successful organizations across various industries, including construction projects. It's a simple yet effective strategy for transforming a group of individuals into a cohesive team. The daily huddle is a quick, 15-minute meeting that kicks off the day, where everyone catches up on the project's status, the day's top priorities, safety, and any roadblocks, and shares crucial information related to the weekly work plan. By the end of the huddle, everyone knows the overall status, priorities, and their individual contributions for the next 24 hours. If someone is stuck, they can share that and get help. This practice builds transparency and accountability (Donarumo and Zandy 2019; Wandahl et al. 2023). Fig. 6.36 shows an example of a typical daily huddle in a construction site.



Fig. 6.36. A typical daily huddle

Holding a daily huddle is a skill that improves with practice. By following some best practices, you can quickly start leveraging them to build reliable plans and a strong project culture day by day. **The logistics of the huddle** include ensuring attendance by everyone who owns a deliverable in the weekly work plan, holding the meeting at the same time and place every day, and using a location equipped with necessary materials like a Kanban board or whiteboard.

Preparation involves knowing what the team is working on for the week and ensuring tasks are ready and constraint-free. The goals of the huddle are to stay on plan, discuss safety, connect dots, and provide a platform for raising issues. Each team member should know their role, and the project leader should keep the meeting productive, spot issues, and ensure everyone speaks and feels heard.

During the meeting, stick to an agenda that starts with covering the plan, safety, or metrics on a team level, followed by individual updates on victories, priorities, and constraints. Trade leaders should routinely answer questions about *their work, crew numbers, constraints, material deliveries, and safety concerns*. This consistent daily meeting allows for effective coordination and collaboration, preventing issues from halting progress and setting everyone up to win the day. This straightforward system is crucial for project risk management and can save hours of confusion and ad-hoc communications throughout the day (Donarumo and Zandy 2019).

6.3.2.5. Control framework

Project control is essential for ensuring that a project stays on track, within budget, and meets its objectives. It involves continuous monitoring and adjusting of project activities to address any deviations from the plan, thereby minimizing risks and ensuring timely delivery. To enhance the quality of the schedule at various levels and to effectively track and monitor different project aspects, this guideline incorporates an improved version of the diagnostic/control framework proposed by Hamzeh et al. (2019b). Fig. 6.37 presents this framework along with the control metrics at different levels of the system. The following section provides an in-depth discussion of the framework, offering detailed insights into its application for maintaining the integrity of the project schedule.

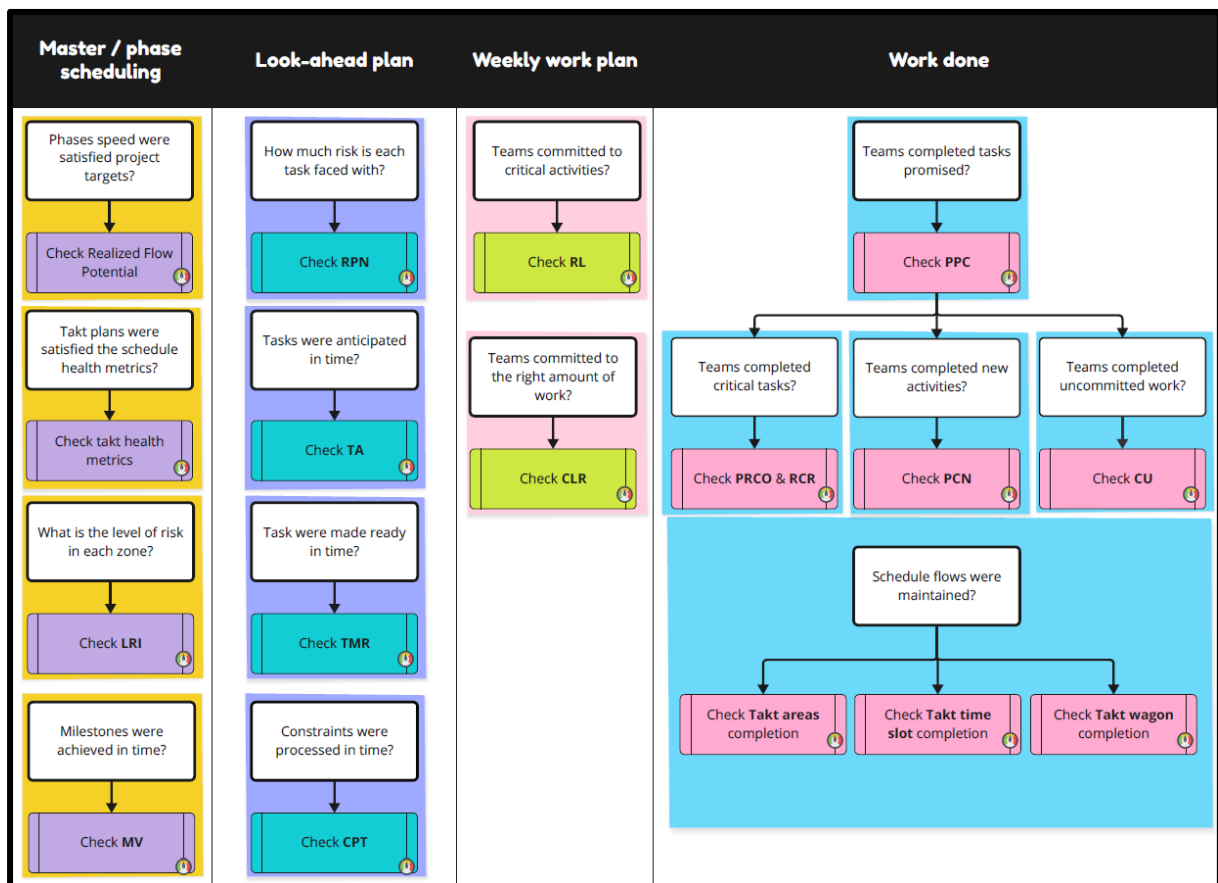


Fig. 6.37. Recommended diagnosis/control framework

Details of the provided control metrics in the framework

1. Master/Phase Scheduling:

Realized Flow Potential (RFP)

- *Definition:* RFP assesses whether the current flow of a Takt train meets the fastest possible flow targets.
- *Purpose:* It evaluates the efficiency and speed of the project phase.
- *Project Aspect Monitored:* Project phase speed and efficiency.
- *Type of metric:* Leading (proactive)

- Formula:

$$RFP = \frac{\text{Phase duration based on the calculated Takt components}}{\text{Phase duration based on one day Takt time (fastest possible flow)}}$$

- **Ideal Range: 35%-50% for macro level and 50%-100% for norm level**

✚ **Takt Health Metrics**

- *Definition:* These metrics evaluate the value, efficiency, and stability of the Takt plans
- *Purpose:* To ensure the plan is balanced, efficient, and maximizes value.
- *Project Aspect Monitored:* Takt plans health.
- *Type of metric:* Leading (proactive)
- *Formula:*

$$\text{Value Parametric} = \frac{\text{Takt wagons}}{\text{Takt zones} - 1}$$

- **Ideal Range: 0.5 to 2.5**

$$\text{Efficiency Parametric} = \frac{\text{Takt wagons}}{\text{Takt zones}}$$

- **Ideal Range: 0.3 to 3.0**

$$\text{Stability Parametric} = \frac{\text{Train buffers}}{\text{End buffers}}$$

- **Ideal Range: 0.5 to 2.0**

✚ **Location Risk Index (LRI)**

- *Definition:* LRI measures the risk level in different project zones.
- *Purpose:* It helps in identifying high-risk areas that may require additional attention or resources.
- *Project Aspect Monitored:* Risk management across different zones.
- *Type of metric:* Leading (proactive)
- *Formula:*

$$LRI^Z = \sum_{r=1}^n (\text{Probability of Risk} \times \text{Impact of Risk})$$

where:

- *Probability of Risk:* The likelihood that a specific risk r will occur.
- *Impact of Risk:* The potential consequence or impact if the specific risk r occurs.
- Z : Each specific zone under consideration.
- r : Each risk identified within the zone.
- n : The total number of risks identified in zone Z .

✚ **Milestone Variance (MV)**

- *Definition:* MV measures the difference in days between the forecasted date to complete all remaining activities and the required date of the milestone.
- *Purpose:* It monitors the adherence to the project timeline and milestone targets.
- *Project Aspect Monitored:* Milestone achievement.
- *Type of metric:* Leading (proactive)
- *Formula:*

$$MV = \text{Forecasted Completion Date} - \text{Required Milestone Date}$$

2. Look-Ahead Plan:

Risk Priority Number (RPN)

- *Definition:* RPN evaluates the level of risk each task is faced with.
- *Purpose:* To prioritize tasks based on their risk level, considering severity, likelihood, and detection ability.
- *Project Aspect Monitored:* Risk prioritization for individual tasks.
- *Type of metric:* Leading (proactive)
- *Formula:*

$$RPN = \text{Severity} \times \text{Likelihood of Occurrence} \times \text{Ability to Detect}$$

Task Anticipated (TA)

- *Definition:* TA measures the percentage of tasks on the weekly work plan that were anticipated in the look-ahead stage.
- *Purpose:* It evaluates the foresight and planning accuracy in predicting future tasks.
- *Project Aspect Monitored:* Planning accuracy and foresight.
- *Type of metric:* Leading (proactive)
- *Formula:*

$$TA = \frac{\text{Anticipated Tasks}}{\text{Total tasks on WWP}}$$

Tasks Made Ready (TMR)

- *Definition:* TMR indicates the proportion of tasks that were made ready out of the total tasks that could potentially be made ready.
- *Purpose:* It assesses the performance of the lookahead planning in identifying and removing the different types of Constraints
- *Project Aspect Monitored:* performance of the lookahead plan.
- *Type of metric:* Lagging (reactive)
- *Formula:*

$$TMR = \frac{\text{Anticipated Tasks completed}}{\text{Total tasks on the WWP}}$$

Constraint Processing Time (CPT)

- *Definition:* CPT measures the average time taken to process constraints.
- *Purpose:* To ensure constraints are identified and resolved promptly.
- *Project Aspect Monitored:* Constraint management efficiency.
- *Type of metric:* Leading (proactive)
- *Formula:*

$$CPT = \text{Planned Removal Date} - \text{Registration Date}$$

3. Weekly Work Plan:

Required Level (RL)

- *Definition:* RL evaluates if teams are committed to critical activities.
- *Purpose:* To help planners determine the criticality level of their committed activities.
- *Project Aspect Monitored:* Criticality level of the weekly work plan.
- *Type of metric:* Leading (proactive)

- *Formula:*

$$RL = \frac{\text{Critical task on the WWP}}{\text{Total tasks on WWP}}$$

Capacity to Load Ratio (CLR)

- *Definition:* CLR measures the relationship between the capacity of a team and the load they are assigned.
- *Purpose:* Aids in tracking how close the team is to adequately utilizing resources.
- *Project Aspect Monitored:* Workload balance and capacity management.
- *Type of metric:* Lagging (reactive)
- *Formula:*

$$CLR = \frac{\text{Total completed tasks (new, and fallback clusters) on the WWP}}{\text{Total tasks on WWP}}$$

4. Work Done:

Percent Plan Complete (PPC)

- *Definition:* PPC measures the percentage of planned tasks that were completed as scheduled within a given period.
- *Purpose:* It assesses the reliability of the planning process and indicates how well the team follows through on its weekly work plans.
- *Project Aspect Monitored:* Planning reliability and execution efficiency.
- *Type of metric:* Lagging (reactive)
- *Formula:*

$$PPC = \frac{\text{Number of tasks completed}}{\text{Number of tasks planned}}$$

Percent Required Complete and Ongoing (PRCO)

- *Definition:* PRCO measures the percentage of required critical tasks that are completed or ongoing and on track.
- *Purpose:* To ensure that critical tasks are being prioritized and completed on schedule.
- *Project Aspect Monitored:* Critical task completion and ongoing task tracking.
- *Type of metric:* Lagging (reactive)
- *Formula:*

$$PRCO = \frac{\text{Completed required tasks} + \text{Ongoing required tasks}}{\text{Total required tasks on the WWP}}$$

Required Capacity Ratio (RCR)

- *Definition:* RCR measures the proportion of required activities that were completed out of the total number of activities executed.
- *Purpose:* To ensure that the required activities are prioritized and completed as planned.
- *Project Aspect Monitored:* Activity prioritization and completion.
- *Type of metric:* Lagging (reactive)
- *Formula:*

$$RCR = \frac{\text{Completed required task}}{\text{Total completed tasks on the WWP}}$$

Percent Complete New (PCN)

- *Definition:* PCN measures the number of new tasks completed with respect to all new tasks committed.
- *Purpose:* To track the completion rate of newly identified tasks.
- *Project Aspect Monitored:* New task completion and adaptability.
- Type of metric: Lagging (reactive)
- *Formula:*

$$PCN = \frac{\text{Completed new tasks}}{\text{Committed new tasks}}$$

Completed Uncommitted (CU)

- *Definition:* CU measures the work performed that was not committed to on the weekly work plan.
- *Purpose:* To assess the extent of unplanned work being executed.
- *Project Aspect Monitored:* Unplanned work and resource allocation efficiency.
- Type of metric: Lagging (reactive)
- *Formula:*

$$CU = \frac{\text{Completed tasks from new and fallback clusters}}{\text{Total completed tasks}}$$

Takt Area Completion

- *Definition:* This metric checks whether tasks within takt areas were completed as planned.
- *Purpose:* To ensure that work within defined takt areas is progressing as scheduled.
- *Project Aspect Monitored:* Takt area progress and completion.
- Type of metric: Lagging (reactive)
- *Formula:*

$$\text{Takt Area Completion} = \frac{\text{Number of wagons completed in each Takt zone}}{\text{Total number of wagons in that Takt zone}}$$

Takt Time Slot Completion

- *Definition:* Evaluates whether tasks scheduled within specific takt time slots were completed on time.
- *Purpose:* To monitor adherence to detailed time slot planning.
- *Project Aspect Monitored:* Time slot adherence and detailed scheduling.
- Type of metric: Lagging (reactive)
- *Formula:*

$$\text{Takt Time Slot Completion} = \frac{\text{Number of wagons completed in each Takt time slot}}{\text{Total number of wagons in that Takt time slot}}$$

Takt Wagon Completion

- *Definition:* Measures the completion of tasks within takt wagons, which are specific work packages.
- *Purpose:* To track the progress and completion of bundled work packages.
- *Project Aspect Monitored:* Work package completion and tracking.
- Type of metric: Lagging (reactive)
- *Formula:*

$$\text{Takt Wagon Completion} = \frac{\text{Number of a specific wagons completed in all Takt zone}}{\text{Total number of that wagon in all Takt zones}}$$

Fig. 6.38 provides a detailed example of the calculation of Takt plan control metrics for further clarification. More information on Takt control can be found in Keskiniva et al. (2021)'s study.

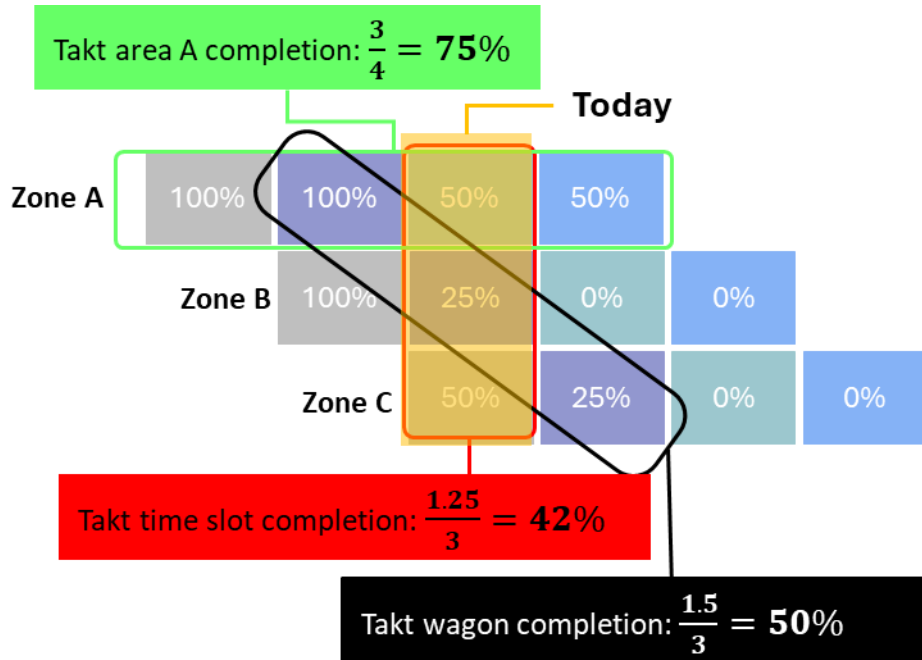


Fig. 6.38. An example of Takt plan control metrics' calculation

Chapter 7. General Conclusion

7.1. Conclusion

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. Moreover, effective management of construction projects is crucial because of their complexity and significant financial implications. In this context, the project planning and control domain plays a vital role in successful project execution, necessitating data-driven and knowledge-based decisions to navigate these complexities and ensure favourable project outcomes. An analysis of the literature and expert feedback reveals a significant gap due to a lack of understanding among project stakeholders about various planning and control methodologies. Furthermore, despite the implementation of various planning and control systems, there remains a substantial gap due to the absence of a data-driven and knowledge-based system that considers the specific needs and applications of the project team, thereby suggesting an optimized solution. To deal with these challenges, this thesis explores the development of an integrated multi-level planning and control system for construction sites, utilizing building information modeling (BIM) and lean construction principles. Employing a design science research methodology as the overarching framework, this study adopts a mixed-methods approach, incorporating systematic literature reviews, document analysis, content analysis, social network analysis (SNA), semantic textual similarity, clustering analysis, expert interviews, rough set theory, and mathematical modelling to meet its objectives.

First, a thorough literature review combined with quantitative SNA was conducted to delineate the existing planning and control systems, clarifying their core concepts. This facilitated a deeper comprehension of the objectives and functionalities essential for project teams. This phase culminated in the identification and analysis of 26 integrated planning methods, 82 control metrics, and 10 process-based and technology-driven collaborative planning techniques, alongside 148 associated objectives termed functionalities of the planning and control systems in this study. Given the breadth of the 148 identified functionalities, a reduction was necessary to distil the essential functional concepts of the planning and control systems. To this end, natural language processing—specifically, semantic textual similarity paired with hierarchical clustering—was deployed as an optimal method for identifying principal functionality concepts and organizing them into a taxonomy across various scheduling levels. This effort resulted in the identification and categorization of 20 key functionality concepts within a taxonomy of project planning and control systems' functionalities. During the subsequent phase of research, one general functionality concept—information-driven decision-making—was excluded to refine the focus further, leaving 19 groups of functionalities as the primary objectives of the planning and control systems. Following the key steps of the design science research method—problem identification, artifact design, development, and validation—semi-structured interviews were conducted

over six months, garnering feedback from ten experts in academia and industry within the project planning and control domains. This comprehensive process led to the development of an integrated multi-level planning and control framework, marking a significant advancement in the field.

Based on the proposed framework and identified functionalities, a decision support system (DSS) was designed, developed, and implemented. To achieve this, a relational diagram of the main components of the multi-level framework was created, serving as a foundation for designing a survey for data collection. Employing a purposive sampling approach, 23 experts participated in semi-structured interviews for data collection. Following approximately 23 hours of data collection, preprocessing techniques, including outlier handling using the Interquartile Range (IQR) method and addressing imbalanced datasets using the Synthetic Minority Over-sampling Technique (SMOTE), were applied to enhance data quality for subsequent analyses.

Rough Set Theory (RST), a method that handled uncertainties in input data, was selected for rule generation and building a knowledge repository for the DSS. This study used the R.ROSETTA package in the R programming language to implement RST and knowledge discovery processes. Following the rule generation and validation process using the RST methodology, a set of 2,280 rules was formulated. These rules were expressed as individual statements or combinations of statements linked by "AND" or "OR" conditions and were classified into three distinct categories: planning methods, control metrics, and schedule levels. The resulting database served as a knowledge repository for project planning and control systems.

To implement the inference engine and rule activation, a forward chaining approach was employed using the Pyke knowledge engine in Python. Additionally, a user interface was designed to collect project team requirements and display the results, forming a multi-level planning and control system. Moreover, a multi-objective mathematical model was developed to optimize the DSS results and propose an integrated and multi-level project planning and control system for construction projects. The objective was to minimize the number of planning methods and control metrics at each schedule level for practical implementation while meeting the maximum project team requirements.

To assess the validity, usefulness, and practicality of the solution, two approaches were adopted. First, a case study was conducted within the IsoBIM project framework to demonstrate the practicality of the DSS and mathematical model in proposing a multi-level planning and control system for a renovation project. Second, quantitative performance measures from satisfaction surveys were used for a general evaluation.

The implementation of the DSS for the renovation case study resulted in the activation and firing of 59 out of the 2,280 rules stored within the knowledge database. Based on the fired rules, 4DBIM, takt time planning, and the last planner system were suggested as planning methods across all three schedule levels. Moreover, MV, PPC, RL, and CLR were proposed as control metrics that aligned with project control requirements. This activation highlighted the dynamic capability of the inference engine to selectively apply relevant rules based on the contextual demands of the project team.

Following the rule activation, the mathematical model was employed to propose optimized solutions across various scheduling levels, guided by the DSS outputs. The outcomes of the

mathematical model were illustrated through Pareto front plots, providing flexibility to the project team for selecting solutions that best aligned with the specific requisites posed by varying project conditions. For the optimized multi-level planning and control system for the case study, at the long-term level, two planning methods—4DBIM and takt time planning—along with a control metric—milestone variance (MV)—were chosen. In the mid-term schedule level, takt time planning and the last planner system were selected for planning methods, while the location risk index (LRI) and task made ready (TMR) were considered as control metrics based on the project circumstances. In short-term planning, takt time planning and the last planner system were again selected as planning methods, complemented by percent planned complete (PPC) and capacity to load ratio (CLR) as control metrics. This integration of various suggested planning methods and control metrics across three scheduling levels functions as a multi-level and integrated system for project planning and control. The general evaluation of the system indicates that this approach significantly enhances effectiveness in achieving project objectives.

In conclusion, this study adopted a data-driven and knowledge-based approach through a comprehensive and integrated process that leveraged a mixed-method methodology to extract and utilize the expertise of construction professionals. By combining qualitative insights from industry experts with quantitative data analysis, the research developed a robust DSS. This approach ensured that the practical experiences and knowledge of engineers were systematically captured and applied, leading to more accurate, reliable, and adaptive project management solutions. To successfully implement the proposed solution for the case study, a methodological guideline was developed, presenting the required details, including processes and workflows, roles and responsibilities, and information for implementing the DSS solution. This research represents a significant advancement in applying decision support systems in construction management. It provides a strong framework to improve project outcomes through multi-level and integrated planning and control systems. The implications of this research are profound and poised to impact current practices and future innovations in the construction industry.

7.2. Thesis Contributions

The academic contributions of this thesis are as follows:

- Identify an appropriate mechanism to integrate various planning methods and control metrics across multiple schedule levels.
- Improve understanding of the underlying theories and concepts of various planning and control approaches between the project stakeholders.
- Provide a comprehensive framework for planning and control that operates across the functional requirements of the project teams.
- Formulate the knowledge and experiences of experts in project planning and control and construct a knowledge repository.
- Develop a data-driven and knowledge-based DSS to recommend well-suited planning and control systems based on specific project requirements.
- Demonstrate the proposed solution's practicality through a case study.
- Propose a rigorous methodology from data collection and analysis to the implementation for developing a data-driven and knowledge-based DSS.
- Develop a multi-objective mathematical model to optimize the DSS's results.

- Develop a detailed methodological guideline for the industry to implement the suggested solution by the DSS more easily and effectively.

Moreover, the following is a summary of the practical contributions:

- ***Simplified Decision-Making Process:*** The developed Decision Support System (DSS) enhances the decision-making process by posing straightforward and sensible questions tailored to the project team's specific requirements. This approach ensures the selection of the most effective planning and control strategies, making the DSS a versatile tool applicable across various project types during the preconstruction phase.
- ***Strategic Value and Practicality:*** The real-world application of the developed multi-level framework and DSS underscores its strategic value and practicality. The positive outcomes from these applications advocate for its broader adoption within the industry.
- ***Industry and Academic Endorsements:*** The framework has received positive evaluations from both industry and academic experts, highlighting its potential to revolutionize production planning and control in construction. This support suggests that the framework can facilitate a transformative shift from methods to systems in construction planning and control practices.
- ***Step-by-Step Methodological Guidelines:*** The developed methodological guideline provides a step-by-step process for implementing an optimized planning and control system for renovation projects. This guideline serves as a practical resource for the industry, ensuring a structured and efficient approach to project planning and control.

7.3. Limitations and Future Directions

Every study has its limitations, and this research is no exception. This section outlines the limitations encountered during the multi-step research conducted in this thesis and offers suggestions for future studies to address these limitations. The key research limitations and corresponding future directions are as follows:

Limitation 1: In applying semantic textual similarity to identify the functional concepts of planning and control systems, this research utilized a pre-trained SBERT model due to the lack of a domain-specific textual dataset for the construction industry. While SBERT is proficient at processing and analysing text, it was not specifically optimized for text mining within the construction domain, potentially leading to discrepancies in semantic understanding.

- ***Future Direction 1:*** Future research could focus on developing customized models trained directly on domain-specific datasets within the construction industry to enhance semantic understanding and accuracy.

Limitation 2: The data collection was limited to 23 experts. Although this sample size was sufficient for the scope of this study, it may not fully represent the broader range of expertise available in the construction management field.

- **Future Direction 2:** Future research could involve a larger number of experts to formalize their knowledge, thereby enhancing the robustness and global applicability of the knowledge repository.

Limitation 3: The study considered only a renovation case study to demonstrate the practicality and validity of the approach. While this provided valuable insights, broader implementation and validation across different types of construction projects is necessary.

- **Future Direction 3:** Future research could implement and validate the framework across various types of construction projects to strengthen its generalizability and applicability in diverse contexts.

Limitation 4: The rules generated by the DSS inference engine may not always be well-fitted or efficient based on the project team's functional requirements.

- **Future Direction 4:** Future studies could focus on developing a new generation of DSSs by integrating rule-based expert systems with reinforcement learning with human feedback (LRHF). This integration would allow for assigning penalties or rewards to the rules based on expert opinions, ensuring the activation of well-suited rules.

Limitation 5: The developed methodological guideline is specific to the suggested solution for the renovation case study in this research. Despite its applicability to general renovation projects, the dynamic nature of DSS solutions based on project team requirements necessitates specific guidelines for each suggested solution.

- **Future Direction 5:** Future studies could explore applying natural language processing to existing project planning and control system guidelines. This would entail extracting essential processes, workflows, roles, and information, and subsequently aligning and integrating these components to develop methodological guidelines tailored for the multi-level and integrated planning and control system proposed by the DSS.

Limitation 6: Implementing a planning and control system and corresponding guidelines in a construction project is a time-intensive process that depends significantly on the project's size and specific characteristics. Given that the developed guideline was the final objective of this thesis, we did not have sufficient time to implement it in a case study to identify potential bottlenecks. Therefore, the current version remains an as-planned and developed guideline.

- **Future Direction 6:** Future research could focus on applying this developed methodological guideline to multiple case studies. This will allow for the evaluation of the guideline as an as-implemented framework. By comparing the processes and workflows of the as-planned versus the as-implemented versions, it will be possible to identify deviations and refine the guideline. This iterative process will help create a more realistic and practical guideline for the construction industry.

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Appendix

Table A1. Identified control metrics

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

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

Table A1. (continued)

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

Table A2. Classes of control metrics and associated reference matrices

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

M30	Estimate-at-Completion (EAC)	-	-	-	X	-	X	M71	Schedule variance (SV)	-	-	-	X	X	-
M31	Expected Progress	-	-	-	X	-	X	M72	Starvation	X	-	-		X	-
M32	Feeding buffer burn rate (FBBR)	-	-	-	X	X	-	M73	Takt Area Completion (TAC)	-	-	-	X	X	-
M33	Glut	X	-	-	-	X	-	M74	Takt Time Slot Completion (TTSC)	-	-	-	X	X	-
M34	Labor Hours Reliability Index (LHRI)	X	-	-	-	X	-	M75	Takt Wagon Completion (TWC)	-	-	-	X	X	-
M35	Labor Utilization Factor (LUF)	X	-	-	-	X	-	M76	Task Readiness (TR)	-	X	-	-	-	X
M36	Lean Workflow Index (LWI)	X	-	-	-	X	-	M77	Tasks Anticipated (TA)	-	X	-	-	-	X
M37	Location Risk Index (LRI)	-	X	-	-	-	X	M78	Tasks Made Ready (TMR)	-	X	-	-	X	-
M38	Milestone Variance (MV)	-	-	X	-	-	X	M79	To-Complete Schedule Compression Ratio (TCSCR)	-	-	-	X	X	-
M39	Misallocation Factor (MF)	X	-	-	-	X	-	M80	To-Complete Schedule Performance (TCSPI)	-	-	-	X	X	-
M40	New duration	X	-	-	-	X	-	M81	Value-in-Process (VIP)	-	-	-	X	X	-
M41	Number of Backlog Activities (NBA)	-	X	-	-	-	X	M82	Weekly Deviation (WD)	X	-	-	-	X	-

Table A3: The results of normalized score and DC for each functionality in each matrix

This step is to compare the results of SNA with Simplified Analysis		Using Simplified Analysis		Using SNA	
Code	Functionalities	Normalized score		Normalized DC	
		Matrix C	Matrix T	Network C	Network T
F1	Allowing just-in-time (JIT) purchasing and delivery of material	0.083	0.040	0.042	0.019
F2	Allowing the interactions of multiple team professionals and stakeholders in a common environment.	0.500	0.400	0.250	0.456
F3	Assisting in reducing waste	0.667	0.440	0.792	0.381
F4	Automated planning of concrete joint layouts	0.000	0.040	0.000	0.063
F5	Automatic generation of the as-built real-time 4D simulation	0.167	0.080	0.354	0.131
F6	Better flow of information	0.167	0.200	0.094	0.225
F7	Constructability evaluation	0.083	0.600	0.156	0.563
F8	Continuous improvement process	1.000	0.120	0.938	0.100
F9	Continuous learning	0.333	0.000	0.531	0.000
F10	Creativity, option generation, and innovation	0.333	0.000	0.365	0.000

F11	Decentralized work tracking and information communication on construction sites	0.000	0.160	0.000	0.169
F12	Detected more logical errors, more accurately, and faster, with less need for intrateam communication	0.167	0.400	0.146	0.381
F13	Dynamic collision detection and spatial-temporal conflict analysis	0.000	0.480	0.000	0.531
F14	Early involvement of key project stakeholders	0.250	0.000	0.281	0.000
F15	Easing of access and low training time	0.000	0.160	0.000	0.206
F16	Effective supply chain practices	0.250	0.000	0.104	0.000
F17	Empowering automated project progress monitoring	0.000	0.560	0.000	0.600
F18	Enabling lean construction adoption and situation awareness	0.167	0.080	0.188	0.081
F19	Enabling project performance prediction	0.333	0.120	0.240	0.169
F20	Enabling real-time collaborative 4D planning to gain a robust construction plan	0.000	0.080	0.000	0.075
F21	Enabling real-time communication with workers	0.000	0.080	0.000	0.106
F22	Enabling real-time tracking in construction site	0.000	0.120	0.000	0.194
F23	Enabling value management/engineering	0.083	0.000	0.156	0.000
F24	Enhancing transparency	0.750	0.080	0.719	0.106
F25	Experiencing and reviewing scheduled sequences on a 1:1 scale	0.000	0.240	0.000	0.344
F26	Facilitating communication with subcontractors	0.500	0.200	0.573	0.300
F27	Fosters the convergence of 4D uses with project documents	0.000	0.080	0.000	0.100
F28	Generating real-time interactive project visualization	0.000	0.160	0.000	0.225
F29	Aligning goals with owner	0.500	0.040	0.458	0.075
F30	Higher sense of immersion and interaction	0.000	0.320	0.000	0.425
F31	Highlighting the importance of short-term planning at crew level	0.417	0.000	0.552	0.000
F32	Identifying possible optimizations	0.167	0.160	0.104	0.150
F33	Identifying time-space conflicts	0.083	0.600	0.156	0.438
F34	Improving alignment of engineering & procurement with construction and commissioning	0.250	0.040	0.115	0.088
F35	Improving collaborative sensemaking	0.417	0.120	0.427	0.106
F36	Improving communication and teamworking between the project team	0.583	1.000	0.625	1.000
F37	Improving decision making among geographically dispersed industry practitioners	0.167	0.160	0.188	0.194
F38	Improving engineering curriculum	0.000	0.240	0.000	0.256
F39	Improving organizational agility	0.333	0.000	0.229	0.000

F40	Improving role description and responsibilities	0.167	0.000	0.135	0.000
F41	Improving safety management on site	0.083	0.800	0.063	0.794
F42	Improving the involvement and the commitment of all the professional groups	0.667	0.120	0.750	0.138
F43	Increasing the work-flow reliability onsite	0.583	0.200	0.583	0.206
F44	Maintaining a workable backlog	0.167	0.000	0.250	0.000
F45	Making decision under a user-centric approach	0.000	0.120	0.000	0.138
F46	Monitoring worker motion and worker location	0.000	0.080	0.000	0.144
F47	More efficient resources management.	0.417	0.440	0.552	0.381
F48	More natural and industry-adapted interactions during a collaboration session	0.000	0.160	0.000	0.181
F49	Moving participants from passive receivers of a schedules to active contributors to the schedule	0.250	0.320	0.167	0.256
F50	Permitting real-time virtual collaboration for stakeholders from different locations	0.083	0.240	0.083	0.294
F51	Providing predictive control/monitoring method to make the best decisions with forwarding simulation	0.083	0.200	0.094	0.231
F52	Providing a digital equivalence to face-to-face communication in construction projects	0.083	0.200	0.083	0.238
F53	Providing better budget control	0.333	0.080	0.219	0.081
F54	Providing enhanced awareness of ongoing work	0.083	0.160	0.094	0.194
F55	Providing ergonomic interactions with the session workflow.	0.000	0.120	0.000	0.119
F56	Pull planning effectiveness	0.333	0.000	0.594	0.000
F57	Real-time safety monitoring	0.000	0.120	0.000	0.156
F58	Reducing information loss in data exchange	0.000	0.080	0.000	0.144
F59	Reducing the change orders during construction	0.167	0.080	0.083	0.144
F60	Reducing the impacts of potential causes of delay	0.167	0.080	0.094	0.063
F61	Reducing uncertainty and risk	0.750	0.320	0.927	0.388
F62	Reshaping an individual's cognitive determinants to influence collaboration throughout project delivery	0.000	0.200	0.000	0.225
F63	Safer learning environment	0.000	0.240	0.000	0.300
F64	Sharing the knowledge and lessons learned	0.333	0.080	0.542	0.100
F65	Site lay-out and environment management	0.000	0.440	0.000	0.394
F66	Solving disputes more efficiently	0.083	0.160	0.031	0.138
F67	Solving site logistic problems	0.000	0.360	0.000	0.369
F68	Supporting the learning and process of planning of offsite construction production	0.000	0.360	0.000	0.288

	challenges				
F69	Supporting co-navigate, co-sort, co-plan, co-simulate and co-talk	0.000	0.200	0.000	0.231
F70	Supporting collaboration through social conversations	0.833	0.200	0.802	0.306
F71	Supporting multi-functional review meetings	0.000	0.200	0.000	0.244
F72	Supporting the trust and reliable promises among the team	0.833	0.000	1.000	0.000
F73	Systematic identification and removal of constraints	0.833	0.040	0.896	0.038
F74	Visualizing alternative construction sequences based on various what-if scenario	0.417	1.000	0.344	0.756
F75	Workspace planning	0.000	0.720	0.000	0.594

Table A4. Extracted functionalities from the literature

ID	Functionalities
F1	Achieving an integrated cost/schedule progress monitoring and control
F2	Aligning goals with the owner
F3	Aligning the work plan assignment with the look-ahead
F4	Allowing just-in-time (JIT) purchasing and delivery of material
F5	Allowing the interactions of multiple team professionals and stakeholders in a common environment.
F6	Analyzing constraints more effectively
F7	Analyzing schedule constructability
F8	Applying analytical method
F9	Applying creativity techniques to planning and scheduling
F10	Assisting in reducing waste
F11	Automated planning of concrete joint layouts
F12	Automatic generation of the as-built real-time 4D simulation
F13	Automatically determines the resource quantities
F14	Automating the generation of schedule
F15	Avoiding omissions and sequencing mistakes
F16	Better flow of information
F17	Considering contractual requirement
F18	Considering Supply chain instability
F19	Considering the continuous flow of work
F20	Constructability evaluation
F21	Continuous improvement process
F22	Continuous learning
F23	Controlling of uncertainty
F24	Controlling project progress and performance
F25	Controlling the cost of the project in progress
F26	Creativity, option generation, and innovation
F27	Decentralized work tracking and information communication on construction sites
F28	Decreasing meeting durations
F29	Decreasing workflow variability
F30	Detected more logical errors, more accurately, and faster, with less need for intrateam communication
F31	Detecting and solving spatiotemporal conflicts
F32	Dynamic collision detection and spatial-temporal conflict analysis
F33	Early involvement of key project stakeholders
F34	Easing of access and low training time
F35	Effective supply chain practices
F36	Eliminating the root causes of variability
F37	Empowering automated project progress monitoring
F38	Enabling lean construction adoption and situation awareness
F39	Enabling project performance prediction
F40	Enabling real-time collaborative 4D planning to gain a robust construction plan
F41	Enabling real-time communication with workers
F42	Enabling real-time tracking in construction site
F43	Enabling the coordination of the look-ahead plans
F44	Enabling value management/engineering
F45	Enhancing the performance of construction project management

Table A4. (continued)

ID	Functionalities
F46	Enhancing transparency
F47	Evaluating the performance of the look-ahead level
F48	Experiencing and reviewing scheduled sequences on a 1:1 scale
F49	Facilitating communication with subcontractors
F50	Filling gaps related to delay analysis
F51	Forecasting project duration
F52	Fosters the convergence of 4D uses with project documents
F53	Generating real-time interactive project visualization
F54	Higher sense of immersion and interaction
F55	Highlighting the importance of short-term planning at the crew level
F56	Identifying and eliminating wastes
F57	Identifying highly sensitive activities
F58	Identifying possible optimizations
F59	Identifying root causes for deviations.
F60	Identifying time-space conflicts
F61	Implementing pull flow control
F62	Improving continuous learning
F63	Improving alignment of engineering & procurement with construction and commissioning
F64	Improving collaborative sensemaking
F65	Improving communication and teamwork between the project team
F66	Improving decision-making among geographically dispersed industry practitioners
F67	Improving engineering curriculum
F68	Improving managerial practices
F69	Improving organizational agility
F70	Improving predictability
F71	Improving production tracking, forecasting and control
F72	Improving role description and responsibilities
F73	Improving safety management on-site
F74	Improving the involvement and commitment of all professional groups
F75	Improving the reliability of the planning
F76	Improving the understanding of the project's progress
F77	Improving the usability of the 4D BIM for workflow analyses
F78	Increasing productivity
F79	Increasing safety on construction sites
F80	Increasing teamwork, and communication between all stakeholders
F81	Increasing the work-flow reliability onsite
F82	Increasing transparency
F83	Integrating offsite and onsite planning for modular and offsite construction
F84	Linking the supply chain and construction process
F85	Maintaining a workable backlog
F86	Maintaining continuity of resources
F87	Maintaining continuity of trade work
F88	Maintaining production rate stability
F89	Making decisions under a user-centric approach
F90	Managing constraints removal
F91	Managing corrective actions
F92	Managing uncertainties
F93	Managing work density
F94	Measuring labour productivity
F95	Measuring labour resource reliability

Table A4. (continued)

ID	Functionalities
F96	Measuring long-term and short-term plan alignment
F97	Measuring reliability and effectiveness of weekly work plan and look-ahead plan
F98	Measuring the achievability of a target project duration
F99	Measuring the efficiency of resource allocation
F100	Measuring the make-ready process
F101	Measuring the percentage of differentiated tasks in the WWP
F102	Measuring the quality of capacity planning
F103	Measuring the quality of the commitments
F104	Measuring the quality of the construction flow
F105	Measuring the reliability and stability of the workflow
F106	Monitoring worker motion and worker location
F107	More efficient resource management.
F108	More natural and industry-adapted interactions during a collaboration session
F109	Moving participants from passive receivers of a schedule to active contributors to the schedule
F110	Permitting real-time virtual collaboration for stakeholders from different locations
F111	Promoting the reliability of the Commitment Plan
F112	Providing predictive control/monitoring methods to make the best decisions with forwarding simulation
F113	Providing a digital equivalence to face-to-face communication in construction projects
F114	Providing better budget control
F115	Providing enhanced awareness of ongoing work
F116	Providing ergonomic interactions with the session workflow.
F117	Providing managerial information
F118	Providing more valuable handouts to the planning meetings' participants
F119	Pull planning effectiveness
F120	Quantifying the reliability of starting or finishing the task on time
F121	Real-time safety monitoring
F122	Reducing information loss in data exchange
F123	Reducing the change orders during construction
F124	Reducing the impacts of potential causes of delay
F125	Reducing uncertainty and risk
F126	Reducing production cycle time
F127	Relating workflow reliability to productivity
F128	Reshaping an individual's cognitive determinants to influence collaboration throughout project delivery
F129	Safer learning environment
F130	Scheduling of modular and offsite construction
F131	Sharing the knowledge and lessons learned
F132	Site layout and environment management
F133	Solving disputes more efficiently
F134	Solving site logistic problems
F135	Supporting co-navigate, co-sort, co-plan, co-simulate and co-talk
F136	Supporting collaboration through social conversations
F137	Supporting human decision-making
F138	Supporting multi-functional review meetings
F139	Supporting the learning and process of off-site construction production planning challenges
F140	Supporting the trust and reliable promises among the team
F141	Systematic identification and removal of constraints
F142	Testing research hypotheses and improving understanding of the schedule
F143	Understanding of the subprocesses more accurately
F144	Understanding the behaviour of the performance indicators
F145	Visualizing alternative construction sequences based on various what-if scenarios
F146	Visualizing the schedules to understand and communicate content to a variety of stakeholders
F147	Visualizing the status of work-in-progress
F148	Workspace planning

Table A5. Detailed definition of the considered SMART functionality concepts in this research

Knowledge domains (Functionality concepts)	Functionality's definitions (User requirements)	S.M.A.R.T. Criteria				
		Specific	Measurable	Achievable	Relevant	Time-bound
Collaboration management	Facilitating collaboration among project teams during the planning and construction phase	+	QL	+	+	L-M-S
Commitment management	Supporting the trust and reliable promises among the project teams to promote the reliability of the weekly work plan	+	QN	+	+	M-S
Communication management	Facilitating communication and interactions between the project teams	+	QL	+	+	L-M-S
Conflict management	Detecting and solving spatiotemporal conflicts and collisions	+	QN	+	+	M-S
Constraint management	Identifying, removing, and mitigating constraints and change orders more systematically and effectively	+	QN	+	+	M
Contract management	Considering managerial and contractual concerns and requirements	+	QL	+	+	L
Integration management	Integrating offsite and onsite planning for modular and offsite construction	+	QL	+	+	L-M-S
	Aligning the schedule levels	+	QN	+	+	L-M-S
Process and workflow management	Aligning the engineering & procurement with construction and commissioning	+	QL	+	+	L-M-S
	Maintaining the work-flow reliability onsite	+	QN	+	+	M-S
Project performance management	Keeping the continuity of trade work	+	QN	+	+	M-S
	Providing budget control	+	QN	+	+	L-M-S
Reliability management	Supporting the monitoring, sharing and controlling of the project progress (time and cost)	+	QN	+	+	L-M-S
	Stabilizing production rate	+	QN	+	+	L-M-S
	Sustaining the reliability and effectiveness of weekly planning	+	QN	+	+	S
Resources management	Controlling the make ready process	+	QN	+	+	M
	Securing quality of capacity planning	+	QN	+	+	M-S
	Maintaining continuity of resources	+	QN	+	+	M-S
Root cause analysis	Ensuring labor resource reliability and productivity	+	QN	+	+	M-S
	Identifying, eliminating and mitigating root causes for deviations	+	QN	+	+	S
Safety management	Supporting safety on construction site	+	QN	+	+	M-S
Supply chain management	Linking the supply chain and construction process	+	QL	+	+	L-M
Uncertainty management	Identifying, analyzing and responding to project risks	+	QN	+	+	L-M-S
Visualization	Visualizing the schedules to improve collaboration and communication with a variety of stakeholders	+	QL	+	+	L-M-S
Waste management	Reducing production cycle time	+	QN	+	+	M-S
Real time management	Enabling real-time collaborative planning for project team	+	QL	+	+	L-M-S
	Enabling real-time tracking in construction site	+	QL	+	+	S
Learning and knowledge sharing	Supporting continues learning	+	QN	+	+	L-M-S

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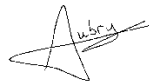

1. Student Identification

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Title: <i>Functionality as a key concept for integrated project planning and scheduling methods</i>					
Current Status of Article:	published	accepted	under review	submitted	in preparation
	✔				
Name of Journal* / Citation	Sheikhhoshkar, M., Bril El-Haouzi, H., Aubry, A., & Hamzeh, F. (2023). Functionality as a key concept for integrated project planning and scheduling methods. <i>Journal of Construction Engineering and Management</i> , 149(7), 04023053, https://doi.org/10.1061/JCEMD4.COENG-13427 .				
* If the article is published or has been accepted for publication, please provide all available details.					

3. Declaration of All Coauthors Other than Student

As the co-author of the article identified above, I authorize Moslem Sheikhhoshkar to include this article in his PhD thesis entitled: <i>“Multi-level and Collaborative Planning and Control of Construction Sites Using BIM and Lean”</i>		
Name co-author	Date	Signature
Hind Bril El-Haouzi	17 Oct 2024	
Alexis Aubry	27 Sep 2024	
Farook Hamzeh	18 Sep 2024	



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2. Article Identification

Title: <i>An advanced exploration of functionalities as the underlying principles of construction control metrics</i>					
Current Status of Article:	published	accepted	under review	submitted	in preparation
	✔				
Name of Journal* / Citation	Sheikhhoshkar, M., Bril El Haouzi, H., Aubry, A., & Hamzeh, F. (2024). An advanced exploration of functionalities as the underlying principles of construction control metrics. <i>Smart and Sustainable Built Environment</i> , 13(3), 644-676, https://doi.org/10.1108/SASBE-12-2023-0379 .				
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2. Article Identification

Title: <i>From process-based to technology-driven: a study on functionalities as key elements of collaborative planning methods for construction projects</i>					
Current Status of Article:	published	accepted	under review	submitted	in preparation
	✔				
Name of Journal* / Citation	Sheikhhoshkar, M., Bril El-Haouzi, H., Aubry, A., Hamzeh, F., & Rahimian, F. (2024). From process-based to technology-driven: a study on functionalities as key elements of collaborative planning methods for construction projects. <i>Production Planning & Control</i> , 1-22. https://doi.org/10.1080/09537287.2024.2360581 .				
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2. Article Identification

Title: <i>From NLP to Taxonomy: Identifying and Classifying Key Functionality Concepts of Multi-level Project Planning and Control Systems</i>					
Current Status of Article:	published	accepted	under review	submitted	in preparation
		✔			
Name of Journal* / Citation	Sheikhhoshkar, M., Bril El Haouzi, H., Aubry, A., Hamzeh, F., & Rahimian, F. (2024). From NLP to taxonomy: Identifying and classifying key functionality concepts of multi-level project planning and control systems. Journal of Information Technology in Construction (ITcon).				
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Current Status of Article:	published	accepted	under review	submitted	in preparation
	✔				
Name of Journal* / Citation	Sheikhhoshkar, M., El-Haouzi, H. B., Aubry, A., Hamzeh, F., & Sakikhales, M. (2024). An Innovative Integrated Framework for Multi-level Production Planning and Control Systems in Construction. <i>Developments in the Built Environment</i> , 100524, https://doi.org/10.1016/j.dibe.2024.100524				
* If the article is published or has been accepted for publication, please provide all available details.					

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As the co-author of the article identified above, I authorize Moslem Sheikhhoshkar to include this article in his PhD thesis entitled: <i>“Multi-level and Collaborative Planning and Control of Construction Sites Using BIM and Lean”</i>		
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2. Article Identification

Title: <i>A Data-driven and Knowledge-based Decision Support System for Construction Planning and Control</i>					
Current Status of Article:	published	accepted	under review	submitted	in preparation
			✔		
Name of Journal* / Citation	Automation in Construction				
* If the article is published or has been accepted for publication, please provide all available details.					

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Abstract

Multi-level and Collaborative Planning and Control of Construction Sites Using BIM and Lean

The effective management of construction projects is essential due to their inherent complexity and substantial financial implications. In this regard, the project planning and control domain plays a vital role in successful project execution, which requires data-driven and knowledge-based decisions to navigate these complexities and ensure successful project outcomes. Despite the presence of various planning and control systems, ineffective planning and control remain major causes of low productivity, budget overruns, and delays in construction projects. Integrating existing planning and control systems can address these issues by aggregating the advantages of each. However, a significant gap exists due to the lack of a multi-level and integrated framework that combines different planning methods and control metrics across various schedule levels, leveraging the strengths of each to offer a more effective solution. Furthermore, there is a deficiency in data-driven and knowledge-based systems that address the specific needs and applications of project teams regarding a planning and control system, proposing optimized multi-level solutions. This study aims to bridge this gap by first developing a multi-level and integrated framework for project planning and control. Subsequently, it develops and implements a data-driven and knowledge-based decision support system (DSS) that leverages a knowledge database built from experts' experiences. This system proposes multi-level and integrated solutions for the planning and control of construction projects, enhancing both theoretical frameworks and practical applications. The developed DSS simplifies the decision-making process by posing straightforward and relevant questions tailored to the project team's requirements, thereby suggesting the most suitable approaches for project planning and control. The developed framework and decision support system were validated by applying them to a renovation case study and receiving positive feedback from experts.

Eventually, a detailed methodological guideline was crafted to facilitate the implementation of the DSS-recommended multi-level planning and control system for renovation projects. This guideline offers clear, step-by-step instructions to ensure straightforward adoption and effective integration into project management practices. This versatile tool can be applied across various project types during the preconstruction phase, determining the most effective planning and control strategies based on the functional requirements of the project team.

Keywords: Multi-level framework, Decision support system, Planning and control system, Knowledge repository, Mathematical model, Functionality

Résumé

Planification et contrôle multi-niveaux et collaboratifs des chantiers de construction à l'aide de la BIM et du Lean

La gestion efficace des projets de construction est essentielle en raison de leur complexité inhérente et des implications financières substantielles. À cet égard, la planification et le contrôle des projets jouent un rôle crucial dans la réussite de l'exécution des projets, nécessitant des décisions basées sur les données et les connaissances pour naviguer dans ces complexités et garantir des résultats positifs. Malgré la présence de divers systèmes de planification et de contrôle, une planification et un contrôle inefficaces restent des causes majeures de faible productivité, de dépassements de budget et de retards dans les projets de construction. L'intégration des systèmes de planification et de contrôle existants peut remédier à ces problèmes en agréant les avantages de chacun. Cependant, un écart significatif subsiste en raison de l'absence d'un cadre intégré et multi-niveaux combinant différentes méthodes de planification et métriques de contrôle à travers divers niveaux d'échéancier, tirant parti des forces de chacun pour offrir une solution plus efficace. De plus, il existe une insuffisance de systèmes basés sur les données et les connaissances qui répondent aux besoins spécifiques et aux applications des équipes de projet en matière de planification et de contrôle, proposant des solutions multi-niveaux optimisées. Cette étude vise à combler cette lacune en développant d'abord un cadre intégré et multi-niveaux pour la planification et le contrôle des projets. Ensuite, elle développe et met en œuvre un système d'aide à la décision (SAD) basé sur les données et les connaissances, qui exploite une base de connaissances construite à partir des expériences des experts. Ce système propose des solutions multi-niveaux et intégrées pour la planification et le contrôle des projets de construction, améliorant à la fois les cadres théoriques et les applications pratiques. Le SAD développé simplifie le processus de prise de décision en posant des questions simples et pertinentes adaptées aux besoins de l'équipe de projet, suggérant ainsi les approches les plus appropriées pour la planification et le contrôle des projets. Le cadre et le système d'aide à la décision développés ont été validés en les appliquant à une étude de cas de rénovation et en recevant des retours positifs de la part des experts.

Enfin, une directive méthodologique détaillée a été élaborée pour faciliter la mise en œuvre du système de planification et de contrôle multi-niveaux recommandé par le SAD pour les projets de rénovation. Cette directive offre des instructions claires et étape par étape pour assurer une adoption simple et une intégration efficace dans les pratiques de gestion de projet. Cet outil polyvalent peut être appliqué à divers types de projets durant la phase de préconstruction, déterminant les stratégies de planification et de contrôle les plus efficaces en fonction des exigences fonctionnelles de l'équipe de projet.

Mots-clés : Cadre multi-niveaux, Système d'aide à la décision, Système de planification et de contrôle, Référentiel de connaissances, Modèle mathématique, Fonctionnalité

