A Comprehensive Literature Review of Project Scheduling Techniques in Construction and Engineering Projects

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Abstract: ***Schedule programming is a core mathematical function of construction and engineering project management. It gives planners and site managers a time-phased view of activities, resources and constraints. Over the past six decades, a wide range of scheduling techniques has emerged, ranging from simple bar charts and classical network methods to resource-constrained and location-based methods. Each technique embodies particular assumptions about activity duration, resource availability, uncertainty and human behaviour, and each has its own advantages and limitations in construction practice. This paper presents a review of project scheduling techniques. Classical network-based methods are reviewed first, followed by resource-constrained and optimisation-based approaches, repetitive and location-based methods, risk and uncertainty-oriented techniques, lean and collaborative scheduling models, and digital and intelligent scheduling tools. Modelling concepts, typical applications, strengths and weaknesses are analysed. Comparative tables synthesise and highlight the conditions under which each technique is most appropriate. According to the review, the practice of project scheduling is inherently hybrid. Network techniques, resource-constrained models, location-based tools, lean planning systems and digital technologies are increasingly combined to address complex project environments. Nevertheless, important gaps remain. One key challenge is integrating uncertainty and risk into schedules that remain understandable to practitioners. The synthesis offered here provides a basis for both researchers and practitioners who wish to combine and further develop scheduling techniques for more reliable and efficient project delivery.***

Keywords: Project scheduling, construction management, Critical Path Method, resource-constrained project scheduling, line-of-balance, Last Planner System, 4D BIM, schedule optimization

1. Introduction

Scheduling converts a static description of project scope into a dynamic plan that allocates activities to time periods while respecting dependencies. In construction projects, the schedule is not only a technical artefact but also a central communication instrument. The Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) established the mathematical foundation of network-based scheduling and provided systematic procedures for computing project start and finish times [1]. Compared to earlier ad hoc schedules, these methods represented a step change.

Real construction projects, however, rarely conform to the underlying assumptions. Weather conditions, labour productivity and supply-chain reliability all affect activity durations. Equipment, crews and workspaces are shared. Spatial layout in construction operations affects the need to maintain continuous flows of work. Despite the availability of network-based scheduling tools, projects continue to suffer from delays and cost overruns, suggesting that techniques alone are insufficient if their assumptions and limitations are not understood [3].

Many of these challenges have been addressed in the literature on project scheduling. One line of work has extended network models into resource-constrained project scheduling problems [4]. Another has developed representations better suited to repetitive and spatially structured projects [7]. A third strand has led to Monte Carlo–based schedule risk analysis and critical chain methods [3]. Lean construction and the Last Planner System make scheduling a collaborative and commitment-based process [9].

Scheduling is also closely linked to other project management knowledge areas such as cost control, risk management and procurement. Cash-flow curves, earned value metrics and incentive schemes are often tied to scheduling decisions. Under regulatory and contractual frameworks, rights and obligations related to delay, suspension and extensions of time must be interpreted in light of the schedule. The choice and interpretation of scheduling techniques therefore have both legal and technical implications. Understanding the literature on scheduling is thus highly relevant for planners and site managers.

Table 1: Major Families of Project Scheduling Techniques

Family of techniques	Typical representation	Main focus	Typical use in construction
Classical network-based (Gantt, CPM, PERT)	Time bars and activity networks	Precedence and critical path	Baseline schedules, contractual programmes
Resource-constrained / optimisation-based	Networks with resource limits	Feasible sequencing under resource caps	Detailed planning, what-if analysis
Repetitive and location-based	Time–location/flowline diagrams	Crew continuity and production flow	Highways, pipelines, multi-storey buildings
Risk- and uncertainty-oriented	Probabilistic networks, buffers	Robustness against variability	Schedule-risk analysis, contingency and buffers
Lean and collaborative	Multi-level plans, PPC metrics	Commitment, reliability, learning	Short-term planning, site coordination
Digital and intelligent	4D models, rule bases, AI tools	Automation, integration, visualisation	Model-based planning, scenario simulation

2. Classical Network-Based Scheduling Techniques

2.1 Bar Charts and Milestone Charts

Bar charts were the first tools used for visualising project schedules. They display activities as horizontal parallel bars on a time axis. Managers can quickly see the start and finish of tasks, as well as the overlap between trades. Key events such as design completion, structural topping-out and handover are highlighted in milestone charts. For small projects with limited interdependencies, bar charts are easy to understand.

However, bar charts become difficult to manage for complex projects. Logical relationships are often implicit, making it hard to understand the impact of changes in one activity on others. With many activities and interfaces, manual updates can be error-prone. Bar charts also do not explicitly account for resource capacity or spatial conflicts. These limitations motivated the development of network techniques that express project logic in a more rigorous form [1].

In contemporary practice, bar charts are rarely used in isolation. They are a presentation layer derived from the underlying network model. The network is used to calculate dates, float and critical paths, while the bar chart offers a familiar view for progress meetings and client reporting. Enhanced variants, such as time-chain diagrams and bar charts with embedded milestones and resource histograms, attempt to overcome some classical limitations but still depend on an underlying logic network. Bar and milestone charts thus complement, rather than replace, formal scheduling techniques.

Digital bar charts are closely integrated with project control systems. Modern tools can show multiple baselines and forecast bars, and can be used to group activities. These capabilities mitigate some cognitive limitations of traditional hand-drawn charts. However, without an explicit logic network or a clear understanding of constraints, a bar chart can still give a false sense of control.

2.2 Critical Path Method (CPM)

In CPM, a project is represented as a directed graph of activities. The critical path is the sequence of activities with zero total float whose delay will directly delay project completion [1]. The model allows evaluation of alternative sequences and time–cost trade-off studies.

CPM has a clear representation of project logic. The method can be applied manually for small networks or automatically for large ones, and it is embedded in virtually all commercial scheduling packages. The concept of float has become part of contractual language regarding delay liability, and the notion of criticality provides a straightforward basis for prioritised management attention. Despite the development of more sophisticated models, CPM remains the core of most practical scheduling systems [3].

At the same time, CPM is based on restrictive assumptions. Resource availability is assumed to be sufficient to execute all activities as soon as their predecessors are complete. In construction, this often leads to schedules that are logically correct but impractical on site. Subsequent extensions have tried to capture more complex overlaps but can make float interpretation more difficult [9]. Alternative formulations have been proposed to address resource limits, repetition and uncertainty.

CPM has also influenced how liability and risk are assigned. A critical path schedule is often used as a reference for assessing compensation events. Disputes frequently arise over whether delays occurred on the critical path and how float should be allocated. Misunderstandings about float ownership and interpretation are major sources of claims [9]. A sound grasp of CPM's theoretical basis is therefore important for planners and project managers.

2.3 Program Evaluation and Review Technique (PERT)

PERT was developed to manage research and development projects. Planners provide three estimates for each activity duration: optimistic, most likely and pessimistic. Expected duration and variance are then used to estimate the probability of meeting specific completion dates [2]. This represented an important conceptual advance over

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deterministic CPM for projects where historical productivity data are limited.

However, classical PERT makes several strong assumptions. It treats activity durations as independent and assumes that path-merging effects can be approximated analytically, even though delays in one activity may affect productivity in others. These simplifications can lead to underestimation of project duration. It is also difficult to obtain reliable three-point estimates from experts, and subjective optimism or pessimism can bias results. For these reasons, PERT is often used as a conceptual model rather than a strictly applied mathematical procedure [3].

In modern schedule-risk analysis, Monte Carlo simulation is widely used. Activity-duration ranges are sampled to generate probabilistic completion dates, sensitivity analyses and contingency plans. The evolution from classical PERT to simulation-based methods illustrates a broader trend in scheduling research: simple analytical formulae are being replaced by computational techniques that can handle complex dependencies at the cost of greater data and modelling effort.

Elements of PERT have been absorbed into everyday project management through techniques such as three-point estimation and risk-adjusted duration setting. Many practitioners implicitly apply PERT ideas when negotiating durations with trades, combining optimistic and pessimistic assumptions to arrive at a realistic figure. PERT's legacy is therefore as much cultural as technical in organisations that do not perform explicit PERT calculations.

2.4 Precedence Diagramming and Float Management

The Precedence Diagramming Method (PDM) extends CPM by representing activities as nodes connected by logical links of different types: finish-to-start, start-to-start, finish-to-finish and, in some implementations, start-to-finish. Planners can model overlaps, such as starting interior finishes before all structural work in a zone is complete, or staggering trades floor-by-floor in multi-storey projects. Lags allow intermediate relationships between purely sequential and fully overlapped scheduling [3].
The introduction of lags and multiple relationship types makes float analysis less intuitive. Conventional float metrics may be misleading in contractual disputes [9]. Activities can appear non-critical in terms of total float but have little practical flexibility due to access agreements or spatial constraints. Path-based indices, criticality probabilities from simulation and buffer-based approaches are alternative measures of criticality [11].

Many project teams use commercial PDM software as the primary scheduling environment but supplement it with visual checks, resource histograms and collaborative planning meetings. Network logic alone is not sufficient for reliable project control. The value of precedence diagrams depends on how they are embedded within broader management processes.

"Logic overload", where planners introduce many lags and complex relationships that field staff struggle to understand or respect, is a recurring issue in the literature. Such models are difficult to maintain. Some researchers advocate representing only the most essential precedence links and handling other coordination needs through location-based or lean planning techniques. The complexity of the network must be balanced against usability for end-users.

3. Resource-Constrained and Optimisation-Based Scheduling

3.1 Resource-Constrained Project Scheduling Problem (RCPSP)

The RCPSP explicitly incorporates resource limitations into the scheduling model. Activities may require multiple resources, and total demand in any period cannot exceed available capacity. The objective is usually to minimise project makespan or total cost. Reviews of RCPSP variants and solution methods show that even relatively simple formulations are computationally hard to solve [4].

To manage the diversity of real-world problems, classification schemes have been proposed that describe scheduling cases in terms of activity characteristics, resource types and precedence structures [4]. Such taxonomies help researchers position new models within the literature and help practitioners recognise when their project corresponds to known problem classes. RCPSP applications include allocating crews across parallel work fronts, scheduling equipment with limited availability and deciding shift patterns.

There is a tension between logical feasibility and resource feasibility. A CPM schedule may satisfy network logic but violate crew limits, while a resource-feasible schedule may require delaying some activities beyond their earliest possible dates. The optimisation perspective clarifies these trade-offs and provides quantitative benchmarks. In practice, RCPSP models must often be simplified or combined with judgement to fit the complexity of real construction environments.

A growing body of work considers multi-project RCPSP, where several projects share common resources. Priority rules and portfolio-level objectives must be defined to balance individual project deadlines with overall resource usage and cash flow. This context typically involves senior managers and central resource owners and is particularly relevant for large contractors and public agencies.

3.2 Exact Solution Methods

Exact methods aim to find the optimal solution. Early approaches relied on implicit enumeration and dynamic programming. Over time, researchers have developed more sophisticated bounding procedures and dominance rules [4]. Commercial-grade exact solvers can now often find optimal schedules for medium-sized RCPSP instances.

The main role of exact methods in the literature is to provide benchmarks. Optimal solutions offer upper or lower bounds against which heuristic performance can be assessed and yield insight into schedule structure. However, specific

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methods struggle with large-scale, highly constrained cases or with additional features such as multiple execution modes [6]. In such situations, computational effort may become prohibitive.

In construction practice, planners rarely use exact optimisation directly. Instead, results inform the design of decision-support tools and rules of thumb. For particularly complex or high-stake projects, exact methods may be applied off-line for scenario analysis. The complementary roles of exact and approximate solution techniques are widely recognised.

There is growing interest in integrating RCPSP solvers with higher-level decision problems. For example, discounted cash-flow models can be combined with scheduling models to explore time–cost trade-offs. This highlights the potential of rigorous optimisation to support strategic, not just operational, scheduling decisions.

3.3 Heuristic and Metaheuristic Approaches

A wide range of heuristic methods related to RCPSP have been explored. Priority-rule-based heuristics use rules such as shortest processing time, greatest number of successors, minimum slack or highest resource demand to select the next activity to schedule [4]. Rules can be combined into multi-criteria procedures. These heuristics generate reasonably good schedules quickly and can be adjusted easily.

Metaheuristics such as genetic algorithms, simulated annealing, tabu search and hybrid methods have also been applied to RCPSP and its extensions [6]. They combine diversification and intensification strategies to explore the solution space. Hybrid approaches often achieve the best performance on benchmark instances [6]. However, their parameter settings and internal mechanisms can be difficult for practitioners to understand and tune.

A recurring theme is the gap between algorithmic sophistication and field adoption. Many published methods are tested on standard benchmark sets rather than messy real project data, and their implementation requires optimisation expertise that may not be available in construction firms. As a result, metaheuristics have had a modest impact in day-to-day scheduling compared with their prominence in academic journals. Bridging this gap remains an important objective for future research.

At the same time, these studies have clarified the nature of scheduling problems. By analysing how solution quality varies with rule design, neighbourhood structure and diversification schemes, researchers have gained deeper insight into the structure of feasible schedules and the trade-off between solution quality and computational effort. Simple rule-based procedures inspired by this work are often embedded in commercial software.

3.4 Robust and Risk-Aware Scheduling

Classical RCPSP models usually treat activity durations deterministically. Schedules that are optimal under expected values may perform poorly when conditions change. Robust scheduling approaches seek solutions that perform acceptably across a range of scenarios, rather than optimising for a single point estimate. Techniques include buffered start times, proactive float allocation and simulation-based assessments [3].

A distinction is often made between proactive strategies, which design baseline schedules with built-in protection against variability, and reactive strategies, which focus on rescheduling policies when disruptions occur [3]. In construction, proactive approaches might include over-allocating resources at critical moments to reduce delay risk or inserting time buffers in work packages with high uncertainty. Reactive approaches emphasise rapid re-planning when equipment breaks down or when work fronts become unavailable. The choice between these strategies depends on contractual conditions, risk tolerance and the availability of real-time information.

Robust scheduling models show promise for improving schedule reliability, but their adoption has been limited by data requirements. Estimating probability distributions for durations and resource disruptions is challenging. There is a need for simplified and visual techniques that make robustness concepts accessible to practitioners.

There is also an inherent interaction between economic performance and robustness. Highly robust schedules may require additional resources, while overly lean schedules may be fragile in the face of disruptions. Multi-objective robust scheduling models attempt to balance these concerns by considering both cost and risk metrics. Although much of this work remains at the research stage, it aligns closely with the practical concerns of contractors.

Table 2: Representative RCPSP-Related Scheduling Models

Model type	Key characteristics	Typical objective	Construction relevance
Basic RCPSP	Single mode, renewable resources, precedence	Minimisemakespan	Crew allocation under fixed methods
Multi-mode RCPSP	Alternative execution modes per activity	Time–cost trade-off	Selecting crew sizes or methods per task
Resource levelling	Fixed project duration, smooth resource profiles	Minimise fluctuations	Stabilising workforce and equipment usage
Time-constrained RCPSP	Deadline imposed, resource use flexible	Minimise resource demand	Determining minimum crews for fixed deadline
Robust/proactive RCPSP	Scenario-based or buffered durations	Maximise robustness	Dealing with weather and productivity risk

4. Repetitive and Location-Based Scheduling

4.1 Linear Scheduling and Line-of-Balance

Repetitive activities are executed in many construction projects. CPM networks tend to overlook the importance of production rates and crew continuity. Linear scheduling techniques address this by plotting activities as lines on a time–location diagram, with the aim of achieving steady crew movement.

Mattila and Park compared the Linear Scheduling Model and the Repetitive Scheduling Method and showed that both approaches can represent repetitive work and allow identification of critical activities based on location and time. Conflicts such as two crews arriving at the same location at the same time, which are difficult to see in CPM diagrams, can be revealed by linear methods. Planners can explore trade-offs between crew size, productivity and project duration.

The main concern in linear infrastructure projects is the length along the alignment. Contractors and owners value the intuitive visualisation of crew flows and the ability to assess disturbance impacts by visually reviewing time–location charts. However, effective use requires reliable information on quantities and production rates. Integration of linear schedules with resource analysis is an active subject of research.

Several authors argue that linear techniques encourage a shift in mindset. Planners focus on shaping a consistent production rhythm and avoiding start–stop behaviour, which aligns with lean construction principles. As digital tools improve, time–location diagrams can be generated automatically from underlying data.

4.2 Location-Based Management Systems

Linear scheduling concepts can be extended from linear infrastructure to general building projects. In such projects, locations may be defined as floors, zones or work areas. Crews are planned to flow through these locations with continuous work and minimal downtime. Kenley and Seppänen's work on location-based management for construction provides a framework that combines flowline diagrams, location-based quantities and control charts [8].

One of the main advantages of Location-Based Management (LBM) is its focus on production flow. By concentrating on how crews move between locations, planners can design schedules that avoid spatial overcrowding and ensure that predecessor work is complete before successors enter the same area. This emphasis on flow and the minimisation of waiting and rework is consistent with lean construction principles. Studies show that location-based schedules can improve on-site communication and coordination [8].

LBM requires changes to information structures and planning processes. Quantities must be linked to locations, and production rates must be estimated for each trade and area. Although commercial scheduling tools are increasingly incorporating location-based features, many organisations still rely primarily on CPM software. Some practitioners therefore combine both representations, generating location-based visualisations from CPM-based logic.

There are implications for control and performance measurement. Deviations from planned production rates can be detected early at the location level. Control charts and trend analysis provide feedback, enabling teams to address the underlying causes of schedule deviations rather than reacting only to end-date slippage.

4.3 Spatiotemporal and Chronographical Models

Recent research has generalised location-based scheduling into spatiotemporal and chronographical models. Francis proposes a site–spatial–temporal modelling approach that represents construction operations as three-dimensional entities in a space–time model [12]. The aim is to represent operations as linear or continuous in both space and time. Other authors have developed related models of space–time conflicts.

Spatiotemporal scheduling models can be applied to practical projects. Planners can examine whether sufficient space exists for simultaneous operations or whether work fronts will interfere with one another. When integrated with 3D BIM models, chronographical methods can support 4D simulations that show not only when but also where activities occur [12].

These methods require specialised software and expertise. Geometric representations and spatial parameters must be linked to each activity, and data must be kept consistent as designs change. Nevertheless, many of the most challenging project delays are associated with spatial conflicts and logistics issues, which these models are well suited to reveal.

The idea of a "digital twin" is closely related to spatiotemporal models. In such a setup, real-time data from equipment, materials and workers would be mapped onto a space–time model to create a continuously updated representation of site conditions. Managers and schedulers could test alternative strategies in a virtual environment before implementing them on site. Ongoing research in scheduling is increasingly connected to this broader digital twin concept.

Table 3: Comparison of Activity-Based and Location-Based Representations

Aspect	Activity-based (CPM/PDM)	Location-based / flowline
Primary dimension	Time	Time and location
Criticality concept	Critical path and float	Critical flows and locations
View of production	Individual activities	Continuous crew movements
Strengths	Strong logic, contractual integration	Visual flow, crew continuity, spatial conflict detection
Weaknesses	Limited spatial insight	Requires quantity and rate data; fewer tools

5. Risk- and Uncertainty-Oriented Techniques

5.1 Stochastic Scheduling and Schedule-Risk Analysis

Uncertainty in activity durations, resource productivity and external conditions can undermine the reliability of deterministic schedules. Stochastic scheduling approaches model the statistical distribution of project completion times. Monte Carlo simulation is widely used to propagate duration uncertainty through the network [2]. Planners specify probability distributions and correlations for activity durations and generate a range of possible completion dates.

The outputs of schedule-risk analysis typically include completion-time distributions, confidence levels for contractual milestones, and sensitivity measures that indicate which activities or paths contribute most to overall risk. These results support more informed decision-making. Scheduling models can be classified as **proactive**, focusing on designing robust baseline schedules, and **reactive**, focusing on dynamic rescheduling policies when disruptions occur [3].

The practical application of schedule-risk analysis is uneven. Some firms use sophisticated risk tools, while others rely on informal judgement. Barriers include the effort required to estimate distributions, concerns about communicating probabilistic outputs to clients and the lack of integration between risk tools and standard scheduling software. Research continues on simplifying risk modelling while retaining essential insights.

Contingency should be managed in line with the outputs of schedule-risk analysis. Some organisations prefer explicit time contingency, while others rely on hidden float. The literature suggests that centralised contingency, visible and managed at project level, is more effective than concealed safety margins. Integration of risk-analysis outputs with buffer management strategies remains an active area of investigation.

5.2 Critical Chain Project Management

Critical Chain Project Management (CCPM) combines resource-constrained scheduling with buffer-management concepts derived from the Theory of Constraints [11]. The *critical chain* is defined as the longest sequence of tasks considering both precedence and resource constraints. CCPM aggregates safety into project and feeding buffers placed at strategic points in the schedule, and execution focuses on monitoring buffer consumption.

The conceptual shift promoted by CCPM is two-fold. First, explicit modelling of resource contention encourages planners to focus on critical-chain activities and limit multitasking. Second, CCPM frames schedule reliability in terms of buffer status rather than task-level float. Conventional scheduling often encourages hidden padding of durations and inefficient behaviour, whereas CCPM encourages shorter task estimates and explicit management of uncertainty through buffers [11].

Empirical experience with CCPM in construction is mixed. In some contexts, on-time completion and lead times have improved when CCPM is supported by practices such as limiting work-in-progress and emphasising single-task focus. However, CCPM requires cultural change, revised contract structures and re-training of stakeholders, which can be difficult to implement. In practice, CCPM concepts are often combined with other methods, such as location-based scheduling and lean planning, rather than implemented as a stand-alone replacement.

CCPM has also stimulated debate about the nature of *criticality*. Defining a single critical chain may oversimplify the complex web of risks in large projects. Advocates argue that the main value of CCPM lies in behavioural change, and that by focusing attention on protecting project completion rather than local task efficiency, it encourages better collaboration among project participants. The tension between analytical and behavioural perspectives is a recurring theme in scheduling discussions.

6. Lean and Collaborative Scheduling

6.1 The Last Planner System (LPS)

Lean construction seeks to create value through reliable flow and waste reduction. The Last Planner System (LPS) is a production planning and control model in which those closest to the work participate in developing and committing to short-term plans [10]. A master schedule defines overall milestones; phase plans break work into manageable packages; look-ahead plans identify and remove constraints; and weekly work plans contain specific, near-term tasks.

Tasks should only be promised when they are *sound*, meaning that required information, materials, labour, equipment and space are available. LPS uses Percent Plan Complete (PPC), the proportion of planned tasks completed as promised, and systematically analyses reasons for plan failures to drive continuous improvement. The focus shifts from producing a detailed predictive schedule to managing the reliability of work execution [9].

Studies show that LPS can improve schedule reliability, reduce variability and enhance collaboration. Successful implementation requires facilitation skills, organisational support and contractual incentives aligned with collaborative planning. LPS provides a model for using schedules as coordination tools rather than merely reporting devices. Many projects now operate with a CPM baseline and an LPS-driven short-term planning process, reflecting the hybrid nature of modern scheduling practice.

Some implementations also track indices such as causes of non-completion, constraint-removal rates and crew productivity. These metrics provide a richer picture of system performance. Information on reasons for plan failure can be used to guide process improvements. LPS can therefore support more reliable execution when combined with appropriate measurement and feedback.

6.2 Integration with Network and Location-Based Models

Research has explored how scheduling representations can be integrated with LPS. Seppänen and co-authors discuss how location-based schedules provide the underlying flow model [8]. In this approach, milestones from the location-based baseline schedule are translated into phase and weekly plans through collaborative sessions, and deviations in production rates trigger adjustments to plans and to productivity assumptions.

Some practitioners use CPM networks as high-level coordination tools, with LPS sessions focusing on critical and near-critical activities. Network logic helps identify which activities have the greatest impact on project completion, while LPS ensures that those activities are made ready and executed reliably. Combining analytical models with collaborative processes is often seen as the most effective way to achieve robust performance.

Digital tools increasingly support these practices, including electronic planning boards, mobile apps for capturing daily constraints and shared dashboards that display reasons for plan failures. The literature emphasises that such tools can enhance transparency and data collection, but cannot substitute for the behavioural principles underlying LPS. In this sense, lean planning acts as a driver for technology rather than a by-product of it.

Collaborative models can also be scaled to multi-project environments. When several projects share designers, suppliers and specialist crews, coordination of commitments and constraints becomes more difficult. Extending LPS concepts beyond a single site to a portfolio or value-chain level requires methodological innovation and new forms of contractual and governance arrangements.

7. Digital and Intelligent Scheduling Techniques

7.1 Decision Models and Expert Systems

Incorporating expert knowledge about construction planning and scheduling into computer systems has been a research topic for several decades. Warszawski discussed how decision models and expert systems could support construction management tasks [14]. Moselhi and Nicholas developed prototype expert systems for construction planning and control to demonstrate how rule-based logic could detect schedule inconsistencies and suggest corrective actions [15].

These early systems were limited by computing power and by the difficulty of formalising tacit knowledge. Nevertheless, key ideas remain relevant: the need to represent qualitative planning rules, the importance of explanation for system recommendations, and the role of interactive human–computer collaboration. Many modern scheduling packages include rule-based checks and advisory modules that can trace their origins to this line of research.

Expert-system research also highlighted the importance of data structuring. Scheduling information must be captured in clearly defined formats if it is to be processed automatically. This push toward structured digital information is one of the foundations of contemporary “intelligent” scheduling tools.

Classic expert systems offer advantages in domains where rules are well understood and transparency is required. Regulatory compliance checks, constructability constraints and safety rules can often be encoded as explicit logic that planners can review and refine. Future generations of scheduling tools are likely to combine such rule-based modules with optimisation or AI components.

7.2 4D BIM and Model-Based Scheduling

4D BIM links each schedule activity to specific building components in a 3D model. Studies comparing the creation of construction schedules in 4D BIM environments with more traditional methods indicate that 4D approaches can reduce effort in schedule generation, improve consistency between design and programme, and support clear visualisation of construction sequences [13].

4D BIM offers several advantages over traditional representations. Stakeholders can see the build-up sequence, detect potential clashes and assess constructability in space and time. Visual simulations make it easier to communicate with non-technical stakeholders. When combined with quantity take-off and cost data, 4D models can support integrated 5D analysis of time and cost in complex projects.

However, 4D BIM requires robust workflows for linking model objects to activities and agreement on the appropriate level of detail for scheduling. Planners can be overwhelmed if activities are defined too finely. The development of automated or semi-automated methods to derive baseline schedules from models still needs human adjustment to reflect actual construction methods and constraints [13]. Success depends on both technological readiness and organisational processes.

An additional frontier is the integration of 4D BIM with advanced analytics and simulation. When schedules are tied to models, planners can explore scenarios such as alternative construction methods, crane locations or logistics routes.

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Realising the vision of a truly integrated, model-based planning environment requires interoperability between software platforms and shared information standards.

7.3 Data-Driven and AI-Enabled Scheduling

Recent advances in data analytics and machine learning have stimulated renewed interest in data-driven scheduling. Examples include case-based reasoning systems that propose schedules based on similarity with past projects, predictive models that estimate activity durations from historical productivity data, and hybrid systems that combine rule-based logic with evolutionary or other metaheuristics trained on real project outcomes. These approaches aim to support human experts rather than replace them.

Data-driven scheduling depends on the availability of high-quality project databases. Many construction firms are now capturing detailed records of past schedules, costs and productivity. Without such data, models risk overfitting or capturing random patterns. Interpretability is also a concern for planners. Some recent systems therefore combine rule-based reasoning with statistical or machine-learning components to balance transparency and predictive power [14].

During the control phase, sensor data, site photographs and progress reports can be analysed to detect deviations from planned schedules. Research on automated progress tracking and predictive delay detection using computer vision and data fusion is expanding rapidly, although it is beyond the detailed scope of this review. The literature suggests that AI-enabled services will increasingly provide decision support in an information-rich environment.

Scheduling tools can also be integrated with collaborative environments such as LPS. Human teams retain final decision authority, while machine-learning models propose look-ahead plans or highlight potential conflicts. Designing scheduling systems in which responsibility and reliance are carefully balanced is a key challenge for both researchers and practitioners.

Table 4: Digital and Intelligent Scheduling Approaches

Approach	Core idea	Typical inputs	Example contributions
Rule-based expert systems	Encode planning heuristics as rules	Activity data, resource libraries	Method selection, schedule checks [14], [15]
Hybrid expert systems	Combine rule bases with optimisation/metaheuristics	Rules, constraints, historical data	Integrated planning and scheduling [15]
4D BIM scheduling	Link activities to 3D model objects	BIM models, CPM/LOB schedules	Visualisation, automated sequencing [13]
Data-driven/AI scheduling	Learn patterns from historical and real-time data	Project databases, sensor streams	Draft schedules, predictive productivity

8. Comparative Synthesis and Research Gaps

According to the literature reviewed, project scheduling has evolved into a multi-faceted field with a variety of techniques tailored to different aspects of project complexity. CPM and PERT are network-based methods that still provide clear logic representation and underpin contractual schedules [1]. RCPSP models can address resource constraints explicitly and offer powerful analytical tools, but they can be difficult to implement at scale [4]. Flow and spatial aspects are introduced for linear and multi-storey projects through location-based and line-of-balance methods [7].

Risk-oriented methods recognise that realistic planning must account for variability. Different strategies for managing uncertainty are demonstrated in Monte Carlo-based schedule-risk analysis [3]. Reliable performance depends on commitment, information flow and learning, not only on computational optimisation, as highlighted by the Last Planner System [9]. Powerful visualisation and decision support can be provided by digital and intelligent techniques [11].

Several research gaps emerge from this synthesis. First, integration across technique families remains limited. There is a need for models that combine resource-constrained, location-based scheduling, risk analysis and lean planning within coherent decision-support systems. Second, there is relatively little empirical evidence on the real-world impact of advanced methods. Longitudinal studies of project portfolios could provide valuable insights. Third, the practical success of scheduling methods is strongly influenced by human factors; behavioural models of planners and site teams are a promising direction.

Despite their relevance for capital programmes, multi-project and programme-level scheduling have received less attention than single-project models. Market conditions can affect schedule risk and resource availability. Integrating portfolio scheduling with enterprise risk management and strategic planning is an important future research area. There is also a need to clarify links between scheduling decisions and environmental performance metrics.

9. Conclusion

This literature review examined major families of project scheduling techniques. Classical network methods, RCPSP models, linear and location-based techniques, risk-oriented approaches, lean planning models and digital/AI-enabled tools have all matured as distinct strands within the field. No single method is sufficient to address every facet of project complexity. The implication for practitioners is that method choice should be based on project characteristics. A scheduling practice may combine several approaches, for example using CPM or LOB for the contractual baseline, RCPSP-style reasoning for resource feasibility, location-based diagrams for production flow, LPS for short-term planning, and 4D BIM or AI-enabled tools for visualisation and decision support. The challenge for researchers is to develop models and tools that integrate these approaches in ways that are robust yet easy to use.

The value of project scheduling lies in enabling more reliable, coordinated and learning-oriented project delivery, not merely in producing elegant charts or mathematically optimal solutions in isolation. By understanding the strengths and limitations of the techniques reviewed, both researchers and practitioners can better exploit scheduling as a central tool of construction management. Future work that bridges analytical rigour, digital innovation and human-centred management has the potential to significantly enhance the contribution of scheduling to the performance of the built environment.

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