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Mitigating Co-Activity Conflicts and Resource Overallocation in Construction Projects: A Modular Heuristic Scheduling Approach with Primavera P6 EPPM Integration

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Abstract: This paper proposes a heuristic approach for managing complex construction projects. The tool incorporates Primavera P6 EPPM and Synchro 4D, enabling proactive clash detection and resolution of spatial conflicts during concurrent tasks. Additionally, it performs resource verification for sufficient allocation before task initiation. This integrated approach facilitates the generation of conflict-free and feasible construction schedules. By adhering to project constraints and seamlessly integrating with existing industry tools, the proposed solution offers a comprehensive and robust approach to construction project management. This constitutes, to our knowledge, the first dynamic digital twin for the delivery of a complex project.

Keywords: heuristics; scheduling algorithms; constraint satisfaction problems; resource allocation; co-activity conflict mitigation

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1. Introduction

The successful delivery of large-scale industrial construction projects often necessitates the development of requisite venues and infrastructural facilities. This undertaking presents a significant industrial project with complex logistical challenges. A central challenge lies in formulating a cohesive construction schedule, which can be categorized as a resource-constrained project scheduling problem (RCPSP). The RCPSP is a well-studied problem in the field of project management, where the objective is to determine the optimal sequence and timing of activities. This paradigm addresses the intricate interplay of various resources such as workspace, machinery, and manpower, all of which are subject to inherent limitations and constraints, alongside a network of tasks characterized by precedence relations and resource requisitions [1–4]. The implementation of the RCPSP in construction projects can potentially minimize project duration, ultimately translating into lower overall project costs [2,5,6]. Additionally, the RCPSP offers a multi-scenario simulation framework, providing valuable insights into the potential outcomes and trade-offs of different scheduling strategies [7–10]. This comprehensive analysis empowers project managers to make informed decisions that enhance both project efficiency and resource utilization.

However, basic RCPSP models may not capture all the complexities of construction projects. While traditional RCPSP models assume deterministic activity durations and resource availabilities, construction projects are inherently stochastic, with unforeseen delays and resource availability fluctuations [11]. In the context of complex construction projects, as exemplified in this study, the RCPSP is further complicated by the need to address spatial conflicts and ensure efficient resource utilization. Spatial conflicts arise when the physical locations of concurrent construction activities overlap, leading to potential clashes and disruptions. Efficient resource utilization is crucial to minimizing delays and optimizing project costs. Addressing these challenges is essential for the successful and timely completion of a project.

Another limitation to consider when applying the RCPSP in construction projects is the complexity involved in solving large-scale instances. Optimizing schedules for extensive construction projects with numerous activities and resource constraints often necessitates the use of specialized scheduling software, which may not be readily accessible or user-friendly for all construction professionals. Diverse solutions have been offered to mitigate the complexities inherent in project scheduling. Notably, Primavera P6 is a pre-eminent project management tool developed by Oracle [12]. With over three decades of development and widespread adoption across industries, Primavera P6 has established itself as a leader in project management software. It offers robust functionality for both local deployment (P6 PPM) and scalable service provision (P6 EPPM), seamlessly integrating with Oracle databases and supporting external data import. It excels at addressing scheduling constraints such as workspace clashes, enabling the formulation of optimized schedules [13]. However, its multifaceted functionalities require comprehensive training for proficiency.

While Primavera P6 provides advanced features for project scheduling, it lacks the inherent functionality to detect potential spatial conflicts that may arise during the construction-planning phase. Traditionally, this verification has been conducted as a separate and disconnected process, often requiring the use of specialized 4D simulation software, such as Synchro4D [14] (chap. 6). Through integration with project scheduling tools, such as Primavera P6, Synchro 4D can import the project plan and link it to a corresponding 3D building information model (BIM). This BIM serves as a digital representation of the construction plan, enabling Synchro 4D to simulate and visualize the construction sequence over time. This capability allows for the proactive identification of potential spatial conflicts between construction elements. Early detection of such clashes is crucial for managing complex projects where coordinating concurrent activities and resources is paramount. However, while Synchro is effective at spatial conflict detection, it has limitations in fully resolving these conflicts. The tool does not possess advanced functionalities for automatically adjusting the construction schedule or resource allocation to eliminate the identified conflicts. Consequently, project managers may need to manually manipulate the schedule or resource plans within Primavera P6 to sequence activities differently and find a feasible, conflict-free solution.

This paper presents Optimizio [8–10], a heuristic scheduling tool enhanced with functionalities that address the limitations associated with conventional resource leveling and conflict resolution processes. Optimizio automates the entire workflow, offering significant advantages for project management, including the ability to tackle complex scheduling problems, flexibility, and ease of use, which eliminates the need for additional training. The proposed approach offers seamless integration from Primavera P6's project planning data to spatial conflict reports from Synchro 4D. This facilitates the streamlined execution of resource leveling and clash resolution while adhering to all predefined project constraints. The resulting feasible schedule is generated in a format that is directly compatible with Primavera P6, enabling efficient workflows for industry professionals. Through rigorous validation by domain experts, the solution demonstrates its promise for addressing real-world challenges in industrial applications.

The proposed Optimizio approach and its implementation details are thoroughly discussed in this paper. The organization of the paper is as follows: Section 2 presents the materials and methods, providing a detailed description of the problem, a benchmark instance utilized for evaluation purposes, and the overall methodology employed by Optimizio. Section 3 showcases the results of the proposed algorithms. Finally, the major findings, implications, and future research directions are explored in Section 4.

2. Materials and Methods

2.1. Statement of the Problem

This study addresses a real-world construction scheduling challenge that extends beyond the core RCPSP formulation. While the RCPSP provides a solid foundation for scheduling activities under logical dependencies and resource constraints, the use case in this study introduces additional complexities, which are given below.

2.1.1. Data Exchange and Software Integration

One such complexity involves establishing seamless data exchange between existing project management software. Construction projects typically involve a multitude of stakeholders and software platforms, each with its own data formats and workflows. Facilitating efficient data exchange and integration among these tools is crucial for leveraging existing project data and enabling streamlined workflows.

In this study, the initial project plan was obtained from the Oracle Primavera P6 Enterprise Project Portfolio Management (EPPM) cloud solution in an extensible markup language (XML) format, which is suitable for automated data parsing. Subsequently, the analysis of spatial conflicts commenced with the generation of a 3D BIM representing the digital construction plan. The model elements were then spatially mapped to their corresponding activities within the Primavera P6 schedule. This integrated data allowed Synchro 4D to simulate and visualize the construction sequence over time, enabling a four-dimensional (4D) representation. This 4D simulation facilitated the identification of potential spatial conflicts, defined as situations where two or more BIM elements occupy the same physical space concurrently.

These spatial incompatibilities need to be resolved to generate a new, conflict-free schedule. However, merging the identified spatial conflicts with the updated Primavera schedule is not a straightforward task. The integration of the spatial conflict information with the revised scheduling approach presents a significant challenge that must be overcome to ensure the successful and efficient execution of the construction project.

2.1.2. Spatial Conflicts and Contractor Coordination

In the construction projects considered here, the work areas are managed by different contractors, necessitating coordination to mitigate spatial incompatibilities and ensure efficient execution. Inappropriately addressed conflicts can lead to suboptimal schedules, rework, and potential project delays.

Resolving spatial conflicts through conventional manual approaches is frequently a time-intensive and resource-demanding process. While techniques such as adjusting activity dates in Primavera P6 or modifying component positions within 3D models can address certain conflicts, the process is inherently iterative. Teams must repeatedly review and update the 4D simulation, which combines scheduling data with 3D models, until an acceptable solution is achieved. This iterative cycle can be time-consuming and inefficient, particularly for complex projects with intricate spatial constraints. In addition, they are prone to errors, as the manual analysis and coordination processes may overlook intricate interdependencies between activities, resource allocations, and spatial constraints. This necessitates the development of automated and optimized solutions to facilitate seamless coordination among contractors and enhance project execution efficiency.

2.1.3. Suboptimal Resource Allocation

Effective resource management is another critical aspect of successful project execution. Project managers must meticulously assess resource needs, availability, and potential limitations to create a comprehensive resource plan aligned with project goals and timelines.

In this study, instances of suboptimal resource allocation in the initial planning stages were identified. Resources were frequently requested in excess of their available units, potentially leading to a bottleneck during project execution, jeopardizing timely completion, and impacting project delivery performance.

While Primavera P6's resource leveling tool is a valuable asset for resource management, it has limitations when dealing with resource allocation within individual activities. The tool is designed to resolve resource conflicts between activities that compete for the same resources, but it cannot address situations where a single activity is overloaded with resource requirements. Additionally, the leveling tool may encounter challenges when handling activities that involve a mix of labor and non-labor resources, potentially leading to inaccurate or incomplete leveling results. Consequently, the leveled schedule may require manual adjustments to ensure it aligns with practical constraints and project execution plans. To address this challenge, a robust methodology that seamlessly integrates resource management considerations into the project planning process is crucial for overall project efficiency and optimal results.

2.2. Problem Instance

This problem instance is an original contribution of this research and has not been previously reported in the existing literature. This study evaluates the proposed solution's effectiveness in handling complex project scheduling scenarios with diverse activity types, resource constraints, and project-specific limitations.

A benchmark instance comprises 24 logically linked activities categorized into two distinct types: level of effort (LoE) and task dependent. These categories exhibit distinct characteristics regarding resource demand, calendar utilization, and workload computation based on duration. The planning process involves the management of three types of resources: Resources A, B, and C. The initial planning revealed an overallocation of Resource A, indicating that the requirement for this resource exceeded its available capacity. Additionally, Resources B and C exhibit incompatibility, precluding their simultaneous utilization.

The objective of this instance is to generate a feasible schedule that adheres to all activity precedence relationships, resource availability constraints, and project-specific limitations.

2.3. Proposed Solution

To address the complex project scheduling problem, we propose Optimizio [8–10], an approach to model and solve complex scheduling problems. Optimizio leverages a greedy heuristic algorithm that dynamically assigns scores to unscheduled tasks at each decision point. These scores are calculated using a cost function that incorporates relevant scheduling criteria [8]. Based on these calculations and the satisfaction of constraints, our tool schedules as many feasible tasks as possible at each time step, ultimately yielding a feasible and relatively optimal schedule. The efficacy of Optimizio has been validated through extensive testing on large-scale industrial scheduling problems encompassing diverse domains [9], including nuclear, defense, and construction industries.

Optimizio is built upon an object-oriented programming (OOP) solution that encapsulates key components of the RCPSP model through three fundamental classes:

- Project class: This class encapsulates the overall project information, including the decision time step for recalculating the cost function, definition of calendars used in the planning, start and end dates of the project, etc. It also serves as a container for tasks and resources and manages the interactions between them.
- Task class: Instances of this class represent individual tasks within the project. Each task object captures task-specific attributes, such as duration, precedence relationships, and resource requirements.
- Resource class: This class represents available resources within the project. These resources can include personnel, equipment, materials, or any other assets that are required to complete the project tasks.

The core Optimizio platform was extended through the integration of additional modules to address specific project scheduling challenges encountered in this use case. These extensions are given below.

2.3.1. Connector Module

This module offers user-configurable parameters for Primavera P6 data input. This functionality enables users to define the specific Primavera version used for the project schedule. Additionally, users can specify XML tags to be excluded or included during the parsing process. This granular control ensures that the extraction of relevant data points is tailored to the specific project requirements. Following the user configuration and project data upload, a dedicated data preprocessing step is initiated. This step extracts information from the uploaded project data encompassing comprehensive information about the scheduled activities, including the activity name, unique identification code, duration, start and finish dates, predecessor and successor relationships, resource assignments, and user-defined parameters specified during the configuration phase. The extracted data are then transformed into instances of the Optimizio–RCPSP classes. This transformation process essentially converts the raw project data into a structured format that is specifically designed for subsequent analysis within the Optimizio application framework.

This module extends its functionality by facilitating the import of a clash report generated by Synchro4D in an Excel format. This report contains pre-identified pairs of locations that are deemed incompatible due to potential spatial conflicts arising during the 4D simulation process. The imported clash report data undergo a transformation process to integrate them with the Optimizio model. Each resource identified in the clash report is converted into a corresponding resource class instance containing an additional attribute that stores information regarding all incompatible resources associated with that particular resource. This process creates a mapping between resources and their associated incompatibility constraints, effectively capturing the spatial conflict information within the model. By incorporating this information, the model accounts for potential spatial conflicts that may arise during the construction-planning phase. The verification of these resource incompatibilities will be addressed in the subsequent section, the resource incompatibility verification module.

In addition to facilitating the retrieval of input data, this module is responsible for exporting the output of the Optimizio solver to Primavera P6, enabling further analysis and integration with downstream processes. The module generates an XML representation of the feasible schedule produced by the Optimizio solver. This output adheres to the Primavera P6 EPPM data format, ensuring seamless interoperability and enhancing usability for project managers and their teams.

2.3.2. Resource Incompatibility Verification Module

To prevent resource conflicts during project execution, this extension verifies the compatibility of resources assigned to concurrent tasks. It checks for predefined incompatibility constraints within the resource class before task execution. These constraints act as rules specifying which resources cannot be used together on overlapping tasks. If incoming tasks require resources incompatible with those used by ongoing tasks, the incoming task is automatically delayed. They will remain in a waiting state until all incompatible resources are freed by completing ongoing tasks. This proactive approach guarantees the feasibility of the project plan by eliminating the risk of resource conflicts.

2.3.3. Resource Availability Verification Module

This module simulates resource unit availability throughout the project schedule. It tracks assigned resource units for each task, considering factors like resource quantities, work calendars, and potential constraints. This ensures resource assignments align with actual availability before tasks begin. By factoring in resource availability alongside other scheduling constraints, Optimizio could generate more realistic and achievable schedules, ultimately increasing the project's success rate.

The integration of the Optimizio algorithm with the latter two modules is shown in Algorithm 1.

Algorithm 1 Heuristic-Based Project Scheduling with Co-Activity and Resource Considerations

```
Set empty list PT for planned tasks
while PT ≠ J do
    for each time step t do
        for activities J_i do
            if predecessor relationships are respected then
                if required resources are available then
                    if required resources have no conflict with resources already allocated to other concurrently scheduled activities then
                        if required resources possess sufficient capacity to accommodate the task launch then
                            Calculate objective score
                        end if
                    end if
                end if
            end if
        end for
        Sort activities to be scheduled
        Execute activities based on sorted list
        Append finished activities to the list PT
    end for
end while
return PT
```

3. Results

The entire benchmark execution achieved a runtime of approximately 0.5 s on an eight-core CPU. This process encompassed data retrieval from Primavera P6 EPPM and Synchro 4D to obtain the initial project plan and resource conflict information. The extracted data were then preprocessed to facilitate the generation of an RCPSP model that captured project requirements and constraints. Subsequently, a heuristic-based scheduling algorithm was employed to simulate and generate feasible project schedules. The quality and feasibility of the generated schedules were then assessed using user-defined key performance indicators (KPIs). Finally, the optimized schedule was exported in an XML format compatible with Primavera P6 EPPM project management software, enabling further analysis and decision-making within the familiar project management environment.

The resource overallocation identified in the initial project plan, as shown in Figure 1a, could lead to various challenges during project execution, such as delays, conflicts, and inefficient resource utilization. By incorporating the Optimizio algorithm integrated with the resource availability verification module, the output schedule exported to Primavera P6 EPPM showed no more resource overallocation issues, demonstrating the effectiveness of the integrated scheduling optimization approach, as demonstrated in Figure 1b.

The baseline project schedule demonstrated the occurrence of spatial conflict. This conflict is visualized in Figure 2 for a comprehensive understanding, showcasing two distinct perspectives: a 3D representation (a) and a top-down view (b). To address this incompatibility, the proposed approach offered useful insights into the scheduling simulation process. The tool generated KPIs that quantified resource occupancy, illustrating the time periods when resources were utilized throughout the simulated project schedule. Figure 2c revealed the overlapping usage of incompatible resources, Resource B and Resource C, in the initial plan. In contrast, the output from Optimizio, as illustrated in Figure 2d, showcased the successful elimination of overlapping occupancy for these two resources. Furthermore, the tool possesses the capability to generate a report of identified spatial conflicts during the simulation (Figure 2e). This report details the resources involved and time frames of the clashes as well as the total duration of the conflicts. These detailed KPIs serve as a valuable tool for project managers, enabling them to anticipate and address co-activity conflicts before they disrupt the project's execution.

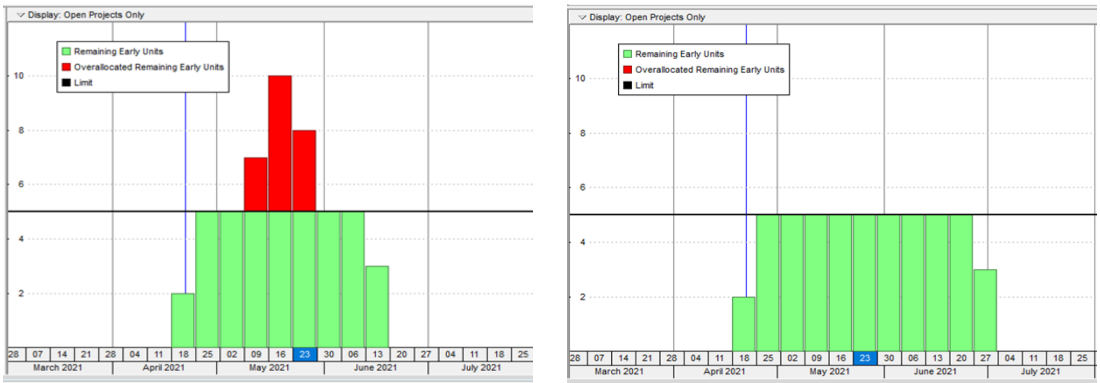
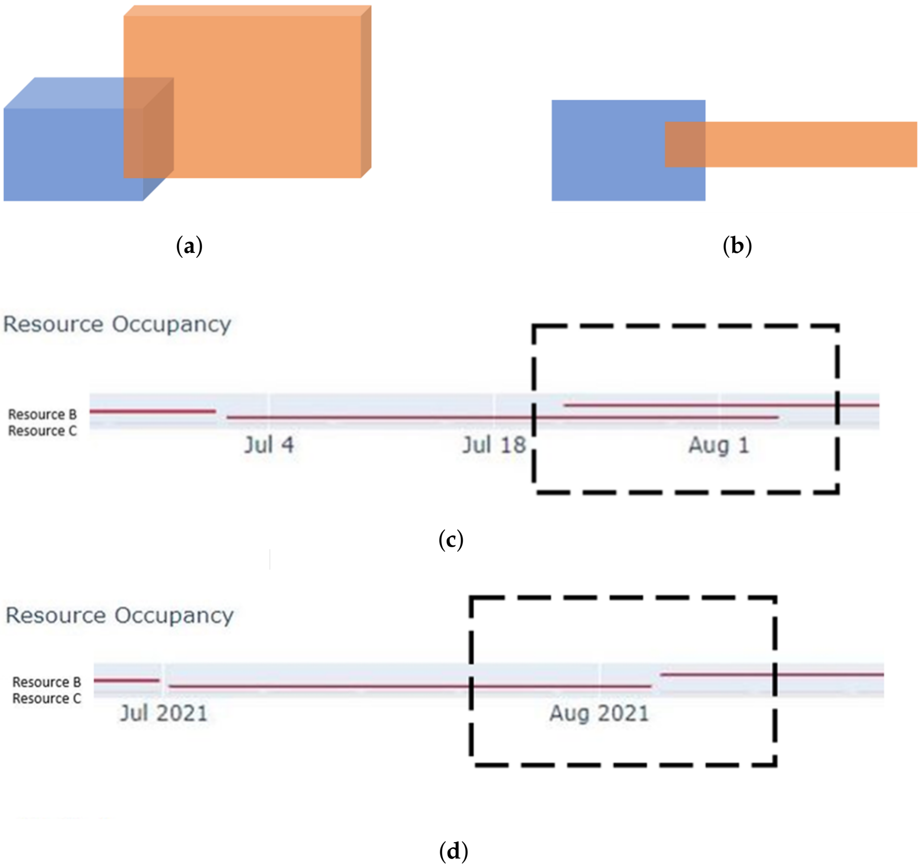


Figure 1. Resource allocation verification. Resource overallocation in the initial project plan, indicating potential issues during project execution (**a**). The schedule generated by Optimizio, demonstrating improved resource allocation for a more efficient and feasible execution plan (**b**).



Resource Id	Incompatible Resource Id	Start of Clash	End of Clash	Duration of Clash
Resource B	Resource C	2021-07-22 08:00:00	2021-08-05 08:00:00	14 days, 0:00:00

(e)

Figure 2. Analysis of co-activity conflicts. The initial project schedule reveals overlapping workspace requirements when visualized from multiple viewpoints, including a three-dimensional representation (**a**), a top-down perspective (**b**), and the aspect reflected by Optimizio's KPI (**c**). (**d**) The updated schedule generated by Optimizio, highlighting conflict resolution. (**e**) List of identified spatial conflicts, including resources involved, start/end times, and total duration of the conflict.

4. Discussion

This work proposes algorithms that bridge the information gap between industrial tools and proactively address scheduling issues caused by resource incompatibility and overallocation. The integration of these approaches into the project management workflow enhances the ability to plan, execute, and monitor projects with greater precision and confidence. Ultimately, this leads to improved project outcomes by minimizing disruptions and delays caused by unforeseen circumstances.

The use case highlights the strategic integration of three key modules. The first module facilitates seamless integration between project management softwares, resulting in the comprehensive consideration of all project perspectives. This integration enables the tool to read input directly from Primavera, along with information on spatial conflicts from Synchro4D. Limited research on Primavera–Synchro4D integration suggests our proposed solution is among the first attempts to bridge the gap between the separate functionalities of these tools. The unified data stream ensures the proposed solution leverages the most accurate project constraints and scheduling information for optimal results. Furthermore, the tool's outputs, which include feasible schedules, can be directly exported back to Primavera P6 EPPM. This bidirectional data flow allows project managers to leverage the capabilities of the proposed tool while maintaining the familiarity and functionality of the Primavera platform.

Additionally, the proposed solution expands its connector capabilities beyond those covered in this publication. Construction projects often face a data integration challenge due to the involvement of multiple stakeholders with distinct project management software preferences. To accommodate this heterogeneity, an additional module was developed to facilitate the transformation of schedules from Microsoft Project, another widely used project planning platform [15], into a format readily interpretable by Primavera. This functionality addresses potential inconsistencies that may arise when utilizing Primavera's built-in conversion features, ensuring seamless data exchange and fostering improved project collaboration.

To further maximize the connector capabilities, the tool offers an additional module that leverages Oracle Web Services to directly interact with project schedules within Primavera. This eliminates the need for manual data exchange through XML files. Users can simply provide their Primavera Oracle account credentials and identify the target project using elements like project object ID, ID, name, or other user-defined identifiers. This streamlines the connection process and facilitates real-time data access.

Acknowledging the widespread use of Primavera P6 EPPM as a leading project management software, one of Optimizio research goals is to facilitate seamless adoption for Primavera users. The ideal approach would involve integrating the proposed tool directly within the Primavera platform as a third-party add-on. This direct integration would streamline the user experience and enhance the accessibility of our constraints engine for the vast user base of Primavera P6 EPPM.

While seamless data integration streamlines processes, real-world project management remains susceptible to unforeseen circumstances. One of the major challenges lies in managing resource overallocation, which occurs when the demands placed on a resource exceed its available capacity. This situation can arise due to various factors, such as improper resource planning, inefficient coordination among stakeholders and contractors, or unexpected changes in project scope. One widely adopted approach is the resource leveling technique, which creates a balanced workload by reallocating resources [16,17]. Primavera's built-in resource leveling features provide effective workload analysis across multiple activities. These features enable project managers to identify instances where a resource is overbooked or assigned to different tasks during the same period, leading to potential overallocation [18]. However, the methods lack the capability to handle situations where a single activity is overloaded or where the requirements are of mixed heterogeneous types.

Construction sites are inherently dynamic environments where numerous activities compete for limited space. By proactively identifying, preventing, and resolving spatial conflicts in construction planning, projects can achieve improved efficiency, enhanced safety, and, ultimately, greater project success. Various optimization methods have been explored to resolve spatial conflicts in construction projects, such as genetic algorithms (GAs) [19,20], particle swarm optimization (PSO) [21], and the building displacement operation (BDGSA) [22]. Alongside optimization approaches, leveraging discrete event simulation (DES) and Unity-based path planning offers a promising automated solution for identifying and resolving potential time–space conflicts [23]. However, the necessity of integrating these algorithms with project planning processes remains a challenge that needs to be addressed.

Several studies propose integrating 4D/5D planning with advanced tools for conflict management in construction projects. One such example is the nD Planning System, which integrates workspace management with critical path method (CPM) scheduling and building information modeling (BIM) data [24]. It provides analytical capabilities for conflict resolution, including adjusting activity schedules, modifying workspace sizes and locations, and exploring alternative construction methods. Nevertheless, a potential limitation of this approach lies in its iterative conflict resolution process, where conflicts are tackled one by one, which may not be optimal for highly complex projects with intricate dependencies.

Our proposed approach addresses limitations in existing methods by incorporating two additional modules that enhance resource management in a practical and efficient way. These modules focus on proactive conflict identification and real-time resource availability verification before tasks commence. While this combined approach may extend the overall project duration, it represents a strategic trade-off. A marginally prolonged yet demonstrably more feasible and executable schedule is a prudent compromise, as it mitigates the risks associated with unforeseen delays, rework, or safety incidents that could potentially arise due to resource incompatibility or unavailability issues.

In this study, the identified spatial overlaps and resource overallocation necessitate delaying the upcoming task's initiation to adhere to stakeholder requirements. Beyond this primary function, the tool offers additional features successfully employed in other scenarios that could be adapted here. Notably, it can compare task priorities and recommend pausing the ongoing task if it has lower priority than the upcoming one. Alternatively, a user-defined rule-based algorithm could be implemented to highlight the tool's versatility.

While the proposed solution offers significant advantages, it is essential to acknowledge its current limitations and outline potential future research directions. At present, Optimizio lacks a cloud-based solution, restricting its usage to local machines. This limitation hinders the ability to directly link team member information to simulations, potentially impacting collaboration and accessibility. To address this limitation, future developments should focus on creating a cloud-based solution for Optimizio. By transitioning to a cloud-based platform, users would gain the ability to access and run Optimizio simulations from anywhere with an internet connection. This enhancement would significantly improve accessibility and facilitate seamless collaboration among geographically dispersed teams.

Despite this current limitation, the scheduling approach presented in this paper offers a comprehensive solution to the complex problem of industrial project scheduling by addressing the key challenges of compatibility with existing tools, flexibility, and domain-specific validation. The successful implementation and evaluation of this approach demonstrate its potential to improve resource utilization, reduce delays, and enhance the overall efficiency of industrial projects. By ensuring data continuity and transparency, this dynamic rule-based engine enriches the capabilities of project management and BIM 4D platforms, ultimately creating a digital twin of the project delivery process.

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