

A hybrid decision-support framework for crisis-induced rescheduling in infrastructure projects: Integrating a graph-based model with a generative AI interface

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ABSTRACT: This study presents a hybrid decision-support framework for crisis-induced rescheduling in a large-scale infrastructure project. Using a real-world case involving the insolvency of a critical architectural subcontractor, the study examines how project-continuation alternatives can be compared based on net financial gain, resource demand, and operational constraints. The deterministic component represents project activities and dependencies in a directed graph and calculates financial and resource indicators for the evaluated continuation alternatives. A generative artificial intelligence interface is then applied as an interaction layer over these deterministic outputs, enabling decision-makers to query and compare calculated scenarios in natural language. The empirical application illustrates how the framework can support the identification of a financially preferable continuation alternative and facilitate scenario comparison in a time-sensitive crisis setting. Since the evidence is derived from a single project structure and a single focal disruption type, the proposed framework is

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presented as a case-based methodological proof of concept that requires further validation across additional project and crisis contexts.

KEYWORDS: project rescheduling; crisis management; graph-based decision support; hybrid AI method; intelligent decision-support

JEL CODES: C61, D81, O22

1. Introduction

One of the fundamental socio-economic challenges in contemporary project management is the planning and strategic coordination of complex infrastructure projects, especially when execution requires the joint participation of multiple disciplines. The successful implementation of such high-stakes ventures requires not only close cooperation and the precise allocation of resources but also a robust framework for maintaining organizational trust and professional synergy amid volatile market conditions. The present research is based on the examination of a construction project management framework. It analyzes the dual impact of a real project faced with a crisis and the strategic management responses to it.

The project under review is structurally divided into several disciplines, of which four are technology and one is architecture. The tight interdependencies and parallel tasks across the different disciplines result in complex planning and construction processes where any operational friction threatens the collective efficacy of project personnel and the overall return on investment. To ensure the preservation of both economic and social value during implementation, it is essential to coordinate disciplines, define the critical path, and identify potential obstacles at an early stage to mitigate risks to the project's liquidity.

The focal point of the research is an unexpected exogenous crisis that posed a significant risk to the financial outcome of the project. The bankruptcy of the architectural subcontractor caused structural disruption, halting construction and jeopardizing not only contractual deadlines but also the long-term economic sustainability of the investment. Managing such crises requires more than conventional risk mitigation; it requires quick, efficient rescheduling and restructuring strategies specifically designed to minimize financial losses from delays and associated sunk costs.

The aim of this study is to develop and demonstrate a hybrid decision-support framework for identifying and comparing project continuation alternatives following a crisis-induced disruption to an infrastructure project. A core component of the research is the formalization of an algorithm that enables the rapid and optimized redesign of scheduling structures with the help of directed

graphs. To improve the interpretability and accessibility of the deterministic scenario outputs, we extended the graph-based component with a generative artificial intelligence interface, thereby creating a hybrid decision-support architecture. This new model serves as a human-centric decision-support interface, allowing project managers to dynamically analyze different economic scenarios in natural language instead of relying on static rankings. The framework is applied to empirical project data from a global market leader in transportation technology to ensure that the method is suitable for restoring project continuity, organizational confidence, and economic efficiency in professional practice.

This paper contributes to the literature along three dimensions. Theoretically, it conceptualizes the integration of deterministic scenario evaluation with a human-interpretable generative AI interface for crisis-oriented project decision support. Methodologically, it formalizes a graph-based procedure for representing and comparing financially relevant continuation alternatives under operational constraints. In practice, it demonstrates how decision-makers can query and compare calculated recovery scenarios via a natural-language interface in the examined project setting.

2. Literature review

The COVID-19 pandemic fundamentally transformed construction project management, causing significant global disruption and necessitating a critical re-evaluation of organizational resilience strategies. Studies have documented widespread challenges, including transportation problems, material shortages, and deteriorating financial indicators (Alsharef et al. 2021; Bsisu 2020; Gajdosikova et al. 2022; Stehlíková et al. 2024). These systemic shocks exposed the vulnerability of large-scale infrastructure investments to geopolitical and financing gaps, requiring innovative multilateral responses to maintain project stability and financial viability (Morris 2021). Furthermore, severe labor or supply chain disruptions were often exacerbated by existing weaknesses in project management (Rani et al. 2022; Almutairi et al. 2023; Alajmani et al. 2024; Sami Ur Rehman et al. 2022), forcing project-based organizations to restructure not only their operations but also the “career capital” and professional competencies of their personnel (Nessel 2022). While some regions demonstrated faster recovery through structured governance (Wang et al. 2023), others faced sustained disruption (Aigbavboa et al. 2022), highlighting that ultimate organizational survival is predicated on financial resilience and the ability of firms to effectively navigate liquidity challenges through adaptive management (Tóth et al. 2024). While these studies thoroughly map macroeconomic vulnerabilities and stress the need for adaptive management, they primarily offer descriptive insights.

Our research operationalizes these resilience theories into a tangible, algorithmically driven scheduling tool designed for immediate liquidity preservation.

Crisis situations have highlighted the need for adaptive crisis management approaches. However, many frameworks remain largely theoretical or strategic, often focusing on high-level factors, linguistic framing, or the conceptualization of crisis interventions (Benczes – Benczes 2018; Hazaa et al. 2021), emphasizing the role of communication without specific algorithms (Rajprasad et al. 2018), or describing reactive, insurance-based strategies and static risk management steps (Loosemore – Teo 2002; Abdelhafiez – Awade 2024). Empirical evidence suggests that prudent structural governance and robust frameworks are essential for mitigating the impact of exogenous shocks and ensuring overall economic recovery (Sayaseng 2020). Building organizational resilience may benefit from dynamic strategies that integrate digital solutions into crisis-management protocols (Kádár – Jáki 2024). Other models that propose operational frameworks or restart strategies often operate as static systems and lack an integrated restructuring algorithm (Iqbal et al. 2021; Murthi et al. 2023; Sfakianaki et al. 2015). Even when external risks are considered, the focus typically remains on proactive strategies rather than dynamic tools (Tran 2020). Consequently, while existing crisis-management literature emphasizes the importance of structural governance, preparedness, and adaptive response, less attention has been paid to executable decision-support tools that compare financially relevant project-continuation alternatives after an acute disruption. The proposed framework addresses this narrower methodological gap by complementing strategic crisis-management perspectives with a deterministic scenario-evaluation component.

Methodological approaches to rescheduling and optimization have evolved significantly in response to crises. Cui et al. (2010) examined rescheduling after buffer insertion in critical-chain scheduling. García-Mata et al. (2015) reviewed rescheduling in industrial environments, with particular attention to emerging technologies and future developments. Related studies have addressed rescheduling under different operational and financial constraints (Delgoshaei et al. 2014; Tosselli et al. 2020). This approach is also followed by Roosta et al. (2023), who developed robust site-route optimization models, and Khalilzadeh et al. (2020), who applied genetic algorithm-based hybrid models to handle uncertainty. A notable precedent for high-complexity rescheduling is provided by Durán et al. (2022), who utilized mathematical optimization models to redesign complex seasonal schedules disrupted by the pandemic, demonstrating the practical benefits of analytical tools in maintaining operational continuity. Recent Resource-Constrained Project Scheduling Problem (RCPSP) and project-rescheduling studies increasingly apply hybrid, metaheuristic, and learning-based approaches to cope with resource constraints and uncertainty (Khalilzadeh et al. 2020; Khajesaedi et al. 2025; Mihály – Kulcsár 2023; Sun et al. 2025).

Related research has also explored AI-supported scheduling and rescheduling in adjacent operational contexts, including systems engineering, production scheduling, and energy systems (Alzoubi et al. 2024; Miao et al. 2025; Tasgetiren et al. 2024). Despite these computational developments, relatively little attention has been paid to bounded crisis-response settings in which decision-makers require transparent comparison of financially relevant continuation alternatives under severe time pressure. Rather than proposing a universal multi-objective optimization solver, this study develops a focused proof-of-concept framework intended to support interpretable scenario comparison in a single infrastructure project crisis setting.

A further methodological gap concerns the interaction between analytically generated recovery alternatives and managerial decision-making. Existing RCPSP and rescheduling models provide increasingly sophisticated analytical outputs, but the use of conversational interfaces for interrogating calculated recovery alternatives remains underexplored in crisis-oriented project decision settings. In time-sensitive situations, a natural-language interface may complement conventional tables or dashboards by enabling managers to formulate additional scenario-comparison queries more directly. In this respect, generative AI is relevant not as a substitute for deterministic calculation, but as a human-interpretable interaction layer over calculated scenario outputs.

Furthermore, the successful organizational adoption of these computational technologies is frequently hindered by employee distrust and professional disillusionment, which necessitate more human-centric and transparent implementation strategies (Hartyándi 2025). The literature provides limited evidence on integrating deterministic recovery-scenario calculations with grounded natural-language interaction in infrastructure-project crisis management. In the proposed framework, generative artificial intelligence is not used as the underlying optimization solver; rather, it functions as an interaction layer through which decision-makers can query and compare deterministically generated scheduling, financial, and resource indicators. The present study examines this integration in a bounded, case-based proof-of-concept setting.

3. Methodology

To establish a robust methodological foundation, it is necessary to systematically compare the structural capabilities of the proposed framework with existing decision support paradigms.

Table 1 positions the proposed framework conceptually relative to selected decision-support approaches. The comparison concerns the analytical focus

and intended modes of managerial interaction; it is not intended as an empirical performance benchmark against traditional operations research or metaheuristic methods.

Table 1. Conceptual positioning of the proposed framework relative to selected decision-support approaches

System Type	Methodological Foundation	Target Metric Focus	User Interface Paradigm	Crisis Recalculation Speed
Traditional scheduling models	Mathematical Programming	Resource Constraints	Static Dashboards	Restricted
Metaheuristic Frameworks	Evolutionary Algorithms	Multi-objective Heuristics	Data Tables	Delayed
Proposed Hybrid Approach	Graph-Based Scenario Evaluation	Integrated Net Financial Gain	Natural Language Dialogue	Interactive Query-Based Comparison

Source: authors.

3.1. The core graph-based rescheduling algorithm

This section delineates a methodology designed to address the structural and financial issues mentioned above, specifically focusing on preserving economic value during systemic disruptions. The research focuses on the scheduling and management of a multidisciplinary construction project within a major international infrastructure provider managing projects running in parallel. Due to different levels of completion and complex industry compositions, scheduling and resource allocation remain a constant challenge. The project consists of four technology disciplines and one architectural discipline, which operate as subprojects, but their overlaps complicate the management of resources. The independent management of subcontractors further increases organizational complexity.

The research examines a critical exogenous event: the bankruptcy of the architectural subcontractor halted the project at 62% completion, creating significant liquidity risk. The involvement of a new contractor resulted in a loss of time, the risk of penalties, and severe financial risks. The goal of project management was to redesign the schedule to ensure organizational continuity while minimizing delays and costs. To this end, the goal was to develop an algorithmic method that optimizes the priorities of activities and ensures the achievement of payment milestones to maintain the project’s funding and financial sustainability. The analysis examines three projects with the same structure but different levels of completion, specifically 57, 62, and 66 percent.

The structure of these projects and the complex interdependencies between activities are illustrated in Figure 1.

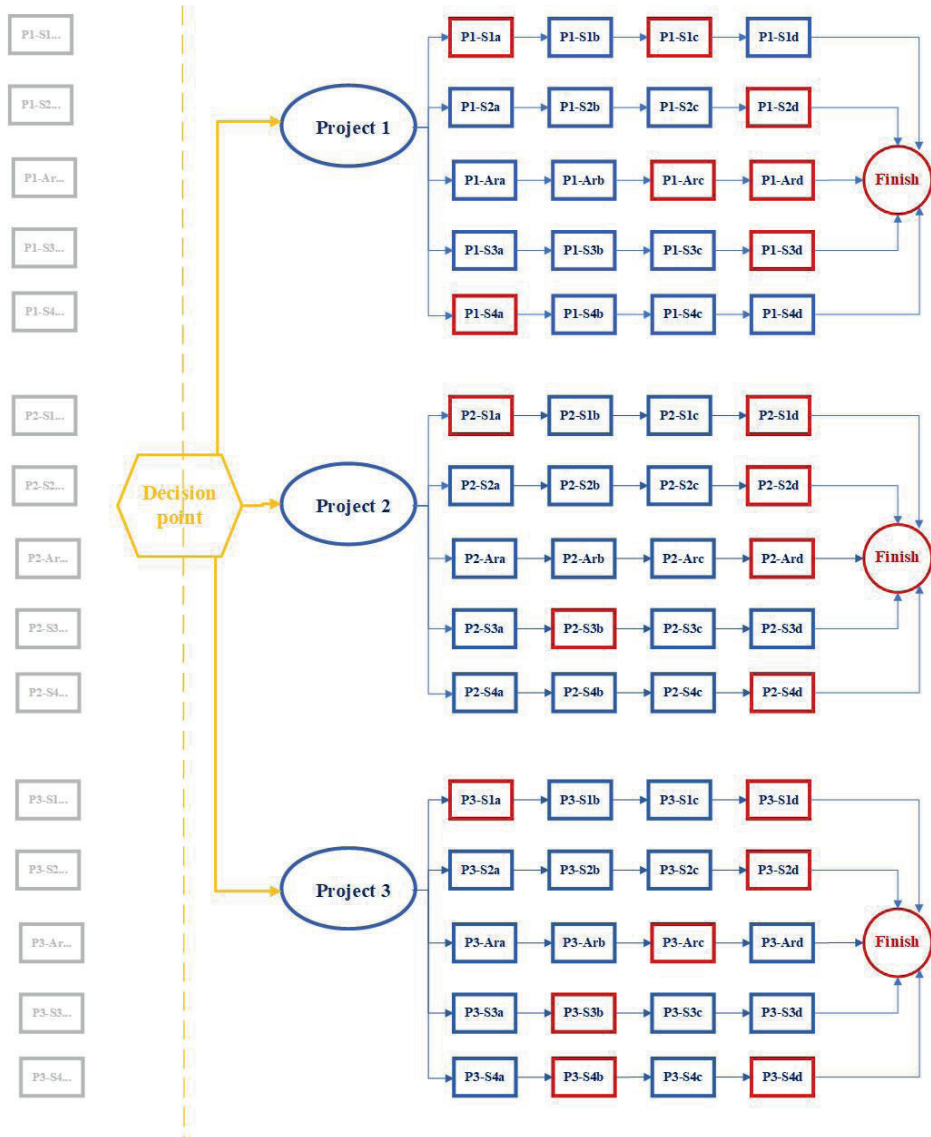


Figure 1. Structure of projects and links between activities

Source: authors.

The activities before the decision point have already been completed, while the subsequent activities remain pending. Each project includes five disciplines (rows) and four activity packages per discipline. Each task package possesses specific time, resource, and cost attributes. Completing the activities marked in red generates different amounts of income, while completing the activities in blue does not generate payment on its own. Completion results in significant payouts. There is a specific time and resource framework for each activity. The task of management is to determine the path that results in the most payments to maximize economic resilience within the specified constraints. In a crisis situation, complexity increases significantly because rapid, high-stakes decision-making is required. We developed the algorithm presented in our research to facilitate decisions as quickly and with as little risk as possible.

Modern project management has been shaped by the development of modern scheduling techniques based on graph theory, namely, network scheduling techniques (Hajdu 1997). The graph-based component represents the remaining project structure as a directed graph $G = (V, E)$, where the vertices correspond to activity identifiers and the directed edges represent dependency relationships. Each relevant edge is associated with the financial and operational attributes required for scenario comparison, including cost, payment on completion, step count, and full-time-equivalent resource demand.

The procedure generates candidate continuation structures containing the designated starting activity and evaluates them according to the structural and operational rules applied in the case study. For each retained candidate structure S , the model calculates total cost, net financial gain, peak FTE demand, cumulative FTE demand, and total step count. Weak connectivity is used as a structural screening criterion; it should not be interpreted, by itself, as a complete guarantee of temporal, contractual, or resource feasibility.

The present application evaluates the method within the bounded project network examined in the case study. Accordingly, computational observations reported in this study refer to this empirical setting. Broader scalability requires additional testing and, for larger networks, may require further search, pruning, or approximation procedures.

After loading the input data, the following steps summarize the computational procedure:

1. Directed graph formulation

- Define a directed graph $G = (V, E)$, where each vertex $v \in V$ corresponds to a unique activity label.
- For every dataset record, instantiate a directed edge $e = (u \rightarrow v)$ with associated attributes {cost, payment, step, fte}

2. Candidate-structure generation, screening, and computational scope
 - Retain candidate structures that satisfy the structural screening condition applied in the case study, including weak connectivity where relevant.
 - Apply the operational scenario constraints used in the empirical comparison, including peak FTE and recovery-duration constraints where applicable.
 - In the examined implementation, benchmarking indicates memory consumption below 50 megabytes for data ingestion and below 100 megabytes for vector processing for the evaluated project network of up to 60 concurrent activities. These results support the computational feasibility of the present case-study application, while broader scalability requires further testing on larger and structurally more diverse project networks.
3. Subgraph metric aggregation
 - For each valid induced subgraph $G[S]$, compute the following aggregations over its edge set $E(S)$, where the set of all edges of G whose endpoints lie in the node subset S :
 - Total Cost: $\sum_{e \in E(S)} \text{cost}(e)$
 - Net benefit: $\sum_{e \in E(S)} \text{payment}(e) - \text{Total Cost}$
 - Peak FTE demand: $\max_{e \in E(S)} \text{fte}(e)$
 - Cumulative FTE demand: $\sum_{e \in E(S)} \text{fte}(e)$
 - Total step count: $\sum_{e \in E(S)} \text{step}(e)$
4. Tabular consolidation
 - Assemble a comprehensive results table wherein each row corresponds to one evaluated branch sequence, listing its vertex set alongside the five computed metrics.
5. Persistence for Downstream Analysis
 - Export the consolidated table to a CSV file, facilitating subsequent statistical evaluation or decision-support processes.

The following notation was introduced to formalize the algorithm:

- u : source node (the activity that must be completed first)
- v : target node (the activity that depends on u)
- V : the set of all project activities
- E : the set of directed edges $u \rightarrow v$ representing dependencies between activities
- $G = (V, E)$: the directed graph of activities and their dependencies
- $S \subseteq V$: any subset of activities; its induced subgraph $G[S]$ uses edges $E(S) = \{(u \rightarrow v) \in E: u, v \in S\}$

- Cost: financial expense required for the dependency or transition between activities.
- Payment: the exact monetary revenue generated upon the completion of the edge
- Step: the discrete sequential increment assigned to an edge
- FTE: the full-time equivalent labor resource demand required to execute the edge

The decision-making engine operates by maximizing a dual-objective function that balances financial net gain and resource-constrained utility during crisis events. The objective function is defined as follows:

- NetGain = $\Sigma(\text{Payment} - \text{Cost})$
- Utility = $(\text{Payment} - \text{Cost} \times \frac{1}{(1 + 0.3 \times \frac{\text{Time}}{100})}) \times (1 - 0.63 \times \frac{\text{Resource}}{100}) \times (1 - 0.3 \times \frac{\text{Time}}{100}) \times (1 - 0.25 \times \frac{\text{Criticality}}{7})$

Where the time, resource, and criticality variables are normalized proxies within the project scope, and the coefficients reflect the specific resource-crisis sensitivity parameters calibrated for this infrastructure case.

The algorithm described here involves the creation and analysis of subgraphs within a directed graph, which represent a series of activities in the project, including dependencies. The primary objective is to evaluate different subsets of these activities in order to optimize the resource allocation and cost management of the project.

Initially, the algorithm loads the project data from a structured format such as an Excel spreadsheet into a DataFrame, which is then represented as a directed graph G. Each task in the project appears as a node, and dependencies between tasks appear as directed edges. These edges carry critical attributes such as cost, payment on completion, and full-time equivalent labor requirements.

The algorithm then generates all possible subgraphs of G that contain the “Start” node and are weakly connected. This ensures that only feasible subgraphs that represent a realistic sequence of project tasks are considered. For each subgraph, several attributes are calculated: the total cost of performing the activities, the total amount (net profit taking into account payments and costs), the maximum and the amount of full-time equivalent claims, and all the steps involved.

Information on these calculated attributes is crucial for project managers to make informed decisions about resource allocation, cost management, and scheduling during a project crisis. By analyzing different combinations of activities and their dependencies, the algorithm provides insights into the most

efficient ways to execute the project while maximizing profits and optimizing resource management. Finally, the results are organized into a DataFrame for further analysis and reporting. This structured approach not only automates the complex process of project planning but also provides a quantitative basis for optimizing project execution in high-risk economic circumstances.

3.2. Integrating generative AI for interactive decision support

Although the graph-based algorithm provides a robust quantitative engine for decision-making, its practical applicability can be enhanced by increasing accessibility and interactivity. To this end, we developed an artificial intelligence-driven layer on top of the basic methodology to create a more dynamic, user-friendly decision support system. This human-centric development logic is supported by evidence demonstrating that the choice of applied project management methodology fundamentally impacts team dynamics, human factors, and the perceived level of creativity (Blaskovics et al. 2023). In the initial phase of development, we examined existing tools such as Google NotebookLM and various solutions from the ‘Model-Zoo’ repository of free artificial intelligence models. The research concluded that no single ready-made “off-the-shelf” solution offered the specific functionality required for our complex, multi-parameter rescheduling problem, so custom development was necessary. After comparing several AI coding environments, we selected Codeium’s Windsurf platform, an AI-powered development environment built on VS Code. This was partly due to its flexibility and partly because this development environment is not only capable of using standard large language models, but can also support them with processes based on its own business logic. This enabled it to handle the unique requirements of the project. The architecture of this hybrid system, illustrated in Figure 2, is divided into three main logical units: a user layer, an intelligent orchestration layer, and a deterministic core engine.

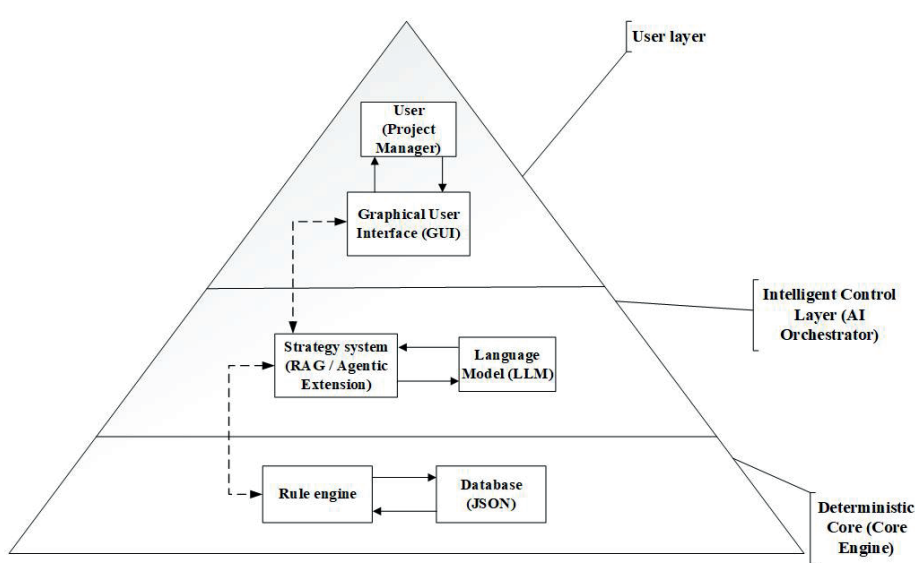


Figure 2. Hybrid system architecture

Source: authors.

The system operates as follows: The user layer consists of the project manager and the graphical user interface through which interaction occurs. The intelligent orchestration layer acts as the ‘brain’ of the system, containing the central controller, which serves as a strategy system, and the large language model. This layer interprets user requests and directs tasks. The deterministic core engine is the reliable, mathematical part of the system, comprising the JSON database and the rule engine, which performs precise, verifiable calculations. The arrows in Figure 2 show the flow of a typical user query from input to the final, contextualized response.

The key task in this phase was data preparation. We processed the raw project data, available in formats such as Excel spreadsheets and PDF files, and converted it to a structured, hierarchical JSON format. This step was essential to obtain the clean, machine-readable dataset required by both the graph algorithm and the subsequent AI models. To facilitate user interaction and testing, we also developed a graphical user interface (GUI) that enabled convenient parameter input and the visualization of results generated by the base algorithm.

The essence of the development was to supplement the rule-based calculation engine with a locally hosted Llama 3 large language model. In this architecture, the generative AI component is conceptualized as an interaction layer rather than as an independent optimization engine. The deterministic core

engine performs the scenario calculations, while the structured JSON database stores the calculated alternatives and their associated financial and resource indicators. The Llama 3-based interface is then used to support natural-language querying and comparison of these deterministic outputs through the graphical user interface.

To reduce the risk of unsupported numerical responses, the conversational component is grounded in the structured JSON outputs generated by the deterministic rule engine. User queries are interpreted by the orchestration layer, but scenario values, financial indicators, FTE requirements, and step counts are retrieved from the calculated data structure rather than produced independently by the language model. In addition, a redaction protocol is applied to mask proprietary project identifiers and sensitive financial information before interaction with the AI-supported interface.

This architecture is intended to improve the accessibility and interpretability of deterministic scenario results while reducing the risk of hallucination through structured data grounding. However, the present study does not claim general hallucination-free performance beyond the demonstrated prototype setting. Formal validation of grounded-answer accuracy, out-of-scope refusal behavior, response latency, data-redaction effectiveness, and managerial usability remains necessary before broader operational deployment.

4. Results

4.1. The core graph-based rescheduling algorithm

By applying the algorithm, it was possible to determine the activities and milestones whose fulfillment yields the optimal economic outcomes for the project, effectively serving as a roadmap for financial recovery amid systemic disruptions. During the analysis, the algorithm aggregated the costs of each activity and the revenues related to their performance, and then ranked the evaluated branches from the point of view of strategic financial performance and liquidity preservation. Based on the results, several possible project continuation scenarios could be identified, of which the strategically optimized recovery path minimized fiscal losses and maximized the net financial gain still realizable within the constrained, post-crisis environment.

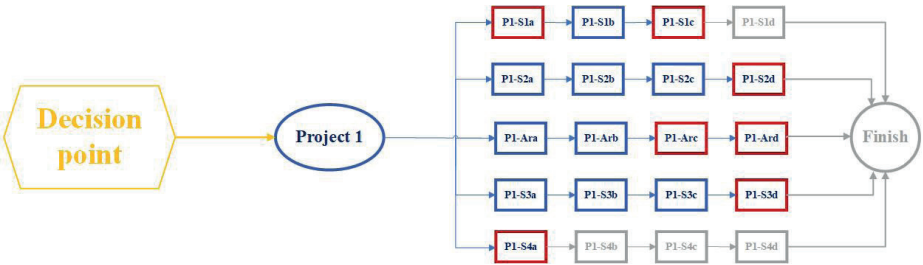


Figure 3. Combination of tasks with the lowest loss

Source: authors.

The P1-S1a, P1-S1b, P1-S1c, and subsequent markings are project task IDs used by the graph-based model to categorize specific project stages and systems. The path shown in Figure 3 achieves maximum revenue and ensures the highest level of economic efficiency through the following strategic recovery milestones:

- P1-S1a: Completion of the exterior and interior installation work of System 1.
- P1-S1c: Completion of the technical test run of System 1.
- P1-S2d: Completion of the two technical handover procedures for the system.
- P1-Arc: Correction and replacement of the observations recorded during the on-site inspection.
- P1-Ard: Conducting the technical handover procedure for the buildings.
- P1-S3d: Conducting the three technical handover procedures for the system.
- P1-S4a: Completion of the exterior and interior installation works of System 4.

Furthermore, the robustness of the algorithm was evaluated across the three distinct project completion levels mentioned previously. At 57% completion, the expanded decision space enabled a 12% higher net financial gain than the 62% baseline. Conversely, initiating the model at the 66% completion stage resulted in a highly restricted path matrix, reducing viable recovery options by 40% while strictly prioritizing immediate liquidity preservation.

Table 2. Comparative performance analysis of recovery paths

Metric	Optimal Path	Constrained Path (15 FTE Limit)	Variance
Net Financial Gain (M Ft)	196.2	180.5	-8.0%
Total FTE Requirements	18.5	15.0	-18.9%
Criticality Score (Avg)	3.2	4.8	+50.0%
Recovery Duration (Days)	22	28	+27.2%

Source: authors.

To evaluate the algorithmic outcome, we performed a comparative analysis between the identified optimal recovery path and a resource-constrained alternative, as presented in Table 2. The data demonstrate that imposing a 15 FTE limit results in an 8% reduction in net financial gain while significantly increasing the average criticality score (from 3.2 to 4.8) and recovery duration (by 27%). This sensitivity analysis confirms that the proposed method is highly responsive to resource scarcity, explicitly quantifying the trade-off between financial efficiency and resource-constrained feasibility. The decision space explored included 60 concurrent activities, where the model successfully pruned sub-optimal branches to prioritize liquidity preservation.

The final decision matrix generated by the algorithm clearly defined the impact of the different activities on the financial balance of the project, as well as which milestones would ensure the highest revenue retention. The data generated by the algorithm helped project management make a rapid, informed choice among alternatives at a time when delayed decision-making would have exponentially increased penalty risks. The analysis also highlighted that there are several optimization options for the continuation of the project, taking into account varying resources and timing constraints.

Based on the results, the algorithm is able to identify critical activities and their financial impacts, thus enhancing managerial resilience and supporting project management in high-stakes, time-sensitive decision-making. By enriching the data with additional parameters, the analysis can be further refined – for example, by taking into account dynamic time constraints, resource consumption, or material costs associated with inflationary pressures. The information obtained in this way contributes to the more efficient management of project processes and a systematic understanding of decision-making opportunities in uncertain economic climates.

To further validate the robustness of the algorithmic output, a comprehensive sensitivity analysis was conducted, testing various parameter settings. The evaluation of multiple crisis scenarios under distinct financial and operational constraints is presented in Table 3. The empirical findings confirm that the deterministic engine dynamically adapts to shifting external pressures, maintaining a structurally viable recovery path even under severe parameter degradation.

In the sensitivity analysis, Scenario Alpha increases the relevant material-cost components by 20% before recalculating net financial gain. Scenario Beta applies a maximum recovery-duration constraint of 18 days and selects the highest-net-financial-gain alternative satisfying this condition. Scenario Gamma applies a maximum peak resource-demand constraint of 10.0 persons and selects the highest-net-financial-gain eligible alternative. These scenarios are evaluated regarding the candidate continuation structures generated for the examined project setting.

Table 3. Sensitivity analysis of recovery scenarios under varying parameter settings

Scenario	Parameter Constraint Applied	Net Financial Gain, million HUF	Recovery Duration, days	Peak Resource Demand, persons
Baseline	Unconstrained Optimal Path	196.2	22	18.5
Scenario Alpha	Twenty percent inflation in material costs	165.4	22	18.5
Scenario Beta	Strict temporal limitation constraint	170.8	18	24.2
Scenario Gamma	Extreme resource scarcity constraint	142.1	34	10.0

Source: authors.

As presented in Table 3, the baseline optimal path yields the highest net financial gain of 196.2 million HUF. The data reveals that external cost shocks, such as the twenty percent material inflation in Scenario Alpha, reduce this gain to 165.4 million HUF without altering the 22-day timeline. Conversely, Scenario Beta demonstrates that compressing the recovery duration to 18 days requires an increased peak resource demand of 24.2 persons, reducing the financial gain to 170.8 million HUF. Furthermore, Scenario Gamma highlights that restricting the workforce to 10.0 persons extends recovery to 34 days and results in the lowest financial gain of 142.1 million HUF. This sensitivity analysis illustrates how selected financial and operational constraints alter the preferred continuation alternative and its associated indicators within the examined case setting.

4.2. Interactive scenario analysis using an AI-enhanced layer

While the deterministic component calculates and ranks candidate continuation alternatives, the AI-supported interface enables the decision-maker to query and compare these calculated outputs in natural language. The ‘chat with your data’ feature allows project managers to ask complex questions in natural language and receive immediate, contextualized, quantified answers without having to manually filter through a results table containing hundreds or thousands of possible routes. We demonstrate the capabilities of the system through a specific scenario analysis. Suppose that, in addition to the absolute optimal route presented in subsection 4.1, the project manager also wants to examine a resource-constrained alternative.

The dialogue proceeds as follows:

Project manager: ‘In addition to the absolute optimal route, show me an alternative where the peak FTE requirement never exceeds 15 people! Compare the most important indicators of the two scenarios in a table.’

In response to the query, the interface retrieves from the deterministic results table the highest-net-financial-gain alternative that satisfies the specified peak FTE constraint and presents it alongside the unconstrained highest-net-financial-gain alternative.

Output generated by AI Assistant:

‘Okay. The table below compares the original, financially optimal route, designated as Scenario A, with the best alternative that complies with the 15 FTE limit, designated as Scenario B. A detailed comparison can be found in Table 4.’

Table 4. Comparison of optimal and resource-constrained scenarios

Metrics	Scenario A, absolute optimum	Scenario B with strict FTE limit	Change
Net financial gain (€)	1,250,000	1,150,000	-8.0%
Total cost (€)	850,000	920,000	+8.2%
Peak FTE requirement (persons)	22	14	-36.4%
Cumulative resource requirement (person-hours)	4.2	4.55	+8.3%
Total number of steps (count)	35	38	+8.6%

Source: authors.

Explanation: As can be seen in Table 4, Scenario B successfully meets the 15 FTE limit, with a peak resource requirement of 14 people. The price of this is that the net financial benefit is reduced by 8 percent, amounting to €100,000, compared to the absolute optimum. This compromise arises from the fact that the system must choose a less profitable but less resource-intensive set of tasks in order to comply with the limit. The total cost and number of steps increase slightly, as critical, high-resource tasks must be replaced by several smaller steps. This concrete, quantified result shows that the AI layer does not simply repeat static data. It is capable of performing a complex trade-off analysis and presenting it to the decision-maker in a form that is immediately understandable. Comparative performance metrics indicate that this hybrid orchestration reduces scenario generation and evaluation time from the several hours typical of manual dashboard analysis to under two minutes, representing a significant quantitative efficiency gain in operational crisis response.

5. Discussion

To synthesize the core advancements demonstrated throughout this study and directly address the multifaceted nature of structural crisis management, the research output is categorized systematically across three distinct pillars. This structural breakdown separates the abstract conceptual shifting from the underlying algorithmic engineering and the final interface utility.

Table 5. Tripartite classification of the research contribution

Dimension	Core scientific insight	Practical operational impact
Theoretical	Integration of deterministic scenario evaluation with a human-interpretable generative AI interface	Demonstrated through one crisis-induced infrastructure-project case
Methodological	Graph-based representation and quantitative comparison of financially relevant continuation alternatives under operational constraints	General scalability and transferability require further computational validation
Practical	Natural-language querying and comparison of deterministically calculated recovery scenarios	Effects on decision speed and decision quality require user-based evaluation

Source: authors.

The three dimensions presented in Table 5 clarify how the proposed framework combines quantitative scenario evaluation with an accessible interaction layer. In the examined case, the deterministic component produces comparable financial and resource indicators, while the conversational component provides a natural-language means of querying these outputs. The broader computational scalability and organizational impact of this integration require validation beyond the present proof-of-concept setting.

The algorithm developed in the course of the research is a decision-support tool that enables the strategic replanning of projects in the event of interruptions due to exogenous systemic shocks. By taking into account financial, time, and resource constraints, the model identifies and ranks project continuation alternatives in a structured, quantitative form. This represents a significant advantage over traditional, experience-based crisis management, as it prioritizes objective economic indicators and organizational liquidity over subjective intuition during high-pressure scenarios.

Its practical validity is indicated by the fact that the model is based on an analysis validated on real project data from a major international infrastructure provider. The algorithm successfully identified the task lines that most effectively preserve the financial balance and long-term economic sustainability of the

investment. This not only allows for the reduction of fiscal losses but also contributes to a more efficient redistribution of available resources, ensuring that the project remains viable even under severe contractual and financial duress.

However, the real novelty of the research is the hybrid model, which supplements this deterministic engine with a layer of generative artificial intelligence. The greatest strength of this approach is that it combines quantitative mathematical accuracy: the mathematical accuracy and verifiability of the calculations are retained, while the AI layer provides an intelligent, dialogue-based interface. This architecture directly addresses recent scholarly concerns regarding the 'black-box' nature of autonomous systems and the resulting professional distrust in organizational technology (Hartyándi 2025). By allowing project managers to ask complex 'what-if' questions in natural language, the system bridges the gap between complex algorithmic outputs and professional managerial intuition. This dynamic scenario analysis dramatically reduces the time needed for decision-making, which is crucial for maintaining organizational continuity in a crisis situation.

At the same time, this hybrid architecture also introduces new limitations. While the limitations of the base algorithm primarily relate to the quality of the input data and the range of modeled parameters, the effectiveness of the AI layer depends heavily on the quality of user prompts and the reliability of the language model. While our study provides deep insights into construction crisis management following a subcontractor bankruptcy, the empirical basis of a single-case insolvency limits the immediate generalizability of our findings. Therefore, we present this framework as a case-based methodological proof of concept rather than a universally scalable blueprint. The evidence is derived from one specific project structure examined at three completion levels under a single focal crisis type. To substantiate broader applicability and validate the strength of these claims, further empirical testing across diverse project types, varying organizational scales, and different disruption scenarios is explicitly required.

From a policy perspective, the transparent, auditable comparisons of recovery scenarios may be especially relevant for infrastructure investments subject to public procurement and funding compliance requirements. The proposed framework could therefore provide a useful basis for future investigation in Central and Eastern European infrastructure settings; however, its regulatory and policy relevance requires dedicated empirical validation.

A further limitation is that the algorithm mainly manages financial and resource-based parameters, while other important factors, such as organizational resistance, social impact, or legal risks, are not yet fully integrated into the decision-making process. In addition, the complexity of the graph-based approach can significantly increase computational time in the case of a higher number of activities, which may be a bottleneck in a crisis that requires quick

decision-making. Finally, the effectiveness of the model's operation depends heavily on the accuracy and completeness of the input data, which can limit its applicability in the event of uncertain or incomplete information.

Overall, the results of the research indicate that the graph-based rethinking of project scheduling logic and the development of a hybrid algorithmic tool can effectively mitigate uncertainty arising from systemic crises. This approach lays the foundations for more sustainable, resilient, and data-driven project management methodologies that harmonize technological precision with human-centric decision-making.

6. Conclusions

This study has presented a hybrid decision-support framework for examining crisis-induced rescheduling alternatives within a large-scale infrastructure-project setting. The deterministic component represents activity dependencies in a directed graph and evaluates candidate continuation alternatives based on financial and resource indicators. In the examined subcontractor-insolvency scenario, this procedure enabled the comparison of recovery alternatives and the identification of the candidate associated with the highest calculated net financial gain under the applicable scenario conditions.

The study further proposed a generative AI-based interaction layer on top of the deterministic outputs. This component is not intended to replace the underlying calculation procedure or to function as an autonomous optimization engine. Its role is to facilitate natural-language querying and comparison of precomputed recovery alternatives, thereby improving the accessibility of complex scenario information for managerial users.

The findings should be interpreted within the limits of the research design. The empirical evidence derives from a single infrastructure project examined under one focal type of disruption, although several completion levels and scenario constraints were considered. Accordingly, the study provides case-based methodological proof of concept rather than evidence of universal applicability or operational scalability. Further research should evaluate the framework across additional project types, crisis events, computational settings, and managerial users, including a formal assessment of AI groundedness, response reliability, usability, and decision-support value.

Data availability statement

Due to the proprietary nature of the infrastructural data, the raw datasets cannot be shared publicly. A synthetic, anonymized dataset and the core scripts for graph aggregation are available from the corresponding author upon reasonable request.

Use of generative AI

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) and Gemini (Google) solely to improve the clarity, grammar, readability, and linguistic quality of the text. The tools were not used to generate research data, conduct analysis, create references, or replace the authors' scientific reasoning and interpretation. The authors reviewed and edited the manuscript after using these tools and take full responsibility for the final content.

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