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An Integrated PMBOK-Based Mixed-Integer Optimization Framework for Rescue-Robot Projects

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ABSTRACT

Objective: This study proposes a novel integrated Mixed-Integer Programming (MIP) framework for managing complex engineering projects in alignment with PMBOK principles. Unlike conventional approaches that address project management knowledge areas independently, the proposed model simultaneously incorporates six PMBOK domains: procurement, schedule, cost, quality, human resources, and integration management within a unified mathematical optimization structure.
Methodology: The framework enables optimal supplier selection based on cost–quality trade-offs, multi-skill workforce allocation, and synchronized task scheduling. A key methodological contribution is the introduction of a task initiation cost mechanism and an active-period minimization structure, allowing the model to capture hidden project overheads and reduce unnecessary task dispersion.
Results: The model is applied to the design and development of a search and rescue robot as a representative high-complexity technological project. Computational experiments demonstrate the model's effectiveness in optimizing resource allocation and reveal the dominant impact of human resource costs on total project expenditure. Sensitivity analyses further highlight nonlinear trade-offs among procurement cost, quality thresholds, and project duration. Notably, results indicate that relaxing quality constraints may reduce procurement expenses but paradoxically increase total project cost and completion time, emphasizing the necessity of integrated decision-making.
Conclusion The proposed framework contributes to the advancement of data-driven project management by bridging PMBOK-based managerial structures with rigorous mathematical optimization. It offers a practical decision-support tool for project managers operating in multi-domain, resource-constrained engineering environments.

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Introduction

Natural disasters such as earthquakes, building collapses, fires, floods, and industrial incidents continue to pose serious threats to human life despite significant technological advancements in monitoring, prediction, and risk mitigation. Consequently, effective rescue operations following such events remain critically important. In this context, rescue robots have emerged as intelligent systems designed to operate in hazardous environments where human access is limited or unsafe. Given the technical and managerial complexity involved in designing and developing rescue robots, the application of structured and scientific project management approaches is essential to ensure project success. Among the most widely recognized frameworks in this domain is the PMBOK Guide, which provides a comprehensive foundation for managing complex projects across diverse industries (Atencio et al. 2022).

PMBOK, a globally recognized framework developed by the PMI, provides standardized management practices and serves as a reference for project managers and organizations aiming to improve project success (PMI 2021). Over successive editions, it has incorporated new methodologies, tools, and best practices to support project initiation, planning, execution, monitoring, controlling, and closure. The 7th edition, in particular, emphasizes a principle-based framework over the traditional process-oriented structure and introduces the “Models, Methods, and Artifacts” section, highlighting tangible project deliverables (Faraji et al. 2022). PMBOK also identifies key knowledge areas such as integration, schedule, cost, quality, human resources, and procurement management, which remain essential for effective project management.

In this research, the project of designing and developing a rescue robot is considered as an example of a complex technological project. The proposed model, by integrating six project management principles with quantitative decision-making methods, provides a tool that enables project managers to make data-driven and mathematically optimized decisions when facing multiple constraints and conflicting objectives. In such projects as the development of rescue robots, which simultaneously confront technical, cost, time, and quality challenges, the need for a scientific decision-making model becomes even more apparent. The development of complex projects, particularly those involving rescue robots, often necessitates the collaboration of diverse, sometimes multi-disciplinary teams. Effective management of these teams, considering their varied skills and ensuring optimal allocation based on competencies, is crucial for project success. As highlighted by research on developing project management competencies, such as the work of Desjardins et al. (2025), fostering the necessary skills within project teams, including those that are cross-functional, is a key factor in achieving successful outcomes. Effective project human resource management practices, including recruitment, team development, and performance evaluation, have been shown to significantly enhance project outcomes in complex organizational settings (Author et al., 2024). This approach represents a step toward transitioning from traditional project management to data-driven and intelligent project management. In fact, this research aims to design a comprehensive and integrated model for simultaneous decision-making across these six areas using mathematical programming. Within this framework, the procurement management domain is modeled through optimal supplier selection based on cost, quality, and supply capability; the human resource management domain addresses employee activity levels, required skills, and workforce allocation; and the time management domain involves precise task scheduling and determination of project activity periods. Likewise, cost and quality management are incorporated respectively into the multi-objective function (combining costs and quality rewards) and the constraints ensuring minimum quality levels.

Despite extensive research on project management and rescue robot development, there is still a lack of integrated decision-making frameworks that simultaneously address multiple PMBOK knowledge areas within a single mathematical model. To fill this gap, the proposed study introduces a unified Mixed-Integer Programming (MIP) framework that consolidates six PMBOK areas: procurement, schedule, cost, quality, human resources, and integration management into a single model. The framework incorporates several innovative features: (1) multi-skill human resource scheduling, (2) supplier selection with mathematical trade-offs between cost and quality, (3) a novel task initiation cost mechanism, (4) the concept of active periods to minimize redundant task durations, (5) a multi-layer relationship linking suppliers, tasks, and human resources, and (6) applicability to highly complex projects such as rescue robot development. Applying this model enables structured, data-driven, and optimized project management from design to implementation, providing a practical tool for managers facing complex multi-domain engineering challenges.

The remainder of this paper is organized as follows. Section 2 reviews the literature on rescue robots and project management frameworks. Section 3 presents the mathematical modeling approach, including problem definition, assumptions, variables, objective function, and constraints. Section 4 reports numerical results, followed by Section 5 with sensitivity analyses. Section 6 discusses managerial insights, and Section 7 concludes with key findings, contributions, and directions for future research.

Table 1. Mapping of the proposed optimization model to the six PMBOK knowledge areas

PMBOK knowledge area	How it is incorporated in the proposed model	Key decisions / Model elements
Project Integration Management	The model integrates human resource allocation, supplier selection, quality control, scheduling, and cost into a single optimization framework with a unified objective function. Trade-offs between time, cost, and quality are handled simultaneously rather than in isolated sub-models.	Unified objective function; shared constraints linking workforce, procurement, quality levels, and project calendar; scenario/sensitivity analysis (e.g., γ, δ, and quality thresholds) to support integrated decision-making.
Project Resource Management (Human Resources)	Human resources are explicitly modeled as a limited, skilled workforce assigned to tasks over discrete time periods. The model captures workforce capacity, number of employees per period, and the cost of specialized personnel as a major cost part.	Decision variables for the number/type of employees assigned per task and period; capacity constraints; cost parameters for human resources; resulting workforce profile over the project horizon.
Project Procurement Management	Procurement is modeled through supplier selection for each required part, considering cost–quality trade-offs and minimum quality requirements. The model selects a subset of suppliers and determines from whom each part is purchased.	Binary allocation of parts to suppliers; supplier-specific cost and quality parameters; minimum quality constraints; analysis of supplier patterns (e.g., frequent selection of suppliers 1 and 9, and effect of relaxing quality constraints).
Project Quality Management	Quality is incorporated via minimum quality thresholds for procured parts and quality-related parameters of suppliers. The impact of relaxing quality requirements on total cost and project duration is analyzed.	Quality indices for suppliers/parts; constraints enforcing minimum acceptable quality; scenario in which the quality constraint is removed to examine its effect on cost and schedule.
Project Schedule Management	The project is scheduled over a finite planning horizon with multiple periods. Task timing, number of active periods, and sequencing (for independent tasks) are optimized jointly with resource and cost decisions.	Binary variables indicating task execution/start in each period; fixed cost per active period (γ); constraints linking task duration, active periods, and resource availability; sensitivity analysis of γ and δ on the number of active periods.
Project Cost Management	All relevant cost parts (human resources, procurement, fixed cost per active period, and task-start cost) are captured in the objective function. The model evaluates how managerial levers (γ, δ, quality levels, supplier choices) change the total project cost.	Objective function minimizing total cost; cost parameters for labor, materials, fixed period activation, and task starts; cost breakdown results (e.g., dominant share of specialized human resources); sensitivity analysis on cost parameters as control levers.

Literature Background

PMBOK has been recognized as a comprehensive guide for standardizing project management processes across industries. Building on this, Lampinen (2019) qualitatively investigated, through semi-structured interviews in a single supply-chain company, how different PMBOK knowledge areas are valued during project planning and found that time and cost management were rated highest by the procurement unit, while communication management emerged as a problematic area requiring stronger project knowledge-management practices. This framework, which defines key knowledge areas such as scope, time, cost, quality, risk, human resources, and communications, provides a systematic basis for managing projects in diverse organizational contexts (Lampinen, 2019; Nguyen et al., 2017). Nguyen et al. (2017) aimed to clarify the role of project management concepts in engineering education by conducting a global survey of project management curricula and showed that risk, cost, and time receive the greatest instructional emphasis, with a generally good alignment between educational focus and practical use, except for scope management, which remains under-taught despite its high practical importance. Previous studies indicate that project managers' familiarity with and mastery of PMBOK knowledge areas play a decisive role in achieving effective project performance. In this vein, Fernandes and Lima (2024) used a quantitative survey of SMEs in Lourinhã to assess managers' knowledge, perceived importance, and use of each PMBOK area and found overall low project management knowledge, with a clear prioritization of cost-related areas and learning occurring mainly through practical application rather than formal training. For instance, Fernandes and Lima (2024) reported that in small and medium-sized enterprises (SMEs), project management knowledge is generally limited, with a predominant focus on cost-related areas. This finding highlights the need for formal and practical training to strengthen PMBOK-based managerial capabilities. In the housing construction sector, Putri et al. (2025) combined correlation and impact tests, Relative Importance Index, and Analytic Hierarchy Process to analyze nine quality-assurance variables based on ISO 9001:2015, PMBOK (6th ed.), and national regulations, and identified leadership, resources, and quality documentation as the most influential factors on local contractors' competitiveness, suggesting optimization solutions such as improving delivered quality, customer retention, and project life-cycle performance.

Furthermore, recent research emphasizes the importance of adapting and contextualizing standardized project management frameworks to real organizational settings. Focusing on organizational evolution, Abreu et al. (2025) applied a project management maturity model in a private IT company to diagnose the current state of PMBOK-based practices and showed that higher maturity levels linked to clearer strategic alignment directly enhance project efficiency and productivity. Their findings show that information technology organizations can identify and address gaps between current and desired practices by using maturity models. Similarly, through a single in-depth case study of a German SME based on six semi-structured expert interviews, Burch (2022) analyzed the interrelations among process standardization, knowledge management, project management, and stakeholder satisfaction and concluded that project management standardization and active knowledge management are key enablers of sustainable growth, improved communication transparency, clearer responsibilities, and higher stakeholder satisfaction.

Beyond organizational structure, scholars have also examined how digital transformation and evolving technological environments reshape project management requirements. For example, Bezruchko et al. (2025) set out to develop recommendations for improving the management of large digital initiatives in a Russian energy company and, by examining multiple concurrent digital projects executed under sanctions and vendor withdrawal while following PMBOK and ISO 21500, empirically showed that classical approaches require process adjustments to provide sufficient flexibility in scheduling and quality management. Their study revealed that classical project management approaches, despite relying on established frameworks such as PMBOK and ISO 21500, require process adjustments to support the flexibility needed for scheduling and quality management in rapidly evolving digital projects. The authors highlight that existing organizational structures often lack dedicated roles such as digital service design managers, which leads to increased development time and costs. They propose redefining responsibilities and introducing new managerial positions, contingent upon evaluating their economic feasibility and alignment with organizational process models.

Parallel to these structural concerns, contemporary research explores the integration of analytical techniques to strengthen project governance and improve managerial insights. In this regard, Zambrano et al. (2024) applied Social Network Analysis to the components of PMBOK's seventh edition to quantitatively map their structural interconnections and levels of centrality, revealing differentiated influence patterns among elements and offering a data-driven tool for designing more coherent organizational processes and strategic alignment. Their findings demonstrate that the framework's elements are linked at varying levels of centrality and influence, offering project managers a quantitative tool for designing more coherent organizational processes and enhancing strategic alignment across project activities.

The significance of hybrid and flexible methodologies has also been recognized. Sikli et al. (2025) addressed the existing knowledge gap on hybrid project management by systematically analyzing the importance, benefits, and drawbacks of different approaches and answering five specific research questions through a structured, table-based synthesis, ultimately providing a conceptual and practical foundation for the application of hybrid methods in business-oriented product and service development. Sikli et al. (2025) examined the concept of Hybrid Project Management, which combines the strengths of traditional and agile methodologies to enhance project adaptability and success. This perspective aligns with broader efforts to harmonize structured managerial principles with the dynamic needs of modern project environments. Extending this line of inquiry, Desjardins et al. (2025) examined the emerging prominence of hybrid approaches by reviewing ISO 21502, PMBOK guidelines, and Agile practice guides, and proposed a comprehensive competency-development model that integrates training activities, such as lessons-learned sessions, into ongoing project management processes, highlighting how predictive, hybrid, and adaptive approaches can be matched to uncertainty in scope and deliverables.

From the human competency perspective, Feussi et al. (2025) explored the relationship between project management competencies and entrepreneurial skills, concluding that modern project managers must complement their technical mastery of PMBOK processes with entrepreneurial abilities such as innovation, risk-taking, and opportunity recognition to perform effectively in dynamic environments. Similarly, Strang (2025) emphasized the critical role of human resource management in project success, particularly regarding leadership, team development, and performance evaluation. In the construction industry context, Oyekunle et al. (2024) conducted a quantitative survey of UK construction project managers, analyzing 60 PMBOK-based project management strategies using descriptive and inferential statistics, and found that widely adopted practices especially in scope, schedule, cost, and integration management are strongly associated with reduced disputes and more successful project outcomes, whereas some techniques such as bidders' conferences remain underutilized.

Overall, the literature reveals an evolutionary trajectory in project management research from a narrow focus on PMBOK's knowledge areas toward the integration of structural reform, analytical techniques, and hybrid managerial approaches. This evolution, particularly evident in digital, engineering, and information technology projects, aims to enhance decision accuracy, cost control, and predictability in project execution (Zhou et al., 2021; Abreu et al., 2025). Zhou et al. (2021), for instance, developed a mathematical planning-based framework for sustainable international engineering project management by combining a systematic literature review, visual clustering analysis of 21 years of research, and a case study, and demonstrated that existing systems contain structural deficiencies that can be addressed through an optimized mathematical model integrating sustainability into project management. Despite these advances, a significant research gap remains regarding the systematic alignment of mathematical and quantitative decision-making tools with standardized project management frameworks such as PMBOK. The present study aims to address this gap by developing and evaluating mathematical models grounded in PMBOK principles to improve decision-making efficiency in project environments.

The literature shows that prior studies have mainly focused on PMBOK knowledge areas, process standardization, maturity models, and hybrid approaches, using qualitative, survey-based, and analytical methods across SMEs, construction, digital, and IT projects. These works highlight the importance of cost, time, risk, communication, and standardization, and introduce tools such as SNA and hybrid methods, but remain largely descriptive or conceptual. A clear gap remains in developing an integrated mathematical optimization framework that simultaneously handles human resource allocation, supplier selection, scheduling, and quality within a unified project management model.

To address this gap, the proposed framework introduces a set of integrated innovations within a single mathematical model: it supports multi-skill human resource scheduling, models supplier selection via explicit cost–quality trade-offs, and incorporates a novel task initiation cost mechanism. It further introduces the concept of active periods to reduce redundant task durations and establishes a multi-layer linkage among suppliers, tasks, and human resources. Designed for highly complex, multi-domain projects such as rescue robot development, the model enables structured, data-driven, and optimized project management from design to implementation, going beyond the primarily descriptive approaches in the existing literature.

Table 2. Comparative coverage of PMBOK knowledge areas in related studies and this study

Article	Time Management	Cost Management	Quality Management	HR Management	Procurement	Integration	Other
Putri et al. 2025			✓				✓
Feussi et al. 2025						✓	✓
Cardenas et al. 2025							Risk
Strang 2025				✓			Risk
Oyekunle et al. 2025	✓	✓					✓
Ismail et al. 2024		✓				✓	
Ismail and Arifin 2022				✓			✓
Shahari 2022	✓	✓	✓				✓
This study	✓	✓	✓	✓	✓	✓	

The review in Table 2 indicates that prior studies have typically focused on a limited subset of project management knowledge areas, most often addressing only time, cost, or quality dimensions. Human resource management and procurement have been largely overlooked, and integration has seldom been treated explicitly or in a systematic manner. In several works, risk appears only as an ancillary element (reported under “Other”) rather than being embedded within a comprehensive project management framework. In contrast, the present study simultaneously incorporates six core areas: time, cost, quality, human resources, procurement, and integration, thus offering a more holistic and integrated perspective than the existing literature.

Materials and Methods

Problem Definition

Projects differ widely in complexity and criticality; among them, the design and construction of a rescue robot constitutes a multidisciplinary, high-stakes project that demands tightly coordinated managerial decisions. In this study, the project is modeled from a managerial and planning perspective, abstracting from detailed engineering design in order to focus on integrated decision-making across key PMBOK domains.

In practice, traditional approaches often address cost, time, quality, procurement, and human resources separately, leading to locally optimal but globally inconsistent decisions. For a rescue robot operating in hazardous and uncertain environments (e.g., debris, smoke, humidity, high temperature), even minor part failures or coordination issues can cause mission-critical breakdowns. Hence, supplier selection cannot be driven by cost alone: each part must be sourced from a single feasible supplier under strict demand and minimum quality requirements, with explicit cost–quality trade–offs.

At the same time, human resource decisions activating multi-skilled employees, assigning them to tasks over time, and coordinating overlapping activities must be aligned with the project schedule and procurement constraints. These interdependencies between supplier selection, part quality, task scheduling, and multi-skill workforce allocation give rise to a mixed-integer programming problem. The proposed model captures these couplings in a unified optimization framework that jointly considers cost, time, quality, procurement, and human resource management to support coherent, system-wide project decisions for complex rescue-robot development.

Assumptions

A set of reasonable assumptions has been considered as follows, allowing the model to represent the complexities of real projects while maintaining computational capability.

- In this model, time is represented by discrete periods rather than continuous or calendar-based time. This abstraction is adopted to support a managerial view of resource allocation and overall scheduling of activities, without modelling detailed operational precedence or shopfloor sequencing. The focus is therefore on analyzing aggregated decisions across different sections of the project, rather than on providing an exact operational

- In this model, similar to many engineering and technological projects, each part is purchased from one supplier due to the high importance of part quality in terms of compatibility during installation, assembly, and implementation. In addition, purchasing a part in larger quantities from a single supplier results in better and lower-cost logistical coordination and helps establish stable relationships with the supplier.
- Supplier cost, capacity, and quality information are known and certain.
- From the human resource perspective, it is assumed that a set of employees with different technical specializations (e.g., mechanical, control, software, and electronic) is available, and each can be active or inactive in different periods.

This set of assumptions not only provides a clear framework for defining the problem boundaries but also reflects the operational logic behind the model. Accordingly, the model can integrate complex project decisions in a structured, quantitative, and PMBOK-based manner within the domains of time, cost, quality, and human resources.

Variables and Parameters

Table 3. Notations

Parameter	Description
p	Set of parts, $P = \{p_1, \dots, p_5\}$
s	Set of suppliers, $S = \{s_1, \dots, s_{10}\}$
j	Set of tasks, $J = \{j_1, \dots, j_4\}$
t	Set of time periods, $T = \{t_1, \dots, t_6\}$
e	Set of employees, $E = \{e_1, \dots, e_{10}\}$
h	Set of skill types, $H = \{$mechanical,control,electrical,software$\}$
c_{ps}	Unit cost of part (p) from supplier (s)
$q_{ps} \in [0,1]$	Quality score of part (p) from supplier (s)
$f_{ps} \in [0,1]$	Feasibility: 1 if supplier (s) can supply part (p), 0 otherwise
d_p	Demand (required units) for part (p)
θ_p	Minimum acceptable average quality for part (p)
α, β	Weights for cost and quality in the supply objective
τ_j	Duration (length in periods) of task (j)
r_{jh}	Number of employees with skill (h) required for task (j)
$\sigma_{eh} \in [0,1]$	1 if employee (e) has skill (h), 0 otherwise
w_{et}	Cost of hiring/activating employee (e) in period (t)
γ	Weight of fixed cost per active period
δ	Cost per task start
y_{ps}	1 if supplier (s) are selected to supply part (p)
U_{ps}	Quantity of part (p) supplied by supplier (s)
x_{et}	1 if employee (e) is active in period (t)
v_{jt}	1 if task (j) starts in period (t)
z_{jet}	1 if employee (e) works on task (j) during period (t)
a_t	1 if period (t) is active (any work done)

The decision variables of the model are designed to translate key project management choices into a coherent mathematical structure. The binary variable indicates whether the supplier is selected to provide part, thereby representing strategic sourcing decisions under cost–quality trade-offs. The continuous variable specifies the quantity of parts ordered from the supplier, linking supplier selection to exact demand coverage. On the human resource side, the binary variable captures whether an employee is activated in a period, while the indicator captures whether an employee is assigned to work on a task in a period; together, they model workforce availability, multi-skill allocation, and associated personnel costs over time. The binary variable denotes the start of the task in the period and drives the temporal positioning of activities within the project horizon. Finally, the binary variable identifies whether the period is an “active” working period for the project as a whole, enabling the model to account for fixed costs per active period and to compress the schedule by discouraging unnecessary calendar spreading. Collectively, these variables couple procurement, scheduling, and staffing decisions into an integrated optimization framework.

Objective Function

$$min\ \alpha \sum_{p\epsilon P}\sum_{s\epsilon S} c_{ps}U_{ps} - \beta \sum_{p\epsilon P}\sum_{s\epsilon S} q_{ps}U_{ps} + \sum_{e\epsilon E}\sum_{t\epsilon T} w_{et}x_{et} + \gamma \sum_{t\epsilon T} a_t + \delta \sum_{j\epsilon J}\sum_{t\epsilon T} tv_{jt} \tag{1}$$

The objective function of the proposed model is designed to minimize the cost and duration of the project while increasing the quality of its execution. The first and second terms of the objective function represent the total cost of purchasing parts from different suppliers and the quality of these parts, respectively, which are weighted by the coefficients $\alpha$and β, indicating the importance of cost and quality in supplier selection decisions. It is assumed that $\alpha + \beta = 1$ to balance the relative influence of cost and quality. The quality parameter q_{ps} is normalized between 0 and 1, while the cost parameter c_{ps} is not normalized; the weights α and β adjust for the scale difference between cost and quality. It is important to note that the second term is included in the objective function with a negative sign so that increasing quality leads to a decrease in the objective value. Considering that each active employee in a period generates a cost for the organization, the third term represents the cost of activating employees in each time period, and the fourth term shows the fixed costs associated with being active in each time period, aiming to reduce the number of working periods. Finally, the fifth term represents the start of tasks, and the variable t in this term indicates that later task initiation increases the cost and leads to project execution in the shortest possible time.

In this study, quality is first defined at the supplier–part level and then aggregated to the project level through a weighted average. The managerial rationale is that the decision maker is ultimately interested in the expected overall quality performance of the project (e.g., reliability of the robot during missions), which is naturally a function of the quality of individual components and their relative importance in the system. The weighted average index allows (i) more critical or higher-usage parts to have a stronger impact on the project-level quality indicator, and (ii) explicit trade-offs between overall quality and total cost to be analyzed in a tractable optimization framework. We acknowledge that any aggregation may smooth out some unit-level quality differences; therefore, in applications where very strict control of specific critical components is required, the model can be extended by adding separate quality constraints for those parts or by incorporating scenario-based reliability constraints.

Constraints

Supply Constraints

1. Single supplier per part:

$$\sum_{s\epsilon S} y_{ps} = 1, \quad \forall p \in P \tag{2}$$

Constraint 2 ensures that each part is supplied by only one supplier, thereby enforcing the single-sourcing policy. The purpose of this constraint is to reduce logistical complexities, facilitate quality control, and prevent coordination issues among multiple suppliers. This restriction enhances the precision and exclusivity of the supplier selection decision-making process.

2. Supplier feasibility:

$$y_{ps} \le f_{ps}, \quad \forall p \in P, s \in S \tag{3}$$

Constraint 3 indicates that selecting a supplier for a specific part is only permissible if that supplier is technically or contractually capable of providing it. In fact, this constraint ensures that project management chooses only among suppliers who are qualified in terms of production capacity, technical expertise, or contractual agreements. This prevents operational risks arising from selecting incapable or unauthorized suppliers, avoids rework and project delays, and guides the procurement process in a realistic and executable manner.

3. Minimum quality per part:

$$\sum_{s\epsilon S} q_{ps} y_{ps} \ge \theta_p, \quad \forall p \in P \tag{4}$$

Constraint 4 ensures that the overall quality score of parts supplied by different suppliers for each type of part does not fall below the acceptable level defined by the organization. It serves as a mechanism to maintain quality standards throughout the procurement process. Adhering to this constraint prevents issues such as part failure, increased maintenance costs, or delays in subsequent project tasks. Moreover, it ensures that decision-making is not based solely on cost, promoting a balanced approach between cost and quality in supplier selection.

4. Demand fulfillment:

$$\sum_{s \epsilon S} U_{ps} = d_p, \quad \forall p \in P \tag{5}$$

Constraint (5) enforces that, for each part, the total quantity procured from all potential suppliers exactly equals the project's required demand. This equality formulation (rather than an inequality) reflects the engineering nature of the project, where both shortages and over-supply are undesirable: a shortage of a critical part can delay downstream tasks or render the robot inoperable, while excess inventory ties up capital, increases storage and handling costs, and may be unusable in future projects due to design specificity. By tightly coupling to, the model guarantees that procurement decisions are fully aligned with the bill of materials of the rescue robot and eliminates any arbitrary "safety stock" effects that could obscure the true trade-offs between cost, quality, and schedule.

5. Supply only if the supplier is selected:

$$U_{ps} \le d_p y_{ps}, \quad \forall p \in P, s \in S \tag{6}$$

Constraint 6 ensures that a part is supplied from a supplier only if that supplier has been formally selected to provide that part. This constraint plays a key role in preventing coordination issues in the procurement process and avoiding disruptions in contract management. In other words, it protects the system from creating off-contract orders or interacting with unauthorized suppliers. Additionally, it enhances financial transparency and accountability within the supply chain, as each supply flow is explicitly linked to a specific selection decision.

Staffing and Task Scheduling Constraints

1. Each task starts exactly once:

$$\sum_{t=1}^{|T|-\tau_j+1} v_{jt} = 1, \quad \forall j \in J \tag{7}$$

Constraint 7 ensures that each task in the project schedule starts exactly once and within a specific time period, guaranteeing that every task has only a single defined starting point throughout the planning horizon and is not repeated across multiple periods.

2. Employee works on a task only if active:

$$z_{jet} \leq x_{et}, \quad \forall j \in J, e \in E, t \in T \tag{8}$$

Constraint 8 ensures that each employee can perform tasks only during the periods in which they are active. It helps accurately control human resource costs and prevents the allocation of unrealistic or unavailable resources.

3. Skill requirement for each task during its duration:

$$\sum_{e \in E} \sum_{t}^{t+\tau_j} \sigma_{eh} z_{jet} \geq r_{jh} v_{jt}, \quad \forall j \in J, h \in H, t \in T \tag{9}$$

Constraint 9 ensures that each task is assigned the required number of employees with the appropriate skills throughout its entire duration. Specifically, for each task j, skill type h, and starting period$t$, the sum of employees $e$who are both active on the task during its duration and possess the required skill must meet or exceed the number r_{jh} needed for that skill. This guarantees that tasks are executed with adequately skilled personnel, preventing delays, quality issues, or inefficiencies caused by understaffing or skill mismatches. By enforcing this constraint across all periods of a task's duration, the model ensures continuity of required competencies for smooth project execution.

4. Employee is active only if the period is active:

$$x_{et} \leq a_t, \quad \forall e \in E, t \in T \tag{10}$$

Constraint (10) links individual employee activation to the global activation status of each time period. If the period is not active (i.e.,), then no employee can be scheduled as active in that period (for all), ensuring that the model does not generate isolated or fragmented work assignments outside the officially planned working horizon. Conversely, when the model is allowed, but not forced to activate specific employees, depending on skill requirements and cost considerations. This coupling serves two purposes: (i) it enables accounting for fixed overhead costs per active period (e.g., facility usage, supervision, general project coordination) through, and (ii) it structurally synchronizes the workforce schedule with the overall project calendar. As a result, the model can discourage unnecessary dispersion of activities over many periods, promote temporal clustering of work, and achieve a more cost-efficient and realistic staffing plan.

5. Single-Task Assignment per Employee per Period Constraint

$$\sum_{j\in J} z_{jet} \leq 1 \quad \forall\, e\epsilon E, t\epsilon T \tag{11}$$

Constraint 11 indicates that each employee can participate in at most one task during any given time period, and assigning a single employee to two tasks within the same period is not permitted. This restriction enhances the accuracy and feasibility of the model by preventing unrealistic allocations, as physical, temporal, and cognitive limitations do not allow an individual to perform multiple activities simultaneously.

Variable Domains

$$y_{ps}, x_{et}, v_{jt}, z_{jet}, a_t \in \{0,1\} \tag{12}$$
$$U_{ps} \geq 0$$

Results

The proposed model considers a multi-period project focused on the design and construction of a rescue robot, integrating both procurement and workforce scheduling decisions. The procurement subsystem includes a set of five essential parts (5 parts, i.e., |P|=5), which may correspond to critical parts of the robot such as motors, sensors, controllers, actuators, or communication modules. These parts are sourced from ten potential suppliers (10 suppliers, i.e., |S|=10), each offering different unit costs and quality levels. The unit costs of the parts range from 550 to 3500 monetary units, while the quality scores vary between 0.60 and 0.98, reflecting a realistic trade-off between cost and quality. Each part has a specified demand (d_p) and a minimum acceptable average quality (θ_p) that must be satisfied to ensure reliable robot operation. The exact optimization model is coded in GAMS, and all computational experiments are carried out on a laptop with an Intel(R) Core (TM) i7-8550U processor and 12.0 GB of RAM, which allows solving the resulting mixed-integer program within reasonable computation times and provides a practical benchmark for the model's applicability in real-world project settings.

On the workforce side, the project consists of four key tasks (4 tasks, i.e., |J|=4) to be scheduled over six time periods (6 periods, i.e., |T|=6). Ten engineers and technicians (10 employees, i.e., |E|=10) are available, each possessing one or more skills from a set of four skill types ($H =$ {mechanical, control, electrical, software}). These skills represent the expertise required to assemble, program, and test the robot. The cost of activating each employee varies across periods, capturing the temporal fluctuation in labor cost. Each task has a predefined duration (τ_j) and requires a specific number of employees with certain skills (r_{jh}) to be assigned during its execution, ensuring that the robot is assembled and tested efficiently and safely.

All detailed numerical values for part demand and minimum quality requirements, unit costs, quality scores, feasibility indicators, employee skills, and task skill requirements, employee cost over time, task duration, and required skills per task are provided in the appendix (Tables A.1–A.8). All these numerical input data are synthetic and have been generated based on realistic engineering assumptions to represent a hypothetical rescue robot development project, rather than a specific real-world case. This setup provides the necessary input for evaluating the optimal combination of supplier selection, task scheduling, and employee assignment while balancing cost, quality, and skill fulfillment constraints in the context of a rescue robot development project.

Table 4. Summary of Cost Parts

Cost Part	Value
Purchase Cost	14,094.00
Quality Benefit	6.408
Personnel Cost	85,200.00
Time Cost	5,000.00
Task Start Cost	5,000.00
Total Objective Value	109,287.59

The results presented in Table 4 indicate that the objective function value, derived from the total cost of part procurement, labor expenses, period activation costs, activity initiation costs, and the quality benefit of the selected parts, amounts to 109287.592. A closer examination of Table 3 reveals that labor cost, with a value of 85,200 units, represents the largest share of the total cost and exerts the most significant influence on the model's optimal decisions. This observation aligns with the nature of specialized projects such as rescue robot development, which inherently require highly skilled personnel with relatively high wages due to the complexity of operations involved, such as programming, assembly, testing, and system integration. Following labor costs, part procurement costs constitute the next most influential cost category, playing a substantial role in shaping the model's decision-making structure.

Table 5. Selected Suppliers and Supplied Quantities

Part	Selected Supplier	Supplied Quantity
p_1	s_1	6
p_2	s_9	2
p_3	s_4	8
p_4	s_1	1
p_5	s_9	1

The supplier selection process was based on two key criteria: cost and quality (Table 5), where the optimal choice for each part was determined by maintaining an appropriate balance between these factors. According to the imposed constraint, once a supplier is selected for a specific part, all required units of that part are procured exclusively from the same supplier. The frequent selection of suppliers 1 and 9 indicates that these suppliers provide the most favorable balance of quality and cost from the model's perspective.

Table 6. Task Starting Times

Task	Start Time
j_1	t_4
j_2	t_3
j_3	t_1
j_4	t_2

Given the independence of activities from one another, the model schedules the start times of tasks by simultaneously minimizing the activity start costs and shortening the overall project duration (Table 6). For example, Task 1 is initiated in period 4, while Task 3 begins in period 1. These tasks can be associated with operations such as chassis fabrication, installation of electrical parts, and similar assembly procedures.

Table 7. Active Project Periods

Time Period	Active
t_1	1
t_2	1
t_3	1
t_4	1
t_5	1
t_6	0

Table 7 indicates that out of the six available periods, the model activates five periods in total. Reflecting the objective of minimizing project duration, the model successfully allocates personnel and schedules all required activities within these five active periods.

Table 8. Number of Active Employees in Each Period

Time Period	Number of Active Employees
t_1	3
t_2	4
t_3	7
t_4	9
t_5	8

The pattern of active personnel reflects a gradual increase in workforce utilization over the course of the project (Table 8). In the first period, only three employees are active, indicating that Task 3, initiated at the beginning of the project, requires relatively limited labor. However, from the third period onward, with the commencement of Tasks 1 and 2, which demand more specialized technical skills, the number of active personnel increases substantially. The maximum workforce engagement occurs in period 4, with a total of nine active employees, involving nearly all specialized staff in the project. This pattern aligns well with the nature of a robot-construction project, as the final phases, such as full assembly, software testing, sensor calibration, and mobility trials, tend to be more complex and therefore require greater resource allocation.

How Dropping the Quality Constraint Shifts Supplier Choices, Costs, and Schedules?

In this section, the constraint enforcing a minimum acceptable quality level for supplied parts is removed from the model, and the results of the two models are compared to provide a clearer understanding of the model's behavior. In practice, this constraint is vital for a critical and sensitive project such as the development of a search-and-rescue robot; however, removing it allows the model to be generalized and enables the presentation of results that may be useful for project managers and domain experts in other types of projects. Eliminating this constraint leads to noticeable changes across multiple PMBOK dimensions, including supplier selection, workforce allocation, task scheduling, and the overall cost structure of the project.

In the procurement part, the absence of a minimum quality requirement drives the model toward selecting cheaper suppliers. For example, under normal conditions (with the quality constraint), part 1 was sourced from the supplier s_1 for 1,600 and a quality level of 0.90. After removing the constraint, the model instead selects the supplier s_3, priced at 1,500 but with a lower quality level of 0.85. Overall, this results in a reduction of 1,074 units in purchase cost, accompanied by a decrease in total quality from 6.408 to 5.656.

In terms of task scheduling, the number of active periods increases from 5 to 6, leading to higher time-related expenses: time cost rises from 5,000 to 6,000, and task start-up cost increases from 5,000 to 6,500. Workforce allocation is also affected; for instance, in the original model, employees 1 and 2 were active during periods. t_4 and t_5, whereas in the modified model, they become active in different periods, and employee 10 becomes active during the additional sixth period. These changes result in a slight reduction in personnel cost from 85,200 to 84,500 while the total project cost increases by approximately 727 units.

In summary, removing the quality constraint leads to lower procurement costs but also lower part quality, along with longer project duration and an overall increase in total cost. The table below (Table 9) summarizes the key impacts of removing the quality constraint on procurement cost, quality, personnel allocation, time-related costs, and total project cost.

Table 9. Comparison of Project Metrics with and without the Quality Constraint

Metric	With Quality Constraint	Without Quality Constraint
Purchase Cost	14094	13020
Quality Benefit	6.408	5.656
Personnel Cost	85200	84500
Time Cost	5000	6000
Start Cost	5000	6500
Total Cost	109287.592	110014.344

All detailed numerical values for part demand and minimum quality requirements, unit costs, quality scores, feasibility indicators, employee skills, and task skill requirements, employee cost over time, task duration, and required skills per task are provided in the appendix (Tables A.1–A.8). This setup provides the necessary input for evaluating the optimal combination of supplier selection, task scheduling, and employee assignment while balancing cost, quality, and skill fulfillment constraints in the context of a rescue robot development project.

To assess the robustness of the proposed model, two additional scenarios were constructed around the base case: an optimistic and a pessimistic scenario. In the optimistic case, all unit purchasing costs were reduced by 10%, while all quality scores were increased by 5% (capped at 1 when necessary). In the pessimistic case, the same parameters were perturbed in the opposite direction, i.e., purchasing costs were increased by 10% and quality scores were decreased by 5%.

Under the optimistic scenario, the model yielded a total cost of 107,205.5, composed of a purchasing cost of 12,312, a personnel cost of 84,400, a time cost of 6,000, a start-up cost of 4,500, and a quality benefit of 6.53. By reconstructing the base case from these variations, the corresponding total cost is approximately 108,573.8, with a purchasing cost of 13,680 and a quality benefit of 6.22. The mirrored pessimistic scenario leads to an estimated total cost of 109,942.1, with a purchasing cost of 15,048 and a quality benefit of 5.91, while personnel, time, and start-up costs remain unchanged across scenarios.

Importantly, for these moderate parameter variations (±10% in costs and ±5% in quality scores), the optimal supplier configuration and project schedule remain unchanged; only the objective value varies within a narrow band of about ±1.3% around the base scenario. This behavior indicates that the proposed model is relatively robust to plausible fluctuations in purchasing costs and quality levels, and that the chosen configuration does not critically depend on finely tuned parameter values.

To assess the robustness of the model with respect to the scale of the purchasing criterion, an additional experiment was conducted in which the purchasing cost table c_{ps} was normalized. The original cost values were transformed into a [0,1] scale using a min–max normalization.

where c^{min} and c^{max} denote, respectively, the minimum and maximum values observed in the purchasing cost table (Table A.2). The quality criterion was already modeled as a score in the range [0,1], and therefore did not require any additional transformation.

After replacing c_{ps} with c_{ps}^{norm} In the objective function and re-solving the model in GAMS, the purchasing cost component in the objective took the value 2.764, while the quality benefit was 6.408. The remaining components of the objective function, personnel cost, time cost, and start cost were 85,200, 5,000, and 5,000, respectively, resulting in a total objective value of 95,196.356. The optimal solution in this normalized-cost setting selected the same suppliers for parts p_1–p_5 (suppliers s_1, s_4 , and s_9) and produced a task and workforce schedule with the same overall structure as in the base case.

These results indicate that the proposed model is stable with respect to normalization of the purchasing costs: representing purchasing costs on a normalized scale does not materially alter the optimal decisions, while the quality dimension continues to be represented as a standardized score in [0,1].

Discussion

Sensitivity Analysis

Given the multi-dimensional nature of the proposed PMBOK-based optimization model encompassing procurement decisions, human resource allocation, task scheduling, and cost–time trade-offs, a sensitivity analysis is conducted to examine the stability and managerial implications of key cost-related parameters. Specifically, this section investigates how variations in two critical parameters, namely the fixed cost of activating project periods (γ) and the task start-up cost (δ), influence project performance across time, cost, and resource management domains. Accordingly, the sensitivity analysis is structured into two subsections, each focusing on one parameter to provide targeted managerial insights aligned with PMBOK knowledge areas.

Sensitivity Analysis with Respect to Fixed Active-Period Cost (γ)

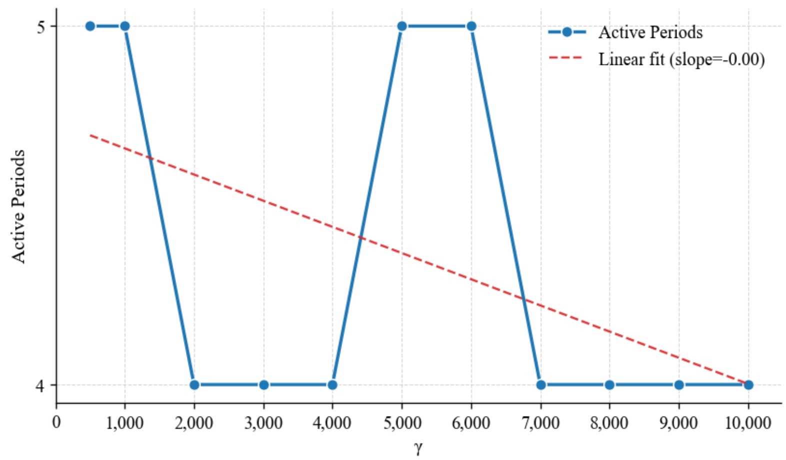

Fig 1. Variation of Active peripds Based on Changes in Weight of fixed Cost per active period

Figure 1 shows that changes in γ, the weight of fixed cost per active period, can shift the project from a minimum of four periods to five periods at specific thresholds. This stepwise, nonlinear pattern means that raising γ does not monotonically shorten the schedule; in fact, at some levels, it lengthens project duration by adding an extra active period. For project schedule management under PMBOK, this implies that "more cost pressure" (a higher γ) does not automatically translate into faster completion and can unintentionally push the project into a longer execution window. A manager who optimizes only for time, without explicitly modeling γ and its impact, may choose a setting that appears aggressive on cost control but actually delays delivery. Thus, γ should be treated as a strategic decision lever: it must be tuned so that the schedule remains near the four-period configuration where possible, while avoiding parameter ranges that trigger unnecessary fifth periods and associated overhead.

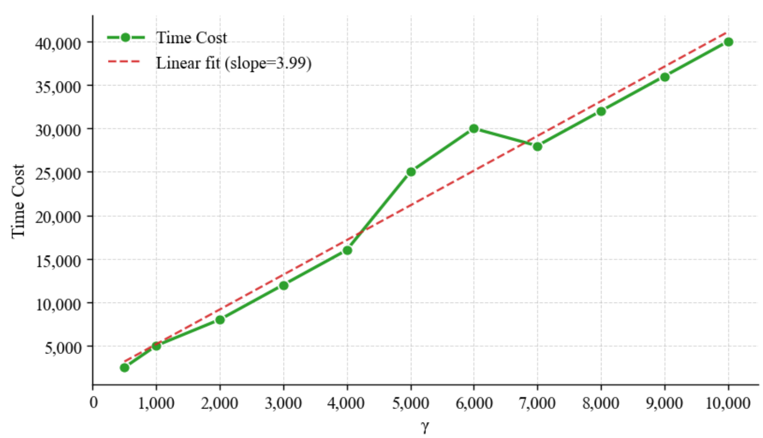

Fig 2. Variation of Time Cost Based on Changes in Weight of fixed Cost per active period

Figure 2 complements this view by showing that, despite local fluctuations, time cost increases almost linearly as γ grows, with a strong positive overall trend. In practical terms, assigning more weight to the fixed cost per active period steadily raises the cumulative time-related cost of the project, even in cases where the number of periods does not change. When combined with Figure 1, this reveals a double risk: at some γ values, managers face both higher time costs and a longer schedule. From a PMBOK-oriented cost and schedule management perspective, γ therefore cannot be treated merely as a penalty parameter; it is a controllable policy variable that shapes the trade-off between duration and expenditure. Effective project management requires selecting γ within a range that keeps the project on a shorter schedule while restraining the growth of time cost, thereby achieving a more economically efficient and realistic project plan.

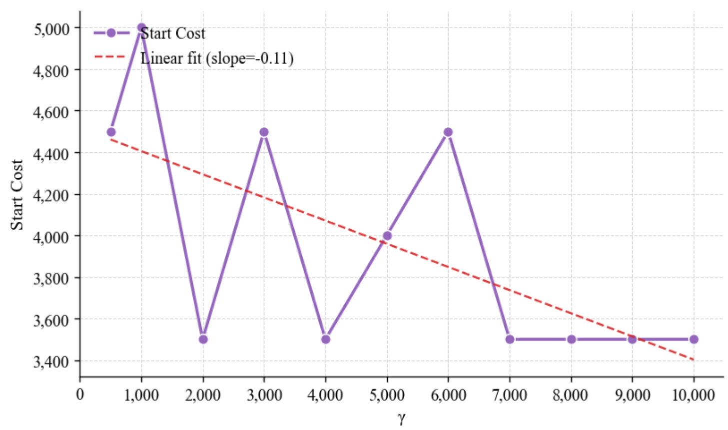

Fig 3. Variation of Start Cost Based on Changes in Weight of fixed Cost per active period

Figure 3 shows that Start Cost is sensitive to changes in γ, the weight of fixed cost per active period. While the individual points fluctuate, the underlying trend is roughly linear, and the most pronounced jumps occur at the same critical γ values where the number of active periods changes. At these points, activating an additional period requires more preparatory and mobilization activities, which sharply increase the Start Cost. From a project management viewpoint, this means that γ is not only a scheduling parameter but also a driver of task initiation patterns and front-loaded expenditures. Within the scope of Project Integration Management, managers must therefore calibrate γ to prevent unnecessary period activation that would inflate Start Cost without adding proportional value.

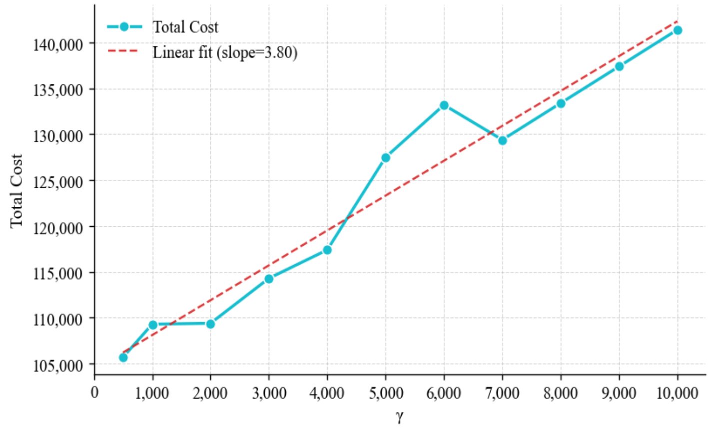

Fig 4. Variation of Total Cost Based on Changes in Weight of fixed Cost per active period

Figure 4 illustrates how Total Cost responds to γ, combining the effects on Time Cost and Start Cost. The relationship is almost linear overall, but the slope becomes steeper at the same critical γ values, reflecting the compounded impact of extra active periods on both time-related and start-up expenses. When γ crosses these thresholds, Total Cost escalates more rapidly, signaling a structural shift in the project's cost configuration rather than a marginal adjustment. From an integrated PMBOK perspective, this confirms that γ simultaneously governs schedule length, resource activation, and the overall cost structure. Consequently, choosing γ should be the outcome of a systematic, sensitivity-analysis-based process that balances time, cost, and efficiency, and explicitly avoids γ ranges that trigger unnecessary periods and disproportionate increases in Total Cost.

Sensitivity Analysis with Respect to Task Start Cost (δ)

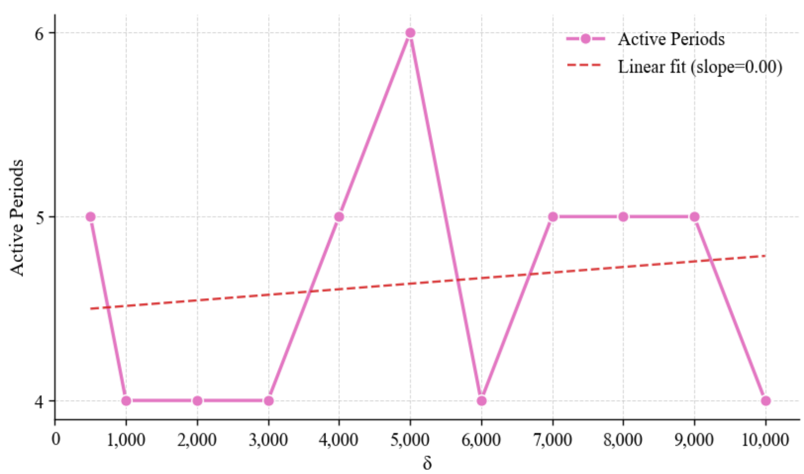

Fig 5. Variation of Active Cost Based on Changes in Cost per task start

Figure 5 shows that changes in δ, defined as the cost per task start, directly affect Project Schedule Management. As δ varies, the number of active periods fluctuates between four and six, with the maximum of six active periods occurring only at $\delta = 5000$; even small changes in δ can therefore trigger discrete shifts in the temporal arrangement of activities. This behavior does not follow a smooth or predictable pattern and, at certain δ values, can push the project duration to its maximum. From an integrated project-management and scheduling perspective, δ must be tuned based on sensitivity analysis to avoid unnecessary activation of periods and unwanted extensions of the project calendar.

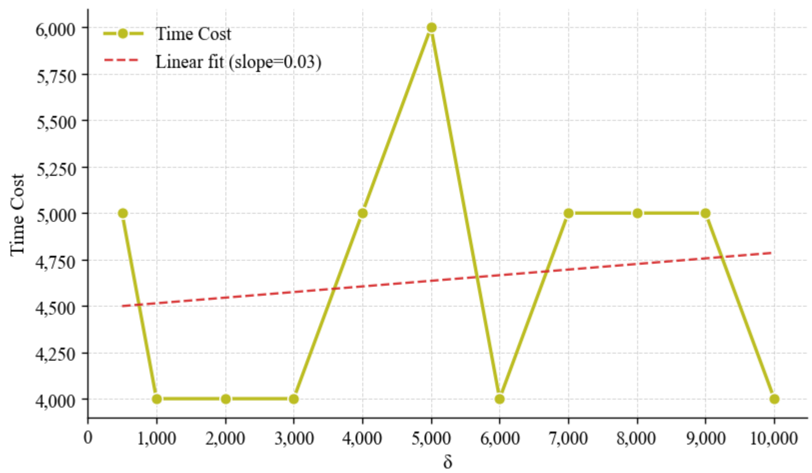

Fig 6. Variation of Time Cost Based on Changes in Cost per task start

Figure 6 confirms that δ influences not only the schedule but also the project's cost structure. As δ changes, Time Cost oscillates roughly between 4000 and 6000, with the main peak occurring at the same point where all six periods are active ($\delta = 5000$), i.e., when the project duration is at its maximum. These fluctuations indicate that decisions about task start-up costs can, in a non-uniform manner, increase both project duration and time-related expenses. From the standpoint of Project Schedule Management and Project Procurement Management, policies regarding start-up costs must therefore be based on a careful, sensitivity-driven assessment to avoid combinations of "maximum duration" and "maximum time cost."

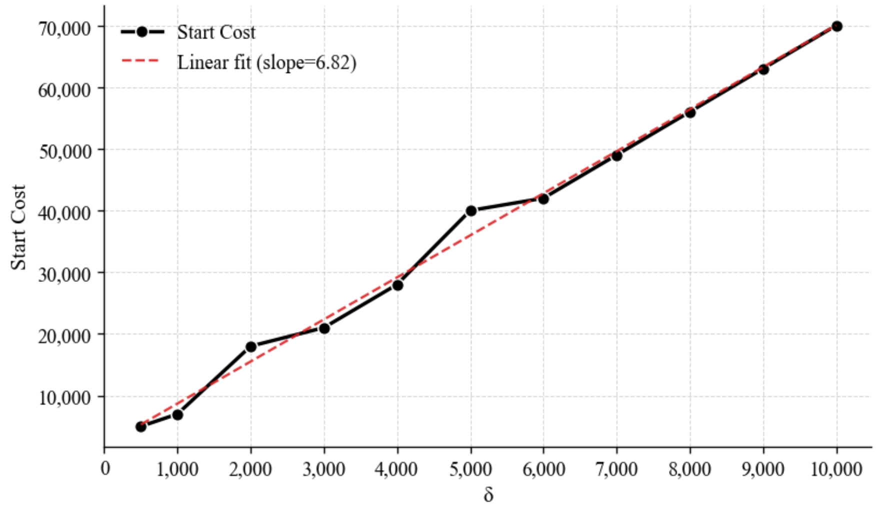

Fig 7. Variation of Start Cost Based on Changes in Cost per task start

Figure 7 shows that δ, defined as the cost per task start, has a nearly linear and strongly positive effect on Start Cost, placing it squarely within the scope of Project Cost Management. As δ increases, Start Cost rises steadily, but at the critical level δ =5000, the slope becomes noticeably steeper, indicating a regime where additional increases in δ translate into disproportionately higher start-up expenditures. This inflection reflects a structural change in the activation pattern of tasks and periods, meaning that an apparently small adjustment to δ can trigger a substantial escalation in procurement and mobilization costs. From a Project Integration Management perspective, setting δ without sensitivity analysis can therefore lock the project into a high-cost configuration that is difficult to reverse.

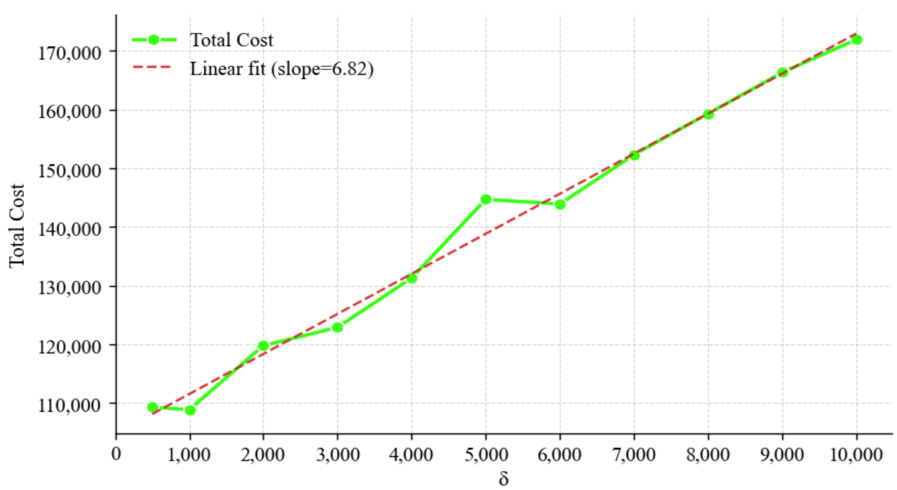

Fig 8. Variation of Total Cost Based in Changes in Cost per task start

Figure 8 extends this insight by demonstrating that the same pattern holds for Total Cost, which incorporates both Start Cost and Time Cost. Total Cost grows almost linearly as δ increases, but again around δ =5000 the rate of growth accelerates, mirroring the sharp rise in Start Cost and coinciding with the maximum project duration identified in earlier figures. This behavior indicates that inappropriate choices of δ can simultaneously inflate duration-related expenses and start-up costs, pushing overall project expenditure to its upper bound. Consequently, δ must be treated as a key integrative control parameter: it should be tuned using sensitivity analysis to balance schedule performance with cost efficiency and to avoid entering the high-cost, long-duration region of the project's operating space.

Managerial Insight

A significant portion of the project's costs is associated with human resources. Given the complex nature of engineering projects such as rescue-robot development, highly skilled personnel are required, and their wages are typically high. Therefore, managers of complex projects should pay special attention to the human resource management aspects of PMBOK and implement diverse strategies to recruit competent personnel, reduce costs, allocate tasks efficiently, and create an environment that facilitates seamless collaboration. Neglecting high-cost personnel or failing to ensure effective teamwork can disrupt the project and negatively affect scheduling. This risk can be mitigated through careful leadership and strategic HR management. In this regard, the proposed model provides project managers with a quantitative tool to determine the optimal combination of employee specializations, workforce size, and activation periods, enabling more informed staffing decisions rather than relying on experience-based judgment alone. This insight strengthens decision-making within the Project Resource Management knowledge area by linking human resource allocation directly to cost and scheduling outcomes.

Setting a minimum quality requirement for parts is an appropriate approach in sensitive and complex engineering projects, as it prevents failures. The model further demonstrates that removing this quality constraint reduces procurement costs but simultaneously increases the total project cost. This highlights the importance of integrated project management in PMBOK, emphasizing that project managers must take a holistic view of the project rather than focusing solely on a single objective (e.g., reducing procurement cost does not necessarily reduce total project cost).

The impact of varying parameters such as the weight of fixed cost per active period (γ) and cost per task start (δ) on different project dimensions is substantial. These parameters can vary depending on environmental and temporal factors, which may differ across countries. Sensitivity analysis reveals that their effects are neither linear nor constant, and critical points exist. For instance, at γ = 5000 and γ = 6000, the number of active periods increases, leading to higher Time Cost and Total Cost. Executing the project at γ = 4000 results in a substantially lower total cost compared to γ = 5000, while surprisingly, operating at γ = 7000 reduces total cost relative to γ = 5000 (see Figure 4), with fewer active periods (see Figure 1). Another example occurs at δ= 5000, which activates the maximum number of periods (Figure 5) and increases total cost (Figure 8), whereas running the project at δ = 6000 reduces both the number of active periods and total project cost. Therefore, considering multiple influential factors simultaneously and identifying critical points is essential for effective project decision-making. Therefore, a very important managerial insight derived from this issue is that the project manager should not view the key parameters γ and δ merely as penalty coefficients in the model; rather, these parameters should be considered as effective control levers in decision-making and as balancing mechanisms between time and cost within the project structure, enabling the identification of the project's critical points. This insight emphasizes the necessity of establishing Project Integration Management, Project Time Management, and Project Cost Management within the project, which can only be achieved through proper sensitivity analysis and careful attention to these parameters.

Given the multitude of project management dimensions and the need to examine them collectively, the most important practical application of the proposed model is its use as a decision-support dashboard for managers of complex engineering projects. The model enables simulation of "what-if" scenarios, allows managers to observe the effects of changes across various project parts, and supports informed decision-making to optimize project performance. Therefore, developing such a dashboard enables the project manager to observe the impacts of their decisions on various PMBOK dimensions, including procurement management, cost management, and time management, and to make the most appropriate decisions while ensuring proper Project Integration Management.

Conclusion

This study developed an integrated optimization framework for planning and managing the construction of a search and rescue robot as a complex engineering project, incorporating simultaneous modeling of human resource allocation, supplier selection, quality control, project scheduling, cost reduction, and integrative decision-making across all related domains, fully aligned with PMBOK principles. The numerical results highlight the distribution of project costs and reveal that the largest share is associated with specialized human resources (e.g., 85,200 out of a total objective value of 109,287.59), which is typical in complex and knowledge-intensive projects and confirms the central role of Project Resource Management in such settings. In procurement, the model consistently selected a small subset of suppliers (mainly suppliers 1 and 9) for all required parts, illustrating how cost–quality trade-offs and minimum quality constraints jointly drive supplier decisions; notably, removing the minimum quality constraint reduced procurement costs but increased both project duration and total cost, clearly demonstrating the critical importance of maintaining an integrated managerial perspective rather than optimizing a single isolated objective.

On the scheduling side, the model scheduled four independent tasks within five active periods out of six, and the workforce profile showed an escalating pattern with up to nine employees active in peak periods, which mirrors the real-world intensification of effort in final integration and testing phases. Furthermore, the sensitivity analysis of the fixed cost per active period (γ) and the cost per task start (δ) revealed the existence of critical breakpoint values (e.g., $\gamma = 5000$ and $\delta = 5000$) that significantly affect the number of active periods and the total cost, sometimes in non-intuitive ways; this underlines the need for identifying, monitoring, and managing such thresholds as genuine control levers in Project Time and Cost Management. A dedicated section on managerial insights translated these analytical outcomes into actionable guidance, showing how managers can use these parameters to balance time, cost, and quality and to strengthen Project Integration Management.

Therefore, the proposed optimization framework can serve as the computational core of a real-time decision-support dashboard, enabling project managers to simulate "what-if" scenarios (e.g., changes in γ, δ, or quality thresholds), observe the resulting impacts on cost, schedule, and procurement in a unified view, and make rapid, data-driven decisions. Extending this framework into a fully-fledged digital dashboard is a promising direction for future research, and the same concepts can be applied to additional PMBOK knowledge areas not covered here, such as project risk management, to uncover further managerial implications. Finally, although the model is particularly suitable for complex engineering projects like rescue-robot development, its structure can be adapted and scaled to large initiatives such as housing development and major infrastructure programs, where integrated management of suppliers, workforce, and schedule is equally critical.

Limitations and future research

Although the proposed framework provides an integrated and practical tool for planning and managing complex engineering projects, it is subject to several natural methodological and tool-related limitations. From a methodological perspective, the model relies on a set of simplifying assumptions that are common in optimization studies, such as a limited number of activities and periods, independent tasks without detailed precedence networks, deterministic parameters for costs and times, and a single-sourcing structure for each part. These assumptions were intentionally adopted to keep the model transparent and solvable and do not affect the general logic of the approach, but they may restrict direct application to very large-scale or highly uncertain real-world environments. From a tool perspective, the model is implemented in GAMS and solved by commercial solvers, which implies a dependency on specialized software and may impose practical limits on scalability when the problem size grows substantially or when only standard hardware is available. These limitations, however, mainly point to promising avenues for future work, such as extending the framework to larger project networks, incorporating uncertainty and risk, embedding the model into a user-friendly dashboard, and exploring alternative solution techniques tailored to very large instances.

Authors' Contributions

Parsa Leylaparast: Formal analysis, Validation, Writing – original draft; Mohammad Reza Gholamian: Conceptualization, Project administration, Supervision; Maryam Noroozi: Investigation, Methodology, Writing – review & editing.

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Data Availability Statement

Not applicable.

Ethical considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of interest

The authors declare no conflict of interest.

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Appendix

Table A.1 – Part Demand and Minimum Quality Requirements

Part	Demand	Minimum Quality
p1	6	0.88
p2	2	0.85
p3	8	0.82
p4	1	0.9
p5	1	0.86

Table A.2 – Unit Cost

Part \ Supplier	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
p_1	1600	1700	1500	1800	1650	1550	2000	2800	1400	1900
p_2	700	800	750	720	850	900	680	1200	820	780
p_3	1050	1100	1150	1200	1250	1300	1020	2100	1180	1220
p_4	2000	2100	2050	1900	2200	2150	2400	3500	1950	2300
p_5	550	600	650	700	750	580	800	1000	650	720

Table A.3 – Quality Score

Part \ Supplier	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
p_1	0.9	0.88	0.85	0.93	0.89	0.87	0.97	0.91	0.8	0.86
p_2	0.78	0.82	0.8	0.75	0.88	0.92	0.7	0.85	0.9	0.76
p_3	0.65	0.72	0.75	0.88	0.96	0.98	0.6	0.83	0.86	0.68
p_4	0.92	0.95	0.93	0.85	0.97	0.9	0.98	0.88	0.91	0.89
p_5	0.75	0.85	0.9	0.95	0.88	0.8	0.96	0.78	0.86	0.92

Table A.4 – Feasibility Matrix

Part \ Supplier	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
p_1	1	0	1	0	0	1	0	0	1	0
p_2	0	1	0	0	1	0	0	0	1	0
p_3	0	0	1	1	0	0	0	1	0	0
p_4	1	0	0	1	0	0	1	0	0	0
p_5	0	1	0	0	1	0	0	0	1	0

Table A.5 – Employee Skill Matrix

Employee	Mechanical	Control	Electrical	Software
e_1	1	0	0	0
e_2	1	0	0	0
e_3	0	1	0	0
e_4	0	1	0	0
e_5	0	0	1	0
e_6	0	0	1	0
e_7	0	0	0	1
e_8	0	0	0	1
e_9	1	0	0	0
e_{10}	0	1	0	0

Table A.6 – Employee Cost Over Time

Employee \ Time	t_1	t_2	t_3	t_4	t_5	t_6
e_1	2300	2350	2250	2400	2500	2350
e_2	2300	2350	2250	2400	2500	2350
e_3	2600	2650	2550	2700	2800	2650
e_4	2600	2650	2550	2700	2800	2650
e_5	2900	2950	2850	3000	3100	2950
e_6	2900	2950	2850	3000	3100	2950
e_7	3200	3250	3150	3300	3400	3250
e_8	3200	3250	3150	3300	3400	3250
e_9	2300	2350	2250	2400	2500	2350
e_{10}	2600	2650	2550	2700	2800	2650

Table A.7 – Task Duration τ_j

Task	Duration (periods)
j_1	2
j_2	3
j_3	1
j_4	2

Table A.8 – Required Skills per Task

Task	Mechanical	Control	Electrical	Software
j_1	2	1	0	1
j_2	1	2	1	0
j_3	0	0	2	1
j_4	1	1	1	1