An Integrated Model for Simultaneous Time–Cost Optimization of Construction Projects through the Integration of System Dynamics, Earned Value Management, and the Simulated Annealing Algorithm

Mahdi Moradi[1], Elmira Mashayekhi Nezamabadi[2*] Soheila Khishtandar[2]

[1] Ph.D. Candidate, Department of Management and Accounting, Qa.C., Islamic Azad University, Qazvin, Iran
[2] Department of Management and Accounting, Qa.C., Islamic Azad University, Qazvin, Iran

*** Corresponding author email address**: e.mashayekhi@iau.ac.ir

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Abstract

This study aimed to develop and evaluate an integrated model for the simultaneous optimization of time and cost in construction projects by combining System Dynamics, Earned Value Management, and the Simulated Annealing algorithm. This applied, quantitative, modeling-based study was conducted using data from 24 construction companies in Tehran and 96 project management, planning, cost control, and engineering professionals. One representative construction project from each company was selected, yielding 24 projects for model calibration and evaluation. Project schedule, cost, resource, progress, rework, and productivity data were extracted from organizational records, while expert assessments were used to validate causal relationships among dynamic variables. Earned Value Management indicators, including SPI, CPI, SV, and CV, were incorporated into a System Dynamics model representing interactions among project progress, schedule pressure, resource utilization, productivity, rework, remaining work, and cumulative cost. The validated model was then linked to a Simulated Annealing algorithm to optimize activity durations and resource allocation under project constraints. Sensitivity analyses and repeated optimization runs were used to assess model stability and robustness. The integrated model significantly improved project performance relative to the baseline condition. Mean project duration decreased from 30.91 to 26.96 months, representing a 12.78% improvement, while mean total project cost decreased from 2,078.54 to 1,898.63 billion rials, corresponding to an 8.66% reduction. Schedule delay relative to baseline declined by 96.84%, while cost growth decreased by 76.25%. SPI increased from 0.88 to 0.99 and CPI from 0.91 to 0.98. Rework decreased by 38.89%, and corrective-action delay decreased by 65.50%. Repeated optimization runs also demonstrated stable convergence toward comparable near-optimal solutions. Integrating System Dynamics, Earned Value Management, and Simulated Annealing provides an effective dynamic decision-support framework for simultaneously improving construction project time and cost performance while reducing rework and improving responsiveness to project deviations.

Keywords: *Construction Project Management; Time–Cost Optimization; System Dynamics; Earned Value Management; Simulated Annealing; Project Control; Resource Allocation*

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1. Introduction

Construction projects are inherently exposed to multiple sources of uncertainty, interdependence, and performance pressure, among which time and cost remain two of the most critical and persistent dimensions of managerial concern. Delays in project completion often generate substantial increases in indirect costs, financing expenses, resource idleness, contractual claims, and opportunity losses, while attempts to accelerate project activities may lead to higher direct costs, intensified resource consumption, congestion, productivity loss, and increased operational risk. The simultaneous management of these competing objectives has therefore become one of the central challenges of construction project management. Traditional project planning approaches frequently treat schedule and cost as relatively static and separable dimensions, whereas actual construction environments are characterized by dynamic feedback interactions among progress, productivity, resource availability, rework, managerial intervention, and expenditure. As a result, optimizing project duration without considering its cost consequences, or controlling cost independently of schedule performance, may lead to locally efficient but globally suboptimal decisions. Recent research has therefore increasingly emphasized the necessity of integrated approaches capable of jointly evaluating time, cost, quality, resource utilization, and project performance under changing operational conditions [1, 2].

The time–cost trade-off problem has historically been formulated around the assumption that activity durations can be shortened by allocating additional resources or adopting more expensive execution alternatives. Under this framework, crashing selected activities may reduce project duration but simultaneously increase direct costs, whereas longer project durations may reduce direct expenditure while increasing indirect and overhead costs. The managerial challenge is consequently to identify a combination of activity durations and resource allocations that produces the most favorable balance between completion time and total project cost. However, practical construction systems are considerably more complex than this simplified relationship suggests. Changes in one activity may influence downstream activities, resource loading, labor productivity, quality outcomes, and rework requirements, while corrective interventions may produce delayed or nonlinear effects. Studies on multi-objective optimization have therefore expanded conventional time–cost models to incorporate quality, risk, profit, and other performance dimensions. For example, genetic algorithm applications have been used to optimize simultaneous trade-offs among time, cost, quality, and risk in construction projects, highlighting the multi-dimensional nature of real project decisions [3]. Similarly, optimization models incorporating resource consumption and project profitability have demonstrated that schedule compression should be examined in relation to resource deployment and economic returns rather than as an isolated scheduling problem [4].

The growing complexity of construction projects has encouraged the application of metaheuristic optimization algorithms capable of searching large and nonlinear solution spaces where exact mathematical optimization is difficult or computationally prohibitive. Numerous algorithms have been introduced to solve time–cost and multi-objective construction scheduling problems, including genetic algorithms, swarm-based methods, weed optimization, and hybrid metaheuristics. The use of comparative metaheuristic analysis for simultaneous optimization of project time, cost, and profit has shown that evolutionary and population-based search methods can identify competitive solutions in complex construction environments [5]. Likewise, optimization of time, cost, and quality in projects with interruptible activities has illustrated the value of metaheuristic approaches in dealing with discrete, nonlinear, and constrained decision spaces [6]. Multi-criteria schedule compression approaches have also emphasized that selecting activities for acceleration should account not only for cost and time but also for quality and risk implications [7]. These developments demonstrate a clear transition from deterministic scheduling toward multi-objective, adaptive, and computationally intelligent optimization frameworks.

Despite this progress, many conventional metaheuristic models remain limited by their dependence on static parameter values. In most optimization formulations, activity durations, crashing costs, resource requirements, and execution alternatives are specified before optimization begins and are treated as fixed during the search process. This assumption neglects the fact that project performance evolves over time and that resource intensification or schedule pressure can themselves alter productivity, quality, and cost. For instance, increasing overtime may initially accelerate progress but later generate fatigue and lower labor productivity; assigning additional workers to congested work areas may increase resource levels without proportionately increasing output; and rapid schedule compression may increase errors and rework, thereby adding new work and additional costs. Consequently, a theoretically optimal schedule derived from static assumptions may perform poorly when implemented in a dynamic construction environment. This limitation has been acknowledged in studies examining quality-based evaluation of time–cost trade-offs, which indicate that optimization results can change substantially when qualitative performance consequences are incorporated into the decision process [8]. Similarly, project optimization based on broader project management knowledge frameworks has shown that quantitative and qualitative performance indicators should be evaluated simultaneously to provide a more realistic basis for managerial decisions [9].

System Dynamics provides a particularly suitable methodological framework for addressing these limitations because it enables project systems to be modeled as interconnected structures of stocks, flows, feedback loops, delays, and nonlinear causal relationships. Rather than representing a project as a static network of activities, System Dynamics conceptualizes project performance as an evolving system in which managerial actions produce direct and indirect consequences over time. Variables such as remaining work, completed work, workforce productivity, schedule pressure, resource utilization, rework, cumulative cost, and managerial response can be linked through reinforcing and balancing feedback loops. For example, schedule delay can increase managerial pressure for acceleration, which may initially increase progress but may also intensify workload and reduce productivity, potentially producing additional rework and further delay. System Dynamics models have been applied in project management to represent such complex causal relationships and to analyze the temporal consequences of managerial interventions [10]. Their key advantage lies in the ability to evaluate not merely the immediate effect of an intervention but also its delayed, cumulative, and feedback-driven consequences.

Although System Dynamics can represent project behavior comprehensively, it does not by itself necessarily identify the best decision among a large set of feasible alternatives. This creates a methodological rationale for integrating System Dynamics with optimization algorithms. In such an integrated architecture, the dynamic simulation model can serve as an evaluation environment in which each candidate solution generated by the optimization algorithm is tested under realistic feedback conditions. Instead of evaluating a candidate activity schedule solely through predetermined time and cost values, the simulation can estimate its implications for progress, productivity, resource use, rework, and cumulative expenditure over time. This integration transforms the optimization process from a static search problem into a simulation-based dynamic decision process. Among available optimization methods, Simulated Annealing is particularly attractive because of its ability to escape local optima by probabilistically accepting inferior solutions during the early stages of the search and gradually reducing this probability as the search progresses. Its flexible structure allows it to be adapted to discrete activity-duration decisions, resource allocations, and complex feasibility constraints. Hybrid applications combining Simulated Annealing with other optimization techniques have demonstrated strong performance in complex scheduling environments, particularly when transportation resources and multiple operational constraints are involved [11].

The relevance of Simulated Annealing to project time–cost optimization has also been reinforced by recent predictive optimization studies. Hybrid approaches combining machine learning with Simulated Annealing have been proposed to improve project time and cost prediction, indicating that optimization performance can be strengthened when predictive information is incorporated into the decision process [12]. This trend corresponds to a broader transformation in construction project management toward data-driven prediction, intelligent scheduling, and adaptive resource estimation. Machine-learning-based project management models increasingly use historical and sequential project information to forecast schedule performance and resource requirements, thereby enabling earlier intervention in potentially problematic projects [13]. Recent hybrid forecasting models have likewise demonstrated that combining predictive algorithms with optimization techniques can enhance the accuracy of construction schedule and budget forecasts [14]. These developments suggest that future project control systems should not merely record deviations after they occur but should integrate prediction, simulation, and optimization to support proactive managerial decision-making.

The increasing availability of project data has also enabled advanced artificial intelligence models to improve cost and schedule estimation. Hybrid deep learning architectures using both sequential and non-sequential project information have demonstrated strong potential for accurate prediction of construction cost and schedule outcomes [15]. However, predictive accuracy alone does not determine which corrective action should be selected. A model may accurately forecast a future delay or cost overrun while leaving managers uncertain about which activities to accelerate, how many resources to allocate, or how corrective actions may affect future productivity and rework. Therefore, predictive analytics should ideally be combined with decision and control frameworks that convert information into actionable optimization strategies. In this regard, an integrated architecture connecting performance measurement, dynamic simulation, and metaheuristic optimization may provide greater practical value than the isolated use of either predictive or optimization techniques.

Earned Value Management represents another essential component of such an architecture because it provides an established and systematic mechanism for integrating scope, schedule, and cost performance. Through indicators such as

Planned Value, Earned Value, Actual Cost, Schedule Performance Index, Cost Performance Index, Schedule Variance, and Cost Variance, EVM allows project managers to quantify deviations from approved baselines and evaluate whether project performance is improving or deteriorating. Early applications of EVM in project cost control demonstrated its practical usefulness for comparing planned and actual project performance and supporting corrective decisions [16]. Statistical monitoring of time and cost performance indicators has further shown that performance indices can be treated as control signals for identifying abnormal project behavior and facilitating timely management response [17]. The importance of EVM is particularly significant in construction because schedule and cost deviations are frequently interdependent and may become increasingly difficult to correct when identified late.

Empirical research has also emphasized the positive relationship between the use of EVM and improved construction project outcomes. Examination of construction projects has indicated that EVM can strengthen project monitoring, provide early warning regarding schedule and cost deviations, and support more systematic corrective action [18]. In environments characterized by uncertainty and imprecision, fuzzy adaptations of EVM have also been used to improve performance assessment where progress and cost information cannot be represented with complete certainty [19]. These applications demonstrate that EVM is more than a reporting mechanism; it can function as a continuous source of state information within an integrated decision-support system. Nevertheless, traditional EVM is primarily diagnostic and predictive rather than prescriptive. It can reveal that a project is behind schedule or over budget, but it does not inherently determine the optimal combination of activities and resources required to correct the deviation. This limitation creates a strong rationale for linking EVM with optimization and dynamic simulation.

Recent research has begun to move in this direction. The integration of multi-objective optimization with Earned Value Management has demonstrated that project optimization models can be enhanced when schedule and cost performance indicators are directly incorporated into the decision framework [20]. Such integration provides a bridge between optimization models developed at the planning stage and actual project performance observed during execution. Instead of optimizing only against the original baseline, the decision model can be updated based on real-time or periodic EVM indicators. This is especially important in construction projects where deviations accumulate progressively and where corrective strategies should be revised in response to actual performance. By embedding EVM indicators within a dynamic optimization architecture, project control can be transformed from periodic reporting into an iterative feedback mechanism.

Another increasingly important consideration is that project optimization should be aligned with broader concepts of value creation and sustainable project management. Construction project success can no longer be evaluated solely through completion within the originally specified schedule and budget. Projects create value through efficient resource use, reduced waste, improved organizational learning, stakeholder satisfaction, and long-term economic and social outcomes. Contemporary project management research has therefore linked sustainable development and value creation to the way project decisions are formulated and controlled [21]. From this perspective, reducing unnecessary rework, avoiding inefficient resource intensification, and minimizing prolonged indirect costs are not merely operational improvements; they contribute to more sustainable and value-oriented project delivery. An integrated time–cost model that explicitly considers dynamic productivity and rework effects may therefore support both efficiency and sustainable resource management.

The literature thus reveals several complementary streams of development. One stream focuses on multi-objective optimization of time, cost, quality, risk, and profit [3, 5]. A second stream emphasizes intelligent prediction and data-driven schedule and cost forecasting [13-15]. A third focuses on EVM as a mechanism for integrated monitoring and control [16-18]. A fourth employs System Dynamics to capture feedback, delay, and nonlinear behavior in project systems [10]. Finally, recent hybrid models indicate growing interest in combining prediction and metaheuristic optimization, including the use of Simulated Annealing [11, 12]. Nevertheless, these streams have largely evolved in parallel. Existing time–cost optimization models often lack a dynamic feedback representation of project behavior, System Dynamics models frequently lack an explicit global optimization mechanism, and EVM applications commonly remain focused on performance diagnosis rather than direct generation of optimized corrective strategies.

A further methodological gap concerns the timing of management intervention. Project deviations are not only functions of their magnitude but also of how rapidly they are detected and corrected. A moderate schedule variance addressed promptly may be less damaging than a smaller variance that persists for several reporting cycles. Similarly, cost inefficiency can intensify through feedback mechanisms when delayed managerial response causes additional resource pressure, overtime, productivity loss, or rework. Consequently, a robust project optimization model should account for both the current performance state and the dynamic trajectory through which deviations develop. The combination of EVM and System Dynamics is particularly suitable for this purpose because EVM provides periodic state measurements while System Dynamics can translate these measurements into future behavioral consequences. Simulated Annealing can then search among alternative corrective strategies by evaluating each candidate within that dynamic environment.

For construction companies operating in complex urban markets such as Tehran, these issues are especially relevant because projects frequently encounter resource constraints, scheduling pressure, cost escalation, design changes, procurement disruptions, and operational uncertainty. Model-based time–cost optimization has therefore attracted increasing attention in urban construction contexts where managers require decision-support systems capable of evaluating numerous interacting constraints [2]. However, practical usefulness depends on whether the proposed model can reflect actual project behavior rather than merely generate mathematically efficient schedules. A model that reduces nominal activity durations at the expense of excessive resource pressure or rework may not provide genuine improvement. The simultaneous integration of dynamic project behavior, earned value feedback, and a robust metaheuristic search mechanism therefore offers a promising path toward more realistic and operationally meaningful time–cost optimization.

Accordingly, the present study was conducted to develop and evaluate an integrated model for the simultaneous optimization of time and cost in construction projects through the combined application of System Dynamics, Earned Value Management, and the Simulated Annealing algorithm.

2. Methodology

This study employed an applied, quantitative, modeling-based research design aimed at developing and evaluating an integrated model for the simultaneous optimization of project time and cost in construction projects. The methodological framework combined three complementary analytical approaches, namely System Dynamics (SD), Earned Value Management (EVM), and the Simulated Annealing (SA) optimization algorithm. The rationale for integrating these approaches was that time–cost optimization in construction projects is inherently dynamic and cannot be adequately addressed through static optimization techniques alone. Changes in activity duration, resource allocation, productivity, rework, schedule pressure, and cost escalation interact continuously throughout the project life cycle. Accordingly, System Dynamics was used to represent the feedback structure and temporal behavior of the project system, Earned Value Management was employed to quantify actual and expected schedule and cost performance, and the Simulated Annealing algorithm was used to search for near-optimal combinations of activity durations, resource allocations, and associated costs under project constraints.

The statistical and empirical population consisted of managers, project control specialists, planning experts, cost engineers, and senior construction professionals employed in active construction companies located in Tehran, Iran. To ensure that the information used in model development reflected actual project-management conditions, only companies with experience in medium- and large-scale construction projects and an established project planning and control system were considered eligible. A total of 24 construction companies operating in Tehran were included in the study. From these companies, 96 experts were selected, with four qualified participants recruited from each company. Purposive sampling was used because the development and validation of the proposed model required respondents with specialized knowledge of construction project scheduling, cost control, earned value analysis, and resource management. The inclusion criteria consisted of having at least five years of professional experience in construction project management or project control, holding at least a bachelor's degree in civil engineering, construction management, industrial engineering, project management, or a closely related discipline, and having direct experience with project scheduling and cost monitoring. Experts who had insufficient access to project performance information or who did not participate in the complete data collection and validation process were excluded from the study. The selected experts had experience in projects involving residential, commercial, administrative, and infrastructure construction, thereby providing a sufficiently heterogeneous empirical basis for identifying the principal causal relationships affecting project time and cost performance.

In addition to expert-based information, detailed project performance data were collected from 24 completed or substantially completed construction projects, with one representative project selected from each participating company. The projects were chosen based on the availability and completeness of baseline schedules, activity-level duration and cost data, resource information, periodic progress reports, and earned value records. Each project was decomposed into its principal work packages and activities, and the baseline and actual values of activity durations, direct costs, indirect costs, resource requirements, physical progress, and inter-activity dependencies were extracted. These project records constituted the primary quantitative input for calibrating the System Dynamics model, computing earned value indicators, defining the feasible solution space for optimization, and testing the performance of the integrated model under realistic construction conditions. The unit of analysis was therefore the construction project and its constituent activities, while expert assessments were used to identify and validate the causal structure, parameter relationships, feedback mechanisms, and practical constraints incorporated into the model.

Data were collected using a combination of document review, structured project-data extraction forms, expert assessment questionnaires, and model-validation instruments. The project-data extraction form was specifically developed for this study to obtain consistent quantitative information from the participating construction companies. The form recorded the planned and actual duration of each activity, activity precedence relationships, planned and actual direct costs, project indirect costs, resource availability, labor and equipment requirements, activity completion percentages, scheduled progress, actual progress, and periodic cost information. The baseline schedule, approved project budget, progress reports, cost statements, resource utilization reports, and project control documents constituted the principal documentary sources. These data were reviewed and cross-checked with project control specialists to reduce inconsistencies between financial and scheduling records.

Earned Value Management indicators were calculated from the collected project records to provide dynamic measures of cost and schedule performance. The fundamental EVM variables included Planned Value (PV), Earned Value (EV), and Actual Cost (AC). Based on these variables, the Cost Performance Index (CPI), Schedule Performance Index (SPI), Cost Variance (CV), and Schedule Variance (SV) were calculated at selected control points throughout the project implementation period. CPI was determined as the ratio of earned value to actual cost, whereas SPI was calculated as the ratio of earned value to planned value. Cost variance was obtained from the difference between earned value and actual cost, and schedule variance was calculated as the difference between earned value and planned value. Forecasting indicators, including Estimate at Completion (EAC), Estimate to Complete (ETC), and Variance at Completion (VAC), were also incorporated into the model whenever sufficient project records were available. These indicators were not treated merely as retrospective performance measures; rather, they served as endogenous inputs to the integrated decision model and influenced subsequent optimization decisions relating to activity acceleration, resource allocation, and corrective scheduling.

A structured expert questionnaire was used to identify and validate the major variables affecting the dynamic relationship between project duration and cost. The questionnaire covered factors such as resource availability, labor productivity, equipment productivity, schedule pressure, overtime, resource congestion, learning effects, rework, quality deficiencies, material delivery delays, changes in scope, inflationary cost pressure, indirect project costs, managerial response delays, and the effects of corrective actions on subsequent project performance. Experts assessed the relevance and direction of causal relationships among the variables and evaluated the relative importance of feedback loops proposed in the initial conceptual model. Content validity of the instrument and the conceptual relationships was examined through expert judgment. The preliminary model was reviewed by a panel of 12 senior specialists drawn from the larger study sample who had more than ten years of professional experience in project management and project control. Their comments were used to revise variable definitions, eliminate redundant relationships, and refine the causal-loop structure before formulation of the quantitative System Dynamics model.

The System Dynamics component of the study was developed by first constructing causal-loop diagrams representing the principal reinforcing and balancing feedback mechanisms influencing project time and cost. These causal relationships were subsequently transformed into a stock-and-flow structure. Major stocks represented accumulated project progress, remaining work, cumulative actual cost, completed work, and available or committed resources, whereas flow variables represented rates of work execution, cost expenditure, rework generation, resource consumption, and corrective action. Auxiliary variables included productivity, schedule pressure, cost performance, schedule performance, resource utilization, and the effects of management interventions. Mathematical relationships between variables were formulated based on empirical project data, earned value indicators, expert assessments, and established project control logic. The model was configured to reproduce project behavior over discrete simulation intervals corresponding to the reporting periods used by the participating companies.

The optimization component was based on the Simulated Annealing algorithm. The decision variables primarily consisted of feasible activity durations and resource-allocation levels for activities that could be accelerated or modified without violating technical precedence relationships. For each activity, minimum and normal durations and their corresponding direct costs were determined from project records and expert estimates. The objective function was designed to minimize a combined time–cost criterion consisting of total project duration and total project cost. Total project cost comprised direct activity costs and time-dependent indirect costs. Penalty terms were incorporated into the objective function to prevent solutions that violated precedence constraints, resource limits, technical restrictions, or allowable duration ranges. The initial solution corresponded to the baseline project schedule. Neighboring solutions were generated by modifying the duration or resource configuration of eligible activities, and each candidate solution was evaluated using the integrated System Dynamics–EVM framework before acceptance or rejection by the Simulated Annealing procedure. This structure allowed optimization decisions to account for dynamic changes in productivity, schedule pressure, cost performance, and project progress rather than relying exclusively on fixed deterministic activity parameters.

Data analysis was performed in several interconnected stages. Initially, the collected project records were screened for completeness and consistency. Baseline and actual schedule information was reconciled with financial and physical-progress reports, and activity-level data were standardized to provide a common analytical structure. Descriptive statistics were used to summarize the characteristics of the participating experts, companies, and projects and to examine the distribution of activity durations, costs, schedule deviations, and cost deviations. EVM indicators were subsequently calculated for each project at successive control points, providing a time-dependent representation of project performance. The resulting SPI, CPI, SV, CV, and forecasting indicators were incorporated into the System Dynamics model to represent the feedback effects of observed project performance on managerial interventions and subsequent project behavior.

The System Dynamics analysis proceeded through causal modeling, formulation, calibration, verification, and validation. Following construction of the causal-loop and stock-and-flow structures, the mathematical equations governing the model were parameterized using the empirical project data. Dimensional consistency and equation logic were examined before simulation. Model verification focused on identifying structural inconsistencies, computational errors, and unreasonable feedback behavior. Validation was conducted through several complementary procedures. Structural validity was assessed by comparing the model architecture with expert knowledge and established project-management relationships. Behavior reproduction tests were performed by comparing simulated project duration, cumulative cost, and progress trajectories with the corresponding historical values of the selected construction projects. Sensitivity analysis was also conducted by systematically modifying influential parameters, including productivity, resource availability, rework rate, schedule pressure, and indirect cost rate, to determine whether the model produced theoretically and managerially reasonable responses. The adequacy of the model was evaluated according to its ability to reproduce the general pattern and magnitude of actual project behavior rather than merely achieving an exact fit to individual observations.

After validation of the dynamic model, the Simulated Annealing algorithm was linked to the simulation environment to identify improved time–cost configurations. For each candidate solution generated by the algorithm, the proposed activity durations and resource decisions were transferred to the System Dynamics model. The model was then simulated over the project horizon, EVM performance measures were updated, and the resulting total project duration and total project cost were returned to the optimization algorithm as components of the objective function. The algorithm began with a relatively high initial temperature to permit broad exploration of the solution space and reduce the probability of premature convergence to a local optimum. The temperature was gradually reduced according to a cooling schedule, thereby decreasing the probability of accepting inferior solutions as the search progressed. A new solution that improved the objective-function value was accepted directly, whereas a solution producing a less favorable objective value could still be accepted probabilistically based on the magnitude of deterioration and the current temperature. This mechanism enabled the search procedure to escape local optima and explore alternative combinations of activity durations and resource assignments.

The optimization process continued until the predefined stopping criteria were satisfied, including convergence of the objective-function value, attainment of the minimum temperature, or completion of the maximum number of iterations. To reduce the influence of stochastic variation inherent in the Simulated Annealing algorithm, repeated optimization runs were performed using different initial random states, and the best feasible solution obtained across the runs was retained. The optimized scenario was then compared with the baseline project condition in terms of total duration, total cost, schedule performance, cost performance, and the magnitude of deviations from planned values. Percentage reductions in project duration and total cost were calculated to assess the practical effectiveness of the proposed approach. Additional scenario and sensitivity analyses were conducted to examine the stability of the optimized solution under changes in key parameters such as indirect cost rates, resource capacity, productivity, rework, and schedule pressure.

The final analytical framework therefore operated as an iterative closed-loop procedure rather than as three independent techniques. Earned Value Management continuously quantified deviations in schedule and cost performance, System Dynamics translated these deviations and managerial responses into changes in future project behavior, and Simulated Annealing searched for alternative decisions capable of improving the combined time–cost outcome. At each optimization iteration, the dynamic consequences of the proposed decision were simulated before its objective-function value was determined. This integration allowed the model to capture nonlinear feedback relationships and time-dependent interactions that are normally omitted in conventional deterministic time–cost trade-off models. The performance of the integrated model was ultimately evaluated by comparing its optimized results with the original project baseline and with the actual performance of the selected construction projects, thereby determining whether the proposed framework could provide a more efficient and practically applicable approach to simultaneous time–cost optimization in construction project management.

3. Findings and Results

The final sample consisted of 96 construction project professionals drawn from 24 construction companies operating in Tehran. All participants provided complete responses and were included in the analysis. Of the 96 participants, 79 were men (82.29%) and 17 were women (17.71%). The mean age of the respondents was 41.36 years (SD = 7.84), with ages ranging from 29 to 59 years. Regarding educational attainment, 38 participants (39.58%) held a bachelor's degree, 49 participants (51.04%) held a master's degree, and 9 participants (9.38%) held a doctoral degree. In terms of professional specialization, 37 participants (38.54%) had an academic background in civil engineering, 24 (25.00%) in construction or project management, 20 (20.83%) in industrial engineering, and 15 (15.63%) in other closely related technical and managerial fields. The participants had an average of 13.47 years of professional experience (SD = 6.21), while their average experience specifically in project planning, scheduling, cost control, or project management was 10.62 years (SD = 5.13). Thirty-one participants (32.29%) were project managers or deputy project managers, 29 (30.21%) were planning and project control specialists, 18 (18.75%) were cost control or earned value specialists, and 18 (18.75%) were senior technical or executive professionals involved in construction project management. These characteristics indicated that the expert sample possessed substantial practical experience with construction scheduling, cost management, progress measurement, and corrective project control, thereby providing an appropriate empirical basis for the development and validation of the integrated model.

The 24 construction projects selected for model calibration and empirical testing included residential, commercial, administrative, mixed-use, and infrastructure projects. The mean baseline project duration was 26.83 months (SD = 8.14), whereas the mean actual or latest forecast duration was 30.91 months (SD = 9.26), indicating an average schedule increase of approximately 15.21% relative to the original baseline. The mean baseline project cost, expressed in normalized billion-rial values to provide comparability across projects, was 1,842.67 billion rials (SD = 769.42), while the corresponding actual or forecast-at-completion cost was 2,078.54 billion rials (SD = 861.37). Therefore, the projects exhibited an average cost increase of approximately 12.80% compared with the approved baseline budgets. These initial observations confirmed that both schedule delay and cost growth were common characteristics of the analyzed construction projects and supported the need for an integrated optimization framework capable of accounting simultaneously for temporal, financial, and dynamic project-control relationships.

Table 1. Descriptive Statistics of the Principal Project Performance and Dynamic Model Variables

Variable	Mean	SD	Minimum	Maximum
Baseline project duration (months)	26.83	8.14	14.00	46.00
Actual/forecast project duration (months)	30.91	9.26	16.20	52.80
Schedule delay relative to baseline (%)	15.21	7.64	3.86	31.42
Baseline project cost (billion rials)	1842.67	769.42	684.30	3586.70
Actual/forecast project cost (billion rials)	2078.54	861.37	751.40	4058.20
Cost increase relative to baseline (%)	12.80	6.95	2.91	27.63
Schedule Performance Index (SPI)	0.88	0.08	0.71	1.01
Cost Performance Index (CPI)	0.91	0.07	0.76	1.04
Resource utilization rate (%)	83.46	8.71	66.80	97.20
Labor productivity index	0.89	0.09	0.69	1.05
Rework rate (%)	6.84	2.67	2.30	12.40
Schedule pressure index	1.18	0.16	0.91	1.53
Average corrective-action delay (weeks)	3.42	1.41	1.20	6.40
Indirect cost share of total baseline cost (%)	14.76	4.18	8.10	23.60

As shown in Table 1, the projects generally operated below their desired schedule and cost efficiency levels. The mean SPI of 0.88 indicated that, on average, the projects completed less work than initially planned for the corresponding control periods, while the mean CPI of 0.91 showed that the value of completed work was lower than the actual expenditure required to achieve it. The simultaneous occurrence of SPI and CPI values below 1.00 demonstrated that schedule delay and cost inefficiency were frequently interconnected rather than independent phenomena. Resource utilization was relatively high, with a mean of 83.46%, although the labor productivity index averaged only 0.89, suggesting that greater resource deployment did not necessarily translate into proportionally greater productive output. The mean rework rate of 6.84% was also operationally important because additional work generated by defects, errors, design modifications, or execution inconsistencies increased both remaining project workload and actual cost. The schedule pressure index had a mean value of 1.18, indicating that many projects experienced elevated managerial pressure to accelerate activity completion after deviations from baseline schedules became evident. However, corrective actions were implemented with an average delay of 3.42 weeks, which potentially allowed adverse schedule and cost feedback to accumulate before management intervention occurred. Taken together, the descriptive findings supported the conceptual assumption of the proposed model that schedule pressure, productivity, resource utilization, rework, corrective-action delay, and earned value performance operate through interconnected feedback structures and therefore should be evaluated dynamically rather than through isolated static indicators.

Table 2. Validation of the System Dynamics Model through Comparison of Actual and Simulated Project Performance

Validation Indicator	Actual Mean	Simulated Mean	Mean Absolute Percentage Error (%)	Correlation between Actual and Simulated Values
Final project duration (months)	30.91	30.28	4.17	0.94
Cumulative project cost (billion rials)	2078.54	2039.62	4.83	0.96
Final physical progress (%)	94.68	93.91	3.26	0.95
Schedule Performance Index	0.88	0.89	3.61	0.92
Cost Performance Index	0.91	0.92	3.74	0.93
Cumulative rework (%)	6.84	6.57	5.12	0.89
Resource utilization rate (%)	83.46	82.71	4.09	0.91
Labor productivity index	0.89	0.90	4.46	0.90

Table 2 presents the behavioral validation results of the System Dynamics component of the integrated model. The simulated values closely reproduced the historical behavior observed across the 24 construction projects. The mean absolute percentage error was 4.17% for final project duration and 4.83% for cumulative project cost, indicating a relatively small discrepancy between the model outputs and actual project observations. Similarly, the errors associated with physical progress, SPI, CPI, resource utilization, and labor productivity all remained below 5%, while cumulative rework exhibited an error of 5.12%. Strong positive correlations were observed between actual and simulated values for all major performance indicators, ranging from 0.89 for cumulative rework to 0.96 for cumulative project cost. The particularly strong correspondence for project cost, physical progress, and project duration indicated that the model reproduced not only isolated parameter values but also the overall behavioral pattern of the construction system. The simulated mean SPI of 0.89 and CPI of 0.92 were very close to the observed means of 0.88 and 0.91, respectively, demonstrating that the model appropriately represented the interaction between schedule progress and cost consumption. Moreover, the close approximation of rework, productivity, and resource utilization supported the internal feedback mechanisms incorporated into the model. These results indicated satisfactory behavioral validity and provided sufficient justification for using the System Dynamics model as the evaluation environment within the subsequent Simulated Annealing optimization procedure.

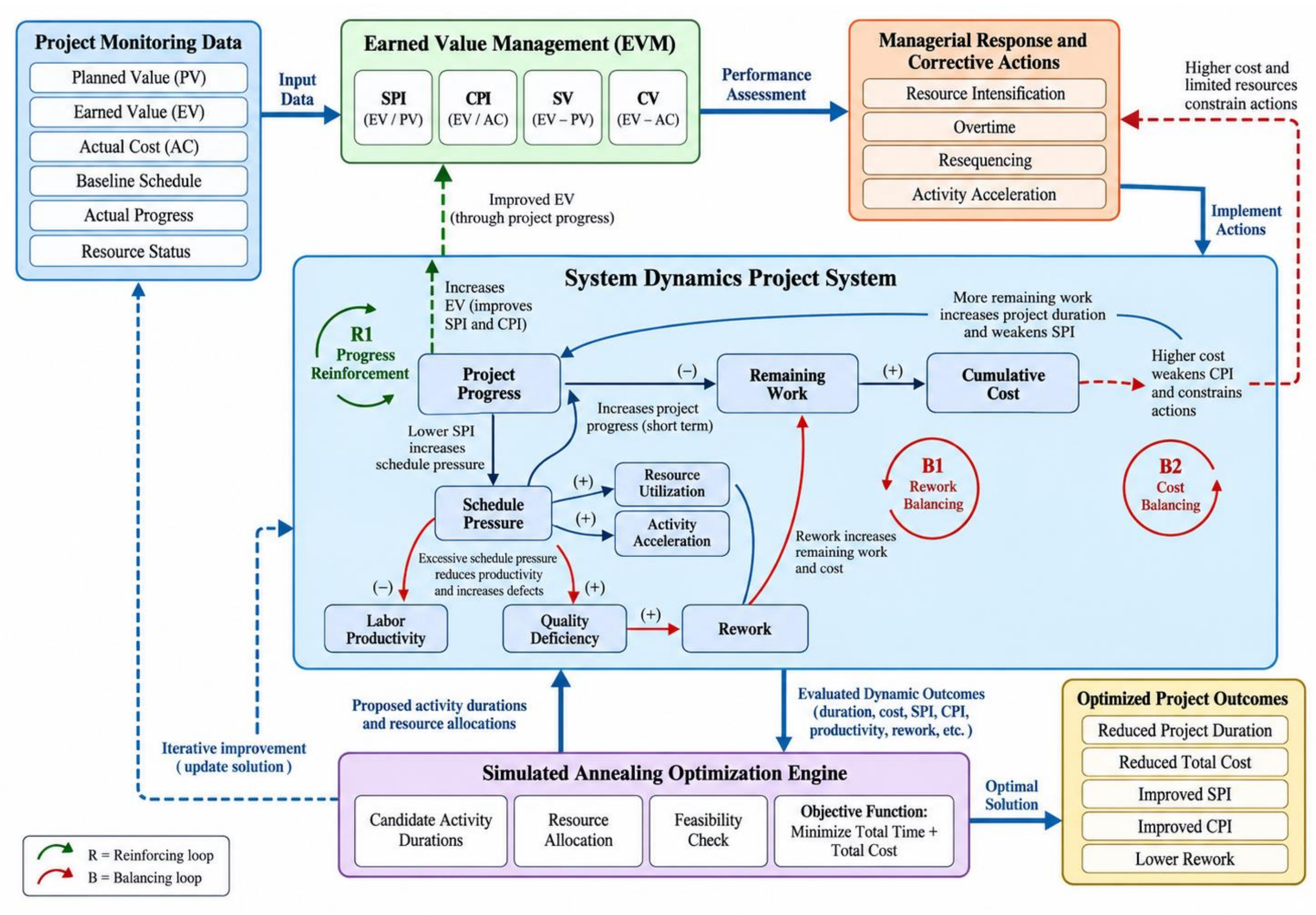

Figure 1. Integrated Feedback Structure Linking Earned Value Performance, System Dynamics, and Simulated Annealing in the Time–Cost Optimization Process

Figure 1 represents the conceptual and computational feedback architecture of the proposed integrated optimization model. In this structure, actual project progress and expenditure generate the Earned Value Management indicators, particularly SPI and CPI, which serve as quantitative signals of schedule and cost deviation. When

SPI decreases, the model generates increased schedule pressure, which may induce managerial responses such as resource intensification, overtime, resequencing of eligible activities, or acceleration of critical work packages. These actions can initially improve the rate of project progress; however, excessive acceleration may reduce labor productivity, increase resource congestion, generate quality deficiencies, and consequently increase rework. Rework, in turn, increases remaining project workload, prolongs project duration, increases direct expenditure, and further affects both CPI and SPI. Cost deterioration can also restrict the availability of financial resources for corrective actions, thereby creating an additional balancing or reinforcing feedback mechanism depending on the severity of the deviation. The Simulated Annealing component operates at the decision layer of this architecture by generating alternative activity-duration and resource-allocation configurations. Each candidate solution is transferred to the System Dynamics model, where its dynamic consequences are simulated, and the resulting time, cost, schedule performance, and cost performance are returned to the optimization procedure. Accordingly, the optimization process does not evaluate candidate schedules solely on the basis of predetermined activity time–cost curves; instead, it evaluates their dynamic consequences after productivity, rework, schedule pressure, resource utilization, and earned value feedback have been taken into account.

Table 3. Baseline, Conventional Corrective, and Integrated Optimization Results for Project Time and Cost

Performance Indicator	Baseline/Actual Condition	Conventional Corrective Scenario	Integrated SD–EVM–SA Model	Improvement of Integrated Model Compared with Baseline (%)
Mean total project duration (months)	30.91	28.74	26.96	12.78
Mean total project cost (billion rials)	2078.54	2006.81	1898.63	8.66
Schedule delay relative to baseline (%)	15.21	7.12	0.48	96.84
Cost increase relative to baseline (%)	12.80	8.91	3.04	76.25
Final Schedule Performance Index	0.88	0.94	0.99	12.50
Final Cost Performance Index	0.91	0.95	0.98	7.69
Resource utilization rate (%)	83.46	87.12	89.38	7.09
Labor productivity index	0.89	0.93	0.97	8.99
Rework rate (%)	6.84	5.71	4.18	38.89
Corrective-action delay (weeks)	3.42	2.24	1.18	65.50

As indicated in Table 3, the integrated SD–EVM–SA model produced superior project performance compared with both the baseline or actual condition and the conventional corrective scenario. The mean total duration decreased from 30.91 months under the observed project condition to 26.96 months under the integrated optimization scenario, corresponding to an improvement of 12.78%. The optimized duration was also approximately 1.78 months shorter than the duration obtained under conventional corrective planning, demonstrating that simply accelerating selected activities without accounting for dynamic feedback was less effective than applying the integrated framework. The mean total project cost decreased from 2,078.54 billion rials to 1,898.63 billion rials, representing an 8.66% reduction relative to the baseline condition. Although acceleration is traditionally associated with higher direct activity costs, the integrated model reduced total cost by balancing selective activity acceleration against reductions in indirect costs, rework, inefficient resource use, and extended project overhead. Schedule delay relative to baseline was reduced from 15.21% to only 0.48%, whereas the conventional corrective scenario retained a schedule delay of 7.12%. Similarly, cost growth was reduced from 12.80% to 3.04%. Final SPI increased from 0.88 to 0.99, indicating that the optimized project configuration approached the planned production rate, while CPI increased from 0.91 to 0.98, showing that expenditures became more closely aligned with the value of accomplished work. Improvements were also observed in resource utilization and labor productivity. Importantly, the rework rate declined by 38.89%, which indicates that the optimization process did not simply maximize resource intensity or compress activity durations indiscriminately. Instead, it identified configurations that reduced excessive schedule pressure and its adverse effects on quality and productivity. The corrective-action delay also declined substantially, from 3.42 weeks to 1.18 weeks, demonstrating the importance of integrating continuous earned value signals into the management response mechanism.

Table 4. Sensitivity Analysis of Key Dynamic Parameters under the Integrated Optimization Model

Scenario	Change in Key Parameter	Optimized Duration (months)	Optimized Cost (billion rials)	SPI	CPI	Rework Rate (%)
Reference optimized scenario	Base parameters	26.96	1898.63	0.99	0.98	4.18
Reduced labor productivity	Productivity −10%	28.73	1987.46	0.94	0.94	5.62
Increased labor productivity	Productivity +10%	25.82	1846.72	1.01	1.00	3.71
Restricted resource capacity	Resource capacity −15%	29.14	1964.38	0.93	0.96	4.76
Increased resource capacity	Resource capacity +15%	26.31	1922.41	1.00	0.97	4.39
Increased rework tendency	Rework parameter +20%	28.08	1993.54	0.95	0.93	6.11
Reduced rework tendency	Rework parameter −20%	26.14	1841.66	1.00	1.01	3.29
Higher indirect cost rate	Indirect cost +15%	26.41	1969.83	1.00	0.95	4.07
Longer corrective-action delay	Response delay +2 weeks	28.36	1976.92	0.94	0.94	5.31
Shorter corrective-action delay	Response delay −1 week	26.27	1859.37	1.00	1.00	3.84
High schedule pressure	Schedule pressure +20%	26.52	1951.74	0.99	0.95	5.48
Controlled schedule pressure	Schedule pressure −15%	26.68	1868.29	0.99	1.00	3.73

The sensitivity analysis presented in Table 4 demonstrated that the integrated model remained stable across a range of parameter changes while also identifying the parameters with the strongest influence on optimized project outcomes. A 10% reduction in labor productivity increased the optimized duration from 26.96 to 28.73 months and increased total cost from 1,898.63 to 1,987.46 billion rials. In contrast, a 10% productivity improvement reduced duration to 25.82 months and cost to 1,846.72 billion rials, while both SPI and CPI reached approximately 1.00. These findings demonstrated that productivity was a major leverage point within the dynamic model. Restricting resource capacity by 15% produced a substantial deterioration in project duration, whereas increasing resource capacity by 15% generated only a moderate additional improvement. This asymmetric response indicated diminishing returns to resource intensification and supported the model assumption that simply assigning additional resources does not necessarily produce proportional schedule benefits. Rework was another highly influential factor. A 20% increase in the rework parameter increased total project cost to 1,993.54 billion rials and reduced CPI to 0.93, whereas a 20% reduction in rework resulted in one of the lowest costs among all sensitivity scenarios, at 1,841.66 billion rials. Corrective-action delay also substantially influenced system performance. Increasing the response delay by two weeks increased both duration and cost, while shortening the response delay by one week improved SPI, CPI, and rework performance. The high-schedule-pressure scenario reduced project duration slightly relative to the reference optimized condition but simultaneously increased total cost and rework, demonstrating the adverse nonlinear consequences of excessive acceleration. Conversely, controlled schedule pressure preserved a near-optimal duration while lowering total cost to 1,868.29 billion rials and reducing rework to 3.73%. Overall, the sensitivity findings confirmed that the optimal time–cost solution was determined not only by nominal activity durations and direct crashing costs but also by the dynamic interaction of productivity, rework, resource capacity, managerial response timing, and schedule pressure.

Table 5. Results of Simulated Annealing Convergence and Comparison across Repeated Optimization Runs

Optimization Measure	Mean	SD	Best Run	Worst Run
Initial objective-function value	1.000	0.000	1.000	1.000
Final normalized objective-function value	0.817	0.014	0.794	0.843
Total project duration (months)	27.18	0.42	26.96	28.04
Total project cost (billion rials)	1911.74	27.61	1898.63	1971.85
Number of accepted improving moves	386.42	21.37	421.00	351.00
Number of accepted non-improving moves	117.58	13.44	139.00	94.00
Iteration at effective convergence	2847.63	318.75	2384.00	3417.00
Feasible solutions among evaluated solutions (%)	92.74	2.31	96.10	88.60

Table 5 reports the stability and convergence characteristics of the Simulated Annealing component across repeated optimization runs. The mean final normalized objective-function value was 0.817 compared with an initial standardized value of 1.000, indicating a substantial overall improvement in the combined time–cost criterion. The best run yielded an objective-function value of 0.794 and corresponded to the final selected solution with a duration of 26.96 months and a total cost of 1,898.63 billion rials. The relatively small standard deviations observed for optimized duration and project cost demonstrated that repeated runs converged toward a similar region of the solution space despite the stochastic nature of the algorithm. The algorithm accepted an average of 386.42 improving moves and 117.58 non-improving moves. Acceptance of a limited number of non-improving solutions was particularly important in the early stages of the search because it prevented premature trapping in local optima and enabled exploration of alternative schedule and resource configurations. Effective convergence occurred after an average of 2,847.63 iterations, although variability between runs was expected because the sequence of candidate solutions depended on random neighborhood generation. More than 92% of evaluated solutions remained feasible after consideration of precedence relationships, technical activity-duration limits, and resource constraints. The similarity of the best, mean, and worst optimization results indicated that the proposed algorithm had adequate numerical robustness and that the final optimized solution was not the result of an isolated stochastic trajectory.

Taken together, the findings demonstrated that the proposed integrated framework provided a clear improvement over both the observed project condition and a conventional corrective scheduling approach. The System Dynamics component satisfactorily reproduced the major historical patterns of duration, expenditure, progress, productivity, resource utilization, and rework. Earned Value Management indicators provided timely quantitative information concerning deviations in schedule and cost performance, while the Simulated Annealing algorithm used this dynamic information to explore alternative activity-duration and resource-allocation strategies. The optimized configuration reduced mean project duration by 12.78% and total project cost by 8.66% compared with the baseline or actual condition while increasing SPI from 0.88 to 0.99 and CPI from 0.91 to 0.98. At the same time, the model reduced rework, moderated inefficient schedule pressure, improved labor productivity, increased effective resource utilization, and shortened the delay between identification of deviation and implementation of corrective action. The results therefore supported the central premise of the study that simultaneous time–cost optimization in construction projects is more effective when optimization decisions are evaluated within a dynamic feedback environment rather than through fixed and purely deterministic time–cost relationships.

4. Discussion and Conclusion

The present study developed and evaluated an integrated framework for the simultaneous optimization of time and cost in construction projects by combining System Dynamics, Earned Value Management, and the Simulated Annealing algorithm. The findings showed that the proposed integrated model was capable of reproducing the observed behavior of construction projects with acceptable accuracy and, more importantly, of generating substantially improved project outcomes compared with both the baseline condition and a conventional corrective scenario. The optimized configuration reduced mean project duration from 30.91 to 26.96 months and decreased total project cost from 2,078.54 to 1,898.63 billion rials. At the same time, the Schedule Performance Index increased from 0.88 to 0.99 and the Cost Performance Index increased from 0.91 to 0.98. These improvements were accompanied by higher labor productivity and resource utilization, lower rework, and a shorter delay between identification of performance deviations and implementation of corrective actions. Collectively, these results suggest that the simultaneous integration of dynamic simulation, performance monitoring, and metaheuristic optimization can provide a more realistic and effective basis for construction project control than approaches that treat time, cost, and managerial response as separate or static dimensions.

One of the most important findings was the ability of the System Dynamics component to reproduce the historical behavior of the selected construction projects. The relatively low mean absolute percentage errors observed for final duration, cumulative cost, physical progress, SPI, CPI, resource utilization, and labor productivity indicated that the model captured the dominant causal relationships governing project behavior. This finding supports the use of System Dynamics in construction project management, particularly where project outcomes are shaped by feedback loops, delayed responses, and nonlinear interactions. Earlier research has emphasized that project management systems cannot always be represented adequately through linear or static models because delays, rework, resource constraints, and managerial actions continuously interact over time [10]. The present findings are consistent with this perspective, because the model demonstrated that schedule pressure could initially accelerate progress while simultaneously generating adverse downstream effects through productivity reduction and rework. This type of behavior is difficult to represent in conventional network scheduling models but is central to real construction environments.

The observed relationship between schedule pressure, productivity, and rework is also consistent with previous research on time–cost–quality optimization. The sensitivity analysis showed that excessive schedule pressure marginally shortened project duration but increased total cost and rework, whereas a controlled level of schedule pressure preserved near-optimal duration while improving cost efficiency and reducing defects. This result reinforces the argument that schedule compression cannot be evaluated solely in terms of time savings. Earlier multi-objective models have shown that acceleration decisions should consider quality and risk consequences in addition to time and cost [7]. Similarly, research on quality-sensitive time–cost trade-off analysis has demonstrated that minimizing duration without accounting for quality effects can generate solutions that are technically efficient but practically undesirable [8]. The findings of the present study extend this reasoning by showing that quality deterioration is not merely an additional objective but may function dynamically as a feedback mechanism through which rework increases remaining work, cost, and subsequent schedule pressure.

The optimization results also support earlier evidence regarding the value of metaheuristic methods for complex construction scheduling problems. The Simulated Annealing algorithm consistently converged toward a similar solution region across repeated runs, and the relatively small variation in optimized duration and cost indicated satisfactory robustness. This is important because construction time–cost optimization generally involves a large, nonlinear, and constrained solution space in which exact methods may be impractical. Previous studies have successfully applied genetic, swarm-based, and other metaheuristic algorithms to optimize multiple project objectives [3, 5, 6]. The present findings align with this body of work but also suggest that the performance of a metaheuristic algorithm can be strengthened when candidate solutions are evaluated within a dynamic simulation environment rather than against fixed activity parameters. In this respect, the model moves beyond conventional optimization by allowing the cost and duration consequences of a candidate solution to emerge from the system behavior generated by productivity, rework, resource use, and corrective-action timing.

The favorable performance of the Simulated Annealing component is also compatible with recent hybrid optimization research. Fontes et al. demonstrated the usefulness of combining Simulated Annealing with other optimization mechanisms for complex scheduling problems involving multiple operational constraints [11]. More directly, the application of Simulated Annealing alongside predictive models for project time and cost has shown that the algorithm can effectively support the exploration of alternative project configurations [12]. The present study extends these applications by embedding Simulated Annealing within a closed-loop framework in which every candidate decision is assessed not only through a mathematical objective function but also through System Dynamics simulation and updated EVM indicators. This integration provides a richer evaluation environment because candidate schedules that appear attractive under static assumptions may prove inferior once their consequences for productivity, rework, and cumulative cost are simulated.

Another major finding concerned the improvement in EVM indicators. The increase in SPI from 0.88 to 0.99 and

CPI from 0.91 to 0.98 indicates that the optimized solution brought schedule progress and cost efficiency substantially closer to the planned baseline. This result supports the use of EVM not only as a retrospective reporting tool but also as an active input to optimization and corrective decision-making. Earlier studies have shown that EVM provides a practical framework for monitoring deviations between planned and actual project performance [16], while statistical control of time and cost indicators can support early identification of abnormal performance patterns [17]. Research has also indicated that EVM can improve project outcomes by strengthening monitoring and enabling more timely managerial intervention [18]. In the present model, EVM indicators were transformed from passive measures into dynamic control signals. A reduction in SPI or CPI triggered changes in schedule pressure, resource allocation, or corrective action, and these decisions were then re-evaluated through the dynamic model. This closed-loop structure helps explain why both indices improved alongside reductions in total duration and cost.

The findings are also consistent with research integrating EVM with optimization techniques. Gupta and Trivedi showed that combining a multi-objective time–cost optimization model with EVM can improve the connection between project planning and execution control [20]. The present study supports this integration while adding a further dynamic layer. Rather than simply combining optimization outputs with EVM performance measures, the current framework allowed EVM indicators to influence subsequent system behavior and optimization decisions. This distinction is important because actual construction projects rarely follow the baseline exactly. A static optimal schedule may become obsolete after unexpected delays, resource shortages, or cost changes. By embedding EVM within a dynamic feedback system, the proposed model can adapt its recommendations to current project conditions.

The sensitivity analysis further demonstrated that labor productivity was one of the strongest leverage variables in the model. A 10% reduction in productivity increased both optimized duration and total cost, whereas a 10% increase generated one of the best-performing scenarios. This finding is consistent with the broader time–cost literature, which has repeatedly emphasized the importance of resource efficiency rather than resource quantity alone. Studies focusing on the balancing of project time, cost, quality, and resource consumption have shown that profitability and project performance depend heavily on how resources are used, not simply on whether additional resources are available [4]. Likewise, analyses of construction optimization within broader project management frameworks have highlighted the importance of quantitative and qualitative performance indicators, including resource productivity and execution efficiency [9]. The present findings reinforce these observations by showing an asymmetric response to resource capacity: reducing resource capacity substantially worsened project outcomes, whereas simply increasing capacity produced only moderate gains. This suggests diminishing returns and supports the idea that unmanaged resource intensification may lead to congestion or inefficiency.

The strong influence of rework in the sensitivity analysis also deserves attention. Increasing the rework parameter substantially worsened both cost and schedule outcomes, whereas reducing rework generated one of the lowest total cost scenarios. This finding is theoretically important because many conventional time–cost trade-off models treat work quantity as fixed. In practice, however, poor quality, execution errors, design changes, and rushed work may generate additional work that did not exist in the original schedule. Earlier multi-objective optimization research has recognized quality as an essential dimension of construction performance [3, 8], while schedule compression models have emphasized the need to consider quality and risk when selecting activities for acceleration [7]. The present study provides a dynamic explanation for these relationships by showing how quality deficiencies feed back into rework, remaining workload, cost, and schedule performance.

The reduction in corrective-action delay from 3.42 to 1.18 weeks was another significant result. The sensitivity analysis showed that increasing response delay worsened project duration, cost, SPI, CPI, and rework, whereas shortening the delay improved nearly all performance indicators. This finding highlights the temporal dimension of project control. The value of monitoring systems is limited if detected deviations are not converted rapidly into corrective decisions. EVM is particularly suitable for this purpose because it provides periodic measures of cost and schedule deviation [16, 17]. Fuzzy EVM applications have also demonstrated the usefulness of adapting performance measurement to uncertain construction environments [19]. The current study extends this logic by showing that the timing of corrective action itself is a dynamic variable that materially affects project outcomes.

The results also align with the recent movement toward predictive and data-driven construction project management. Studies using machine learning and hybrid optimization methods have shown that improved prediction of schedule and cost performance can enhance managerial decision-making [13, 14]. Hybrid deep learning models have likewise demonstrated that combining sequential and non-sequential project information can significantly improve cost and schedule estimation accuracy [15]. However, the present findings suggest that prediction should be linked to intervention. Accurate forecasting of delay or cost overrun is valuable, but project managers also require a mechanism for identifying the best corrective action. The proposed framework addresses this requirement by linking monitored project performance to dynamic simulation and optimization. In this sense, the model complements predictive approaches and may serve as a decision layer capable of converting forecasts into operational time–cost strategies.

The overall reduction in both time and cost is also compatible with recent model-based construction optimization studies. Archandani emphasized the importance of integrated model-based approaches for improving time and cost performance in urban construction projects [2]. The systematic review by ElSahly et al. similarly showed that time–cost optimization remains a central research area in construction management and that hybrid and multi-objective models offer significant potential for addressing increasingly complex project environments [1]. The present study contributes to this line of research by demonstrating that hybridization can occur not only between optimization algorithms but also across fundamentally different methodological paradigms: performance measurement through EVM, dynamic behavioral simulation through System Dynamics, and search-based optimization through Simulated Annealing.

The findings can also be interpreted from a value-creation perspective. The optimized model did not achieve improved results simply by shortening project duration at any cost; rather, it reduced indirect cost exposure, limited rework, improved resource utilization, and increased productivity. These outcomes are consistent with contemporary project management perspectives that associate successful project delivery with broader value creation and sustainable resource use [21]. Reducing unnecessary rework and avoiding excessive schedule pressure can decrease waste, energy use, labor inefficiency, and financial losses. Therefore, the proposed model may contribute not only to conventional time–cost performance but also to more efficient and sustainable project delivery.

Overall, the results support the central proposition that construction project optimization should be treated as a dynamic and iterative management problem rather than a one-time scheduling exercise. Conventional optimization models often generate solutions from fixed assumptions at the planning stage, while real projects continuously evolve. The integration of EVM, System Dynamics, and Simulated Annealing allows the optimization process to respond to actual project conditions, evaluate the delayed consequences of corrective actions, and update decisions iteratively. This integrated approach is consistent with previous evidence on the usefulness of multi-objective optimization, dynamic modeling, EVM, and intelligent predictive methods, while addressing an important gap between monitoring and prescriptive decision-making [1, 12, 20].

This study had several limitations that should be considered when interpreting the findings. First, the empirical data were obtained from 24 construction companies and 24 representative projects located in Tehran, and therefore the calibrated parameter values may reflect the institutional, economic, contractual, and operational characteristics of this specific construction environment. Second, some dynamic relationships, including the effects of schedule pressure, rework, and managerial response, were partly informed by expert judgment and may therefore be subject to perceptual bias. Third, the proposed model necessarily simplified certain aspects of real project environments and did not explicitly incorporate all potential sources of uncertainty, such as abrupt regulatory changes, severe supply chain disruptions, contractual disputes, extreme inflation shocks, or major design revisions. Fourth, the optimization objective emphasized project time and total cost, while quality, safety, environmental performance, and stakeholder satisfaction were represented only indirectly through selected dynamic variables rather than as explicit optimization objectives. Finally, the results were based on simulation and historical project data rather than a prospective field experiment in which the optimized decisions were implemented in real time throughout the full project life cycle.

Future studies should validate the proposed model across larger and more diverse samples of construction projects, including infrastructure, transportation, industrial, energy, and megaproject environments. Comparative studies across different cities or countries would help determine the degree to which the model parameters are transferable across economic and institutional contexts. Future research could also extend the objective function to incorporate quality, safety, environmental impact, carbon emissions, cash flow, and stakeholder value alongside time and cost. The integration of probabilistic uncertainty analysis, fuzzy logic, Bayesian updating, or Monte Carlo simulation could further improve the model's ability to deal with uncertain project conditions. Another promising direction is the incorporation of machine learning models for real-time prediction of productivity, delay, and cost deviation, with the predicted values subsequently feeding the System Dynamics and optimization components. Future studies may also compare Simulated Annealing with alternative metaheuristics or multi-objective algorithms to determine which search mechanisms offer the best balance between solution quality, computational efficiency, and robustness. Finally, longitudinal field studies in which the integrated model is implemented during live project execution would provide stronger evidence regarding its practical effectiveness.

Construction companies should move toward integrated project control systems in which schedule, cost, resource, productivity, and quality information are analyzed jointly rather than in separate functional units. Project managers should use EVM indicators as active early-warning signals and establish predefined corrective-action protocols for substantial changes in SPI and CPI. Particular attention should be given to reducing the delay between detection of a performance deviation and implementation of a corrective response, because the findings indicate that delayed intervention can amplify both schedule and cost problems. Managers should also avoid excessive reliance on resource intensification and overtime as default schedule-recovery strategies, since aggressive acceleration can reduce productivity and increase rework. Greater emphasis should instead be placed on targeted acceleration of critical activities, balanced resource allocation, early identification of quality deficiencies, and rapid correction of rework-generating processes. Organizations with sufficient project-control maturity should consider embedding dynamic simulation and optimization engines within their digital project management systems so that alternative corrective strategies can be evaluated before implementation. Such systems can provide managers with a more reliable basis for selecting actions that improve project duration and cost simultaneously while avoiding the hidden downstream consequences of short-term schedule compression.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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