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An Integrated Time, Cost, Safety Optimization Framework for Fast-Tracked Construction Projects

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Abstract-*An Fast-tracked construction is increasingly adopted to meet rising infrastructure demands and compressed project timelines. However, schedule acceleration often leads to cost escalation, design–execution conflicts, rework, and heightened safety risks. Existing studies primarily address time–cost trade-offs, with limited integration of safety as a quantitative decision parameter. This study proposes a Time–Cost–Safety (TCS) optimization framework to support balanced decision-making in fast-tracked projects. A mixed-method approach is used, including a review of 40+ international studies, three case studies from Tamil Nadu and Pondicherry, and a questionnaire survey to derive stakeholder weights and safety sensitivity factors. Findings indicate that schedule compression beyond 10–15% significantly increases safety risks and rework, while costs escalate non-linearly beyond critical thresholds. The proposed framework integrates activity overlap analysis, crash-cost relationships, and safety risk modeling, supported by digital tools such as BIM-4D and AI-based monitoring. The study identifies optimal "safe compression limits" and highlights the need for controlled acceleration, real-time safety tracking, and integrated planning. The framework serves as a practical tool for achieving faster project delivery without compromising cost efficiency or worker safety.*

Key Words: Fast-tracked construction; Schedule compression; Time–Cost–Safety (TCS); Project optimization; Construction safety; Activity overlapping; Crash cost; Risk management; BIM-4D; AI-based safety monitoring

1. INTRODUCTION

The construction industry is increasingly driven by the need for rapid project delivery due to urbanization, infrastructure demand, and competitive pressures, leading to the widespread adoption of fast-tracked construction methods. By overlapping design, procurement, and execution phases, fast-tracking significantly reduces project duration; however, it simultaneously introduces challenges such as cost escalation, design–execution conflicts, rework, and elevated safety risks. Traditional project optimization approaches primarily focus on time–cost trade-offs, often neglecting safety as a quantifiable and decision-critical parameter. In practice, schedule compression intensifies resource utilization, site congestion, and worker fatigue, thereby increasing the likelihood of accidents and operational inefficiencies. Despite advancements in scheduling techniques and digital construction tools, there remains a lack of integrated frameworks that simultaneously evaluate time, cost, and safety in accelerated project environments. This study addresses this gap by proposing a Time–Cost–Safety (TCS) optimization framework that quantifies the interdependencies among these parameters and identifies safe compression limits. Supported by case studies, survey data, and digital tool integration such as BIM-4D and AI-based monitoring, the framework aims to provide a practical decision-support approach for achieving faster project delivery without compromising cost efficiency or worker safety.

2. METHODOLOGY

This study employed a mixed-method research approach to develop and validate the proposed Time–Cost–Safety (TCS) optimization framework for fast-tracked construction projects. Initially, a comprehensive literature review of international journals was conducted to examine existing time cost trade-off models, schedule compression techniques, safety risks, and the application of digital tools such as BIM, AI, and IoT in construction management. Primary data were obtained through a structured questionnaire survey administered to construction professionals in order to determine stakeholder priority weights for time, cost, and safety, along with safety sensitivity factors under accelerated schedules. Secondary data were collected from project schedules, cost records, and safety reports of selected live case studies, namely Sky Tower, Tower C, and Star Towers, located in Chennai and Pondicherry. The collected data were analyzed to identify the impact of schedule compression on project duration, cost escalation, rework probability, and safety performance. Based on these findings, an integrated TCS optimization framework was developed by combining time–cost relationships, safety risk functions, and activity overlapping effects. Finally, the framework was validated by comparing model outputs with actual case study observations and identifying safe schedule compression limits for practical implementation.

3. LITERATURE REVIEW

Fast-tracked construction has become an important project delivery strategy in response to increasing demand for rapid infrastructure development, tight client deadlines, and competitive market conditions. Unlike conventional construction, where design, procurement, and execution follow a sequential process, fast-tracking overlaps these phases to shorten the overall project duration. Although this approach offers clear time advantages, it also increases project complexity, coordination requirements, cost uncertainty, and safety exposure. Therefore, understanding the relationships among time, cost, and safety is essential for effective fast-track project management.

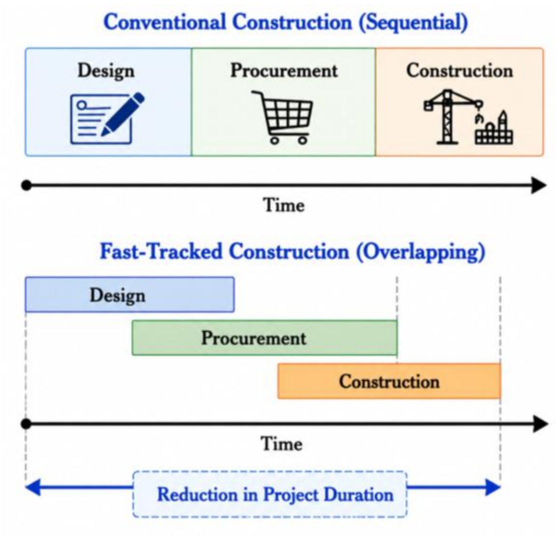

Fig -1: Conventional vs Fast-Tracked Construction Timeline

3.1 Time–Cost Trade-Off Models in Construction

The Time–Cost Trade-Off (TCTO) problem is one of the most widely studied areas in construction project management. Traditional methods such as the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) focus on reducing project duration by crashing critical activities through additional resources. These approaches generally assume a linear relationship between time reduction and cost increase.

However, recent studies show that real construction projects rarely follow linear behaviour. Ballesteros-Pérez et al. demonstrated that cost rises non-linearly when activities are excessively compressed, due to overtime inefficiency, reduced productivity, and coordination losses. Similarly, metaheuristic techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Firefly Algorithm (FA) have been used to generate more realistic time–cost optimization solutions. These models improve decision-making by identifying multiple feasible duration–cost combinations.

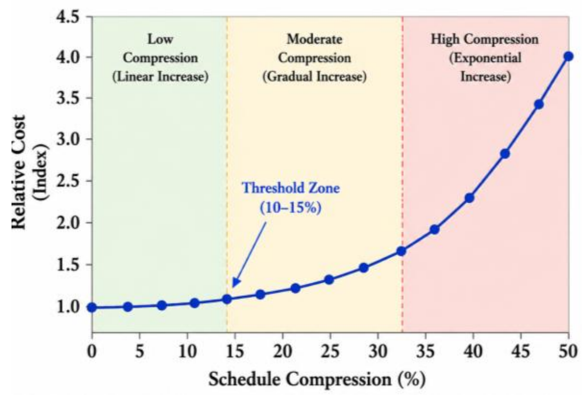

Fig -2: Typical Time–Cost Relationship under Schedule Compression

Table -1: Evolution of Time–Cost Optimization Models

Model Type	Main Feature	Limitation	Model Type
CPM Crashing	Reduces critical path duration	Assumes linear cost	CPM Crashing
PERT	Handles uncertain durations	Limited cost integratio n	PERT
Linear Programmin g	Optimized solutions	Simplified assumptio ns	Linear Program ming
GA / PSO / FA	Multi-solution optimization	Often excludes safety	GA / PSO / FA

3.2 Safety Challenges in Fast-Tracked Construction

Safety is one of the most affected parameters in accelerated projects. Schedule compression often requires extended working hours, multiple shifts, workforce congestion, and simultaneous trade operations. These conditions increase physical and mental fatigue, reduce supervision quality, and create unsafe interfaces between teams.

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Studies by Webb et al. found that projects with prolonged overtime and aggressive compression recorded higher OSHA injury rates compared with normally scheduled projects. Other research indicates that accident probability may increase significantly when schedule compression exceeds moderate levels without proportional safety controls.

Fast-tracked environments also face challenges such as:

- Reduced time for toolbox talks and safety training
- Limited inspection windows
- Frequent design changes during execution
- Increased equipment movement in congested areas
- Communication failures between subcontractors

Table -2: Common Safety Risks in Fast-Tracked Project

Risk Factor	Impact
Overtime fatigue	Human error, accidents
Site congestion	Collision and fall hazards
Trade overlap	Interface conflicts
Reduced supervision	Unsafe practices

These factors demonstrate that safety cannot be treated as a secondary outcome in accelerated projects.

3.3 Time–Safety and Cost–Safety Relationships

The interaction between time, cost, and safety is dynamic. Reducing project duration generally requires additional resources, overtime, or parallel work fronts. While these actions improve speed, they increase direct costs and may reduce safety performance.

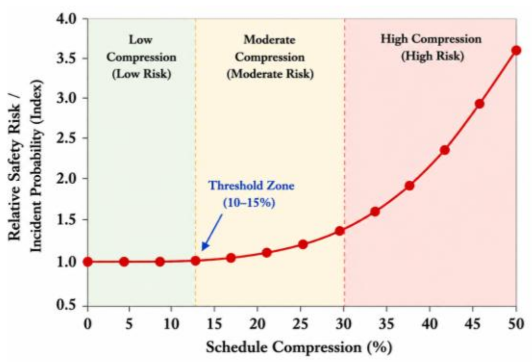

Fig -3: Safety Risk Trend with Increasing Compression

The time–safety relationship is particularly critical in fast-tracked construction. Moderate acceleration may be manageable with proper controls, but excessive compression often creates fatigue, rushed work behavior, and inadequate hazard management. Similarly, the cost–safety relationship shows that insufficient investment in safety systems may reduce short-term cost but increase long-term losses through accidents, delays, claims, and reputational damage.

Therefore, project decisions should not be based only on immediate cost savings or early completion targets. Instead, they should consider the hidden costs of unsafe acceleration.

Table -3: Common Safety Risks in Fast-Tracked Project

Parameter Reduced	Immediate Benefit	Potential Negative Impact
Time	Early completion	Higher cost, safety risk
Cost	Lower spending	Reduced controls, accidents
Safety budget	Lower direct cost	Claims, stoppages, delays
Parameter Reduced	Immediate Benefit	Potential Negative Impact

3.4 Multi-Objective Optimization Approaches

Recent research has moved toward multi-objective optimization models that consider more than two project variables. Some studies incorporate quality, sustainability, or risk in addition to time and cost. Techniques such as NSGA-II, NSGA-III, and hybrid algorithms have shown strong capability in generating Pareto-optimal solutions.

However, fully integrated Time–Cost–Safety (TCS) models remain limited. In many studies, safety is treated qualitatively rather than mathematically. There is also limited use of real project data for calibrating safety sensitivity under compression scenarios. This creates a need for practical frameworks that convert safety into measurable indicators and integrate them into optimization logic.

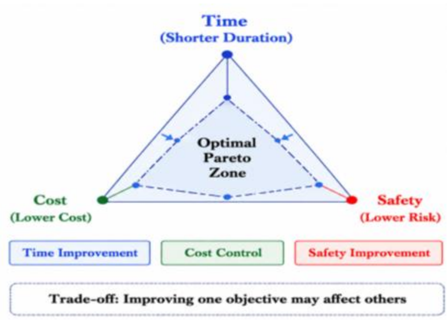

Fig -4: Multi-Objective Trade-Off (Pareto Zone)

3.5 Role of Digital Technologies

Digital construction technologies provide new opportunities to manage accelerated schedules more safely and efficiently.
BIM-4D: Links schedule data with 3D models for sequencing and clash detection.
AI-based Monitoring: Detects PPE violations, unsafe proximity, and hazardous behavior through computer vision.
IoT Sensors: Track worker location, equipment movement, scaffold tilt, and environmental conditions.
Digital Twins: Enable real-time simulation and predictive control of project risks.
Studies report that these tools improve visibility, reduce rework, and support proactive safety management. However, their integration into optimization frameworks is still developing.

Table -4: Digital Tools for Fast-Tracked Projects

Technology	Application	Benefit
BIM-4D	Sequencing, clash detection	Better coordination
AI Vision	PPE / hazard detection	Faster response
IoT	Real-time monitoring	Risk alerts
Digital Twin	Predictive simulation	Better decisions

4. LIVE CASE STUDIES

The live case studies were conducted to examine the practical implications of fast-tracked construction under real project conditions and to validate the proposed Time–Cost–Safety (TCS) optimization framework. Three projects located in Chennai and Puducherry were selected because they involved schedule acceleration, overlapping construction activities, compressed execution cycles, and varying levels of fast-tracking intensity. The analysis focused on understanding how schedule compression influences project duration, construction cost, workforce productivity, rework probability, and safety performance. These projects provided valuable insight into the operational challenges that arise when project schedules are accelerated beyond conventional execution practices. The case studies also helped identify safe compression limits and establish the relationship between time reduction, cost escalation, and safety deterioration.

4.1 Live Case Study 1 – Sky Tower, Chennai

Project Overview

Sky Tower is a high-rise residential project located in Chennai, consisting of multiple residential floors and associated infrastructure facilities. The project was undertaken during a period of high market demand, where early project completion and timely handover were considered critical objectives by both the client and contractor. Due to these schedule expectations, the project team adopted moderate fast-tracking techniques to reduce overall construction duration while attempting to maintain cost control and site safety. The project served as an important example of controlled acceleration in a residential construction environment where schedule compression was introduced gradually rather than aggressively. The project planning team focused on maintaining repetitive floor cycles and efficient trade coordination in order to achieve steady project progress without creating excessive operational pressure on the workforce.

4.1.2 Fast-Tracking Approach

The project adopted a moderate fast-tracking strategy by overlapping several construction activities that would normally occur sequentially in conventional execution. Structural work on upper floors continued simultaneously with masonry activities on lower floors. MEP rough-in works were initiated before complete masonry closure, while plastering and flooring activities began in partially completed zones to improve continuity of work. Additional manpower was deployed during peak construction stages to maintain repetitive floor-cycle progress and reduce idle time between trades. Material procurement and site logistics were also coordinated carefully to avoid interruptions caused by delayed deliveries. Unlike aggressive fast-tracked projects, the Sky Tower project maintained controlled sequencing between trades, thereby minimizing the possibility of excessive rework and trade conflicts. The project team also ensured continuous communication between structural, architectural, and MEP teams to maintain workflow coordination under compressed timelines.

4.1.3 Time Impact

The implementation of controlled fast-tracking strategies resulted in an estimated reduction of approximately 10% in the total planned project duration compared with the original baseline schedule. The repetitive floor-cycle approach significantly improved construction continuity and enabled faster completion of structural and finishing milestones. The overlapping of activities reduced waiting periods between trades and improved overall workflow efficiency. Since schedule compression remained within manageable limits, the project was able to sustain productivity levels without major disruptions during execution. The project demonstrated that moderate acceleration, supported by proper planning and trade coordination, can successfully improve project delivery timelines without causing severe operational instability.

4.1.4 Cost Impact

Although schedule compression generally results in increased project cost, the Sky Tower project experienced only moderate cost escalation because acceleration was introduced in a controlled manner. Additional costs were mainly associated with increased labor deployment, overtime payments during critical stages, and temporary site logistics arrangements. Since the overlapping strategy was carefully managed, major rework and coordination failures were avoided, thereby preventing substantial corrective expenses. Equipment utilization remained efficient throughout most stages of execution, and material wastage was also minimized through proper planning. Overall, the project demonstrated that moderate fast-tracking can improve project timelines while maintaining relatively stable cost performance when supported by strong coordination and supervision systems.

4.1.5 Safety Impact

Safety performance remained relatively stable throughout the project despite schedule acceleration. The project maintained regular toolbox meetings, routine safety inspections, and trade-zone segregation to reduce the impact of overlapping activities. Since work congestion remained within manageable levels, the project did not experience significant operational hazards during execution. Only minor near-miss incidents were reported, and no major lost-time injuries occurred during the construction period. Worker fatigue was also controlled because overtime requirements remained moderate compared with highly compressed projects. The case study demonstrates that controlled acceleration, combined with effective supervision and site management practices, can maintain acceptable safety conditions even under fast-tracked execution environments.

4.1.6 Key Observation

The Sky Tower project clearly demonstrates that moderate fast-tracking strategies can successfully reduce project duration without causing major cost escalation or safety deterioration. The project highlights the importance of controlled activity overlapping, proper trade coordination, and strong site supervision in maintaining project stability under compressed schedules. The findings suggest that schedule compression within approximately 10–15% can achieve balanced project performance when supported by effective planning and monitoring systems.

4.2 Live Case Study 2 – Tower C, Chennai Project Overview

Tower C is a residential tower project located in Chennai and executed under highly aggressive completion deadlines. The project was driven by strict client handover requirements and market pressure for early occupancy, forcing the contractor to adopt extensive fast-tracking practices throughout the execution period. Unlike the Sky Tower project, Tower C involved simultaneous execution of multiple trades across several floors under highly compressed timelines. The project environment became increasingly complex as structural, architectural, and MEP works progressed concurrently in different zones of the building. The project serves as an example of high-intensity fast-tracking where schedule acceleration was prioritized aggressively in order to achieve early project delivery.

4.2.2 Fast-Tracking Approach

The project adopted extensive activity overlapping across all major construction stages. Structural work, block work, plastering, MEP installation, false ceiling, and finishing activities were executed simultaneously on different floors and zones of the building. Extended working hours and night shifts were introduced during peak stages to accelerate progress further. Additional subcontractors and workforce teams were mobilized to handle multiple work fronts concurrently. Material procurement packages were divided into smaller delivery cycles to support faster execution and minimize delays in material availability. However, the high level of overlapping created coordination complexity between trades, especially in congested work areas where several teams operated simultaneously within limited space.

4.2.3 Time Impact

The aggressive fast-tracking strategy enabled the project to achieve nearly 20% reduction in planned project duration during the initial stages of execution. Early structural and finishing milestones were achieved ahead of schedule, and productivity levels remained high during the first phases of acceleration. However, as the project progressed, congestion and coordination issues reduced workflow efficiency. Frequent interruptions between trades, rework requirements, and restricted access to work zones slowed down later stages of execution. Although the project achieved significant schedule gains overall, the effectiveness of compression reduced considerably due to operational complexity and increasing site pressure.

4.2.4 Cost Impact

Tower C experienced substantial cost escalation as a result of aggressive schedule acceleration. The project recorded approximately 22% overspend compared with the original estimate. Major contributors included overtime wages, additional labor deployment, temporary logistics arrangements, extended supervision requirements, and equipment idle time caused by site congestion. Rework costs also increased because incomplete or changing information often resulted in clashes between structural, architectural, and MEP activities. Productivity losses due to overcrowded work fronts further reduced cost efficiency. The project clearly demonstrates that aggressive compression often produces non-linear cost escalation, where additional acceleration results in disproportionately high expenditure.

4.2.5 Safety Impact

The aggressive execution environment significantly affected safety performance throughout the project. Congested work zones, overlapping activities, and extended working hours increased worker fatigue and operational risk. Several near-miss incidents and minor safety events were reported during peak stages of construction. Simultaneous trade operations reduced visibility and limited effective supervision, while worker movement across multiple active zones increased the possibility of accidents. The project environment became increasingly difficult to manage as acceleration intensified. Although major accidents were avoided, the overall safety performance deteriorated compared with projects operating under moderate compression conditions.

4.3 Live Case Study 3 – Star Towers, Puducherry Project Overview

Star Towers is a mixed-use development project located in Puducherry and was selected as the third live case study because it provided an opportunity to evaluate multiple schedule compression scenarios under similar project conditions. Unlike the previous projects, this case study focused not only on actual fast-tracking practices but also on scenario-based simulation and comparative analysis. The project involved residential and commercial components with multiple construction blocks executed simultaneously. Due to increasing client expectations for early completion, the project team explored different levels of schedule acceleration to evaluate how varying compression percentages influence project duration, cost performance, workforce productivity, and safety conditions. This project was particularly useful in identifying the practical limitations of aggressive fast-tracking and in establishing safe schedule compression thresholds for the proposed Time–Cost–Safety (TCS) optimization framework.

4.3.2 Compression Scenarios

Three different schedule compression scenarios were analyzed within the project to understand the progressive impact of acceleration on project performance. The first scenario involved approximately 10% schedule compression, representing controlled and moderate fast-tracking. The second scenario involved nearly 30% compression, where higher levels of overlapping, labor intensification, and concurrent activities were introduced. The third scenario represented an extreme compression condition of nearly 50%, where project execution was accelerated aggressively through extensive overlapping of trades, additional shifts, and maximum resource deployment.

Each scenario was evaluated based on multiple performance indicators including duration reduction, cost escalation, rework probability, site congestion, workforce fatigue, and operational safety risk. The comparison between scenarios helped identify how increasing compression levels affect overall project efficiency and stability.

4.3.3 Time Impact

Under Scenario A (10% compression), the project achieved balanced schedule acceleration with improved workflow continuity and manageable operational pressure. The overlapping of selected low-risk activities reduced idle time between trades and enabled smoother floor-cycle progression. Productivity levels remained relatively stable because the compression level was moderate and supported by proper coordination.

Scenario B (30% compression) achieved higher time savings but introduced significant execution complexity. Multiple trades operated simultaneously across congested work zones, resulting in coordination difficulties and workflow interruptions. Although planned schedule reduction improved initially, productivity losses caused by rework and trade interference reduced the overall efficiency of acceleration.

Scenario C (50% compression) produced the highest theoretical reduction in project duration. However, in practical execution conditions, productivity efficiency declined substantially due to severe congestion, restricted work access, trade clashes, and repeated interruptions. Frequent rework and operational disruptions reduced the actual time-saving benefit achieved under this extreme acceleration condition.

4.3.4 Cost Impact

The project demonstrated a clear non-linear relationship between schedule compression and project cost. Under Scenario A, cost increase remained relatively low and was mainly associated with additional labor deployment and limited overtime. Since operational conditions remained stable, major corrective work and productivity losses were avoided.

Under Scenario B, project cost increased significantly due to increased manpower requirements, extended supervision, temporary logistics arrangements, and coordination-related rework. Resource utilization became more intensive, and material movement within congested work zones reduced overall efficiency.

Scenario C resulted in severe cost escalation because of extreme acceleration pressure. Continuous overtime, additional workforce mobilization, equipment intensification, productivity losses, and repeated corrective work caused project expenditure to rise disproportionately. The analysis confirmed that beyond moderate compression thresholds, cost behavior becomes exponential rather than linear.

4.3.5 Safety Impact

Safety performance deteriorated progressively with increasing compression levels across the three scenarios. Under Scenario A, safety conditions remained manageable because trade overlap and workforce density were controlled within acceptable limits. Proper sequencing and supervision helped maintain stable working conditions throughout execution.

Scenario B introduced higher levels of workforce congestion and simultaneous operations, increasing the probability of accidents and near-miss incidents. Worker fatigue became more visible because of extended shifts and increased workload intensity. Reduced supervision efficiency in congested work zones further increased operational risk.

Scenario C created highly unsafe execution conditions due to extreme overcrowding, excessive overtime, and uncontrolled overlapping of activities. The possibility of falls, equipment-related incidents, and trade interference increased significantly. Worker fatigue and stress levels also became critical concerns under this compression level. The scenario clearly demonstrated that excessive schedule acceleration creates severe safety exposure and unstable site conditions.

4.3.6 Key Observation

The Star Towers case study confirmed that while aggressive schedule compression may theoretically reduce project duration, the practical consequences include severe cost escalation, productivity loss, coordination complexity, and significant safety deterioration. The analysis clearly identified that moderate compression levels produce the most balanced project outcomes, whereas excessive acceleration creates diminishing returns and unstable construction conditions. The findings strongly support the need for an integrated Time–Cost–Safety optimization approach that evaluates schedule decisions based not only on time savings but also on cost efficiency and worker safety.

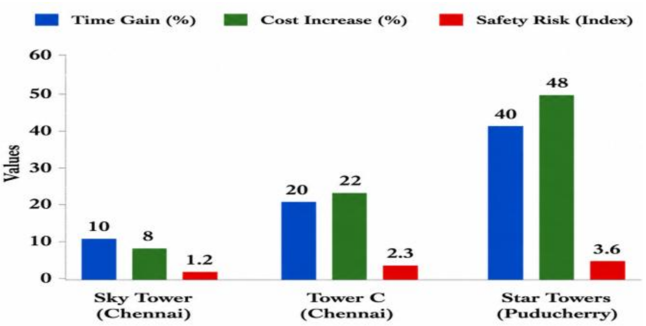

Fig -5: Comparative Case Study Performance

4.4 Key Findings from Case Studies

- Schedule compression beyond 10–15% leads to disproportionate increases in cost and safety risks
- Activity overlapping significantly improves time but introduces coordination complexity
- Rework is a major contributor to cost escalation in fast-tracked projects
- Safety risks are strongly linked to fatigue, congestion, and lack of supervision
- Controlled fast-tracking with proper planning and monitoring yields optimal results.

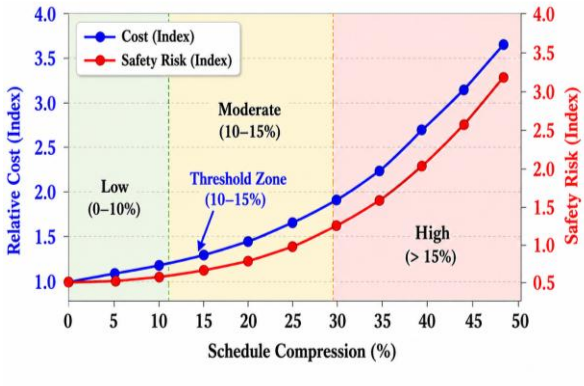

Fig 6: Compression vs Cost–Safety Relationship

5. TCS FRAMEWORK DEVELOPMENT

The proposed framework integrates three primary variables:

Time (T): Project duration
Cost (C): Direct + indirect cost
Safety (S): Risk probability

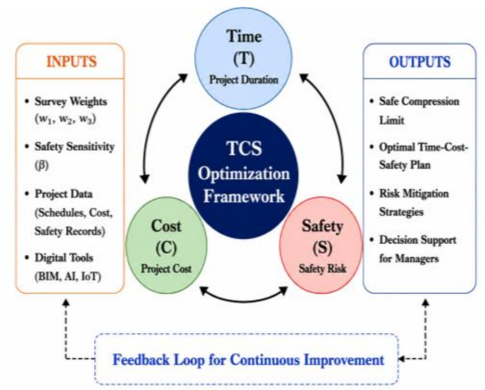

Fig 7: TCS Framework Model

Mathematical Representation
TCS Objective Function:
Z=wT(T)+wC(C)+wS(S) Z = w_T(T) + w_C(C) + w_S(S) Z=wT(T)+wC(C)+wS(S)
Where:

wT, wC, wS = stakeholder weights
β = safety sensitivity coefficient
Framework Features
Non-linear crash cost modeling

The framework was designed to integrate time, cost, and safety into a unified decision-making model capable of identifying balanced schedule compression limits for fast-tracked construction projects. The framework development process was based on findings obtained from literature review, questionnaire survey analysis, and live case study observations. The primary objective of the framework was to establish a practical relationship between schedule acceleration, cost escalation, and safety deterioration under compressed construction conditions.
The framework considers three major variables: project duration (Time), project expenditure (Cost), and safety performance (Safety). Time represents the extent of schedule compression and acceleration achieved through overlapping activities, crashing, and resource intensification. Cost includes both direct and indirect project expenses resulting from acceleration, such as labor overtime, additional equipment usage, supervision costs, and rework expenditure. Safety represents operational risk, accident probability, workforce fatigue, and overall site safety performance during fast-tracked execution.

The framework integrates non-linear relationships between these variables because practical case study analysis demonstrated that cost and safety impacts do not increase proportionally with compression. Moderate schedule acceleration may produce manageable cost and safety impacts, while excessive compression results in exponential cost growth and severe safety deterioration. The framework therefore establishes a “safe compression zone” where project duration can be reduced without creating unstable construction conditions.

To improve practical applicability, the framework also incorporates stakeholder priority weights and safety sensitivity coefficients obtained from questionnaire survey responses. These parameters allow project managers to evaluate different trade-off scenarios depending on project objectives and risk tolerance levels. The final framework generates optimized decision zones by balancing schedule reduction against cost efficiency and safety performance. The developed model therefore provides a structured and data-driven approach for managing fast-tracked construction projects more effectively.

Table 5: Framework Parameters

Parameter	Description
T	Project duration
C	Project cost
S	Safety risk
β	Safety sensitivity
wT, wC, wS	Weights

6. RESULTS AND DISCUSSION

Optimal compression range: 10–15%
The analysis carried out through literature review, questionnaire survey, and live case studies revealed a strong interrelationship between schedule compression, project cost, and safety performance. The results indicate that moderate schedule acceleration improves project delivery efficiency; however, excessive compression leads to severe operational challenges including productivity loss, cost escalation, rework, and increased safety exposure.

The live case studies demonstrated that schedule compression up to approximately 10–15% remained manageable in most projects and produced balanced outcomes. Within this range, overlapping activities improved workflow continuity and reduced idle time between trades without creating excessive operational instability. However, beyond this threshold, project performance deteriorated rapidly. Cost escalation became increasingly non-linear because additional acceleration required higher labor deployment, overtime work, extended supervision, equipment intensification, and corrective rework.

Safety performance was also significantly influenced by increasing compression levels. Aggressive acceleration created congested work environments, overlapping trade conflicts, workforce fatigue, and reduced supervision efficiency. These conditions increased the likelihood of accidents, near-miss incidents, and operational errors. The case study findings confirmed that safety cannot be treated as a secondary factor in fast-tracked construction because schedule decisions directly influence workforce behavior and site risk conditions.

The study further demonstrated that rework becomes a major contributor to both time loss and cost escalation under highly compressed schedules. Although aggressive acceleration initially improves progress, coordination failures and incomplete information often reduce actual productivity gains. This indicates that excessive compression may create diminishing returns, where additional acceleration produces disproportionately high operational consequences.

The integration of digital construction technologies such as BIM-4D, AI-based monitoring systems, and IoT-enabled safety tracking was also found to improve project coordination and real-time risk management. These technologies enhanced visibility of overlapping activities, improved hazard identification, and supported proactive decision-making under accelerated construction conditions. However, their effectiveness depends on proper integration into project planning and management systems.

Overall, the results validate the proposed TCS framework and confirm that successful fast-tracked construction requires balanced optimization rather than aggressive schedule reduction alone. The findings strongly support the need for integrated decision-making models that simultaneously evaluate time, cost, and safety impacts during project acceleration.

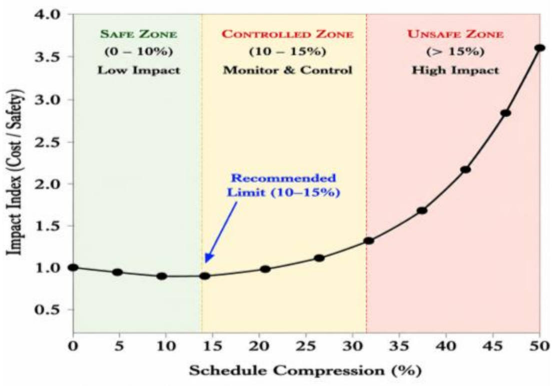

Fig 8: Safe Compression Zone Identification

Table 6: Framework Parameters

Compression (%)	**Cost Trend**	**Safety Trend**
0–10	Linear	Stable
10–15	Increasing	Moderate risk
>15	Exponential	High risk
Compression (%)	Cost Trend	Safety Trend

7. CONCLUSION

This study developed an integrated Time–Cost–Safety (TCS) optimization framework for fast-tracked construction projects by combining literature analysis, questionnaire survey findings, and live case study validation. The research addressed a major limitation in existing fast-tracking studies, where safety is often neglected as a quantitative parameter during schedule optimization. The findings confirmed that schedule compression directly influences project cost, workforce productivity, and operational safety.

The study demonstrated that moderate schedule acceleration can improve project delivery efficiency when supported by proper planning, supervision, and coordination. However, aggressive compression beyond safe thresholds creates severe cost escalation, rework, and safety deterioration. The analysis identified a practical safe compression zone of approximately 10–15%, within which balanced project performance can be achieved. The findings also highlighted the importance of integrating digital technologies such as BIM, AI, and IoT into fast-tracked construction management systems.

The proposed TCS framework provides a practical and structured decision-support tool for evaluating schedule acceleration strategies in real construction environments. By integrating time, cost, and safety relationships into a single optimization model, the framework enables project managers to identify balanced execution strategies rather than relying solely on aggressive acceleration.

8. RECOMMENDATIONS

Based on the findings obtained from literature analysis, questionnaire surveys, and live case studies, several recommendations are proposed for improving the performance of fast-tracked construction projects. Schedule compression should be limited within a controlled range of approximately 10–15%, beyond which cost escalation and safety deterioration increase significantly. Project planning should adopt integrated Time–Cost–Safety evaluation methods rather than focusing only on duration reduction. Overlapping activities should be selected carefully based on risk level, workspace availability, and coordination feasibility.

Construction organizations should strengthen safety management systems during accelerated execution by increasing supervision frequency, conducting regular toolbox talks, and improving workforce monitoring. Extended overtime and excessive workforce congestion should be minimized to reduce fatigue-related risks and productivity loss. Digital construction technologies such as BIM-4D, AI-based PPE monitoring, IoT sensors, and digital dashboards should be integrated into project management systems to improve real-time coordination and hazard identification.

The study also recommends the implementation of structured approval systems before introducing aggressive schedule compression. Project managers should evaluate the impact of acceleration on cost, safety, logistics, and workforce conditions prior to execution.

Finally, future fast-tracked projects should adopt data-driven optimization frameworks such as the proposed TCS model to achieve balanced project delivery while maintaining cost efficiency and worker safety.

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