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Research Article

Prefabricated bridge segmental construction in urban areas: Optimization of erection sequences using BIM-integrated 4D simulation

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Abstract

Urban bridge construction is challenging because of limited space, traffic constraints, and resource requirements. This study proposes a BIM-based 4D simulation and Genetic Algorithm (GA) optimization framework for improving erection sequence planning in prefabricated segmental bridge construction. The framework integrates 3D BIM modeling with time-based scheduling to dynamically represent construction processes, while GA identifies optimized sequences considering construction time, cost, and traffic disruption. Practical constraints, including crane capacity, work-hour restrictions, and urban traffic regulations, are incorporated to ensure feasibility. The proposed framework consists of two complementary components. First, BIM-integrated 4D simulation is used to develop the three-dimensional bridge model, associate construction activities with scheduled time periods, and visualize the erection sequence under urban construction constraints. Second, a Genetic Algorithm (GA) is applied independently to optimize the encoded erection sequence by minimizing construction time, cost, and traffic disruption while satisfying crane capacity, work-hour, and traffic restrictions. The optimized sequence is subsequently incorporated into the 4D environment to visualize and assess the resulting construction plan. A simulation study of the Viadotto Annunziata bridge in Reggio Calabria demonstrates the effectiveness of the proposed approach. The optimized construction strategy reduces construction duration from 204.14 to 149.40 hours and cost from $272,287.63 to $174,795.23. The results also indicate reduced traffic disruption, improved resource utilization, and enhanced safety, demonstrating the framework's potential for efficient and sustainable urban bridge construction.

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1. Introduction

The speed of urbanization and population growth together with the need to keep public spaces operational create difficulties for urban infrastructure development (Moussa et al. 2024; Zou and Xu 2024). The construction of bridges in these locations encounters major restrictions because of their small operational space and their situation between two different traffic conditions and their requirement to comply with safety rules [1, 24]. The conventional construction methods are unable to handle these project requirements which results in construction delays and higher expenses and major public disruptions [21, 5]. The construction industry requires new building methods which will improve operational efficiency while decreasing their effects on city transportation systems and nearby natural areas [17].

The construction method of prefabricated segmental bridges has developed into an effective solution that solves existing challenges [6]. The method achieves construction time and labor

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reduction and decreased on-site disturbance through its process of producing bridge parts at remote locations which are later combined at the construction site [19, 31]. The construction methods of balanced cantilever and span-by-span erection enable construction teams to finish projects more quickly while maintaining better quality control [13]. The process of planning erection sequences remains challenging despite the presence of beneficial aspects [10]. Urban environments create extreme operational limitations which make it difficult for businesses to manage their resources because inefficient scheduling results in safety hazards and resource clashes and increased expenses and traffic interruptions [23].

The traditional methods which construct erection schedules depend entirely on manual work because they need engineers who use fixed scheduling systems which do not provide visual elements and adaptable features [16, 14]. The constraints of urban construction projects are constantly changing, consequently several solutions have to be combined to handle these constraints [29]. BIM and 4D simulation have been developed and accepted as crucial means for displaying construction processes in the time domain of a project [8]. The full integration of these systems makes the scheduling of projects more efficient due to conflict identification and can be used to simulate construction projects in real-time [3]. The BIM-based simulations proved not to yield the best results for the sequencing problem, which leads to the need of a better optimization methodology [11, 28].

This study proposes a 4D simulation system based on Building Information Modeling (BIM) using Genetic Algorithms (GA) to arrange the construction sequence for urban prefabricated segmental bridge (UPSB) projects. The proposed method considers a variety of sequence alternatives for comparison for multiple criteria: construction time, cost and traffic disruption. The result is validated by the case study of an urban bridge, which illustrates its potential to enhance decision-making and construction efficiency and to reduce urban impact. The research contributes to smart construction planning by introducing a novel integrated approach merging visualization and optimization methods. Urban prefabricated segmental bridge construction, erection sequencing is influenced by restricted working hours, limited crane operating capacity, traffic regulations, and the need to minimize disruption to existing road users. Conventional sequence planning may not adequately evaluate alternative erection orders under these interacting constraints. Therefore, the research problem is formulated as a constrained sequence optimization problem in which alternative segment erection orders are evaluated according to construction time, cost, and traffic disruption while satisfying practical urban construction requirements. The proposed framework addresses this problem by using WBS-based sequence encoding within a Genetic Algorithm (GA), while BIM-integrated 4D simulation provides the spatial and time-based representation needed to visualize and assess the optimized erection plan. Thus, GA performs the sequence optimization, whereas BIM and 4D simulation support schedule integration, visualization, and construction-plan assessment under urban constraints. The study integrates computational structural engineering, BIM-based 4D simulation, and evolutionary optimization for bridge erection planning.

This combination addresses constrained structural construction systems through advanced simulation and metaheuristic optimization. The novelty of this study lies in integrating WBS-based erection-sequence encoding, BIM-integrated 4D simulation, and Genetic Algorithm optimization within a unified framework for prefabricated segmental bridge construction. The proposed approach simultaneously considers construction time, cost, traffic disruption, and practical urban constraints to generate and visualize feasible optimized erection sequences.

1.1 Primary Contributions

- Integration of BIM, 4D simulation, and GA in a unified framework for the optimized planning of erection sequence.
- Time-cost-traffic disruption are simultaneously optimized under the real construction constraints.
- Parameter normalization according to the structure and sequence encoding based on WBS are proposed to GA optimization.
- Combination of 3D BIM and scheduling enables dynamic 4D simulation and enhances the planning processes.

- Simulation-based assessment showing benefits in efficiency, resource consumption, safety and environmental sustainability.

The rest of this article is arranged in the following manner: Section 2 provides the related literature review and the research gaps are identified. The problem statement and the research objectives are given in Section 3. The BIM-based 4D simulation and GA-driven optimization approach is described in Section 4. Section 5 describes the experimental configuration, Section 6 the results and discussion, and Section 7 the conclusion and future work.

2. Literature Review

[20] The BIM-based integrated design methodology improves precision and safety in prefabricated steel structures but is limited to structural safety, excluding scheduling and resource management. [4] The review highlights how robotic technologies in construction, including BIM and automation, enhance sustainability through improved efficiency, precision, and circular economy utilization under Industry 4.0. [27] The monitoring system for tied steel box arch bridges ensures alignment and force control during construction, with results showing high precision and robust performance, with errors under 10%. [25] The hybrid prefabricated segmental bridge piers improve seismic performance by reducing damage, enhancing deformation and self-centering, though with slightly lower energy dissipation compared to cast-in-place piers.

[18] The 3D FE modeling of a segmental precast subway station shows robustness against collapse, but stress concentration at joints and bolt connections increases during backfilling under nonuniform loads. [26] The UHPC jacket retrofitting enhances the seismic performance of deteriorated precast segment bridge columns, improving energy dissipation, strength, and stiffness, with performance influenced by jacket height and thickness. [2] The tests on precast segmental unbonded post-tensioned piers showed that tensile prestressing improves bearing capacity, stiffness, and self-centering, but reduces energy dissipation. [22] The experimental study on precast segmental concrete beams revealed that segmental joints, tendon patterns, and prestressing affect shear capacity, with open joints reducing structural capacity. [7] The methodology assesses the risk of aging post-tensioned bridges in Slovakia, highlighting operational limitations like lane closures and load posting due to tendon issues. [9] The SPMT-based large segment cutting demolition method reduces carbon emissions and preserves structural safety, achieving accurate deformation control and fast, low-impact demolition in 28 days, supported by FEA and LCA.

The reviewed studies show several common research limitations across the various studies. The research by [20] specifically examines design and project-based situations of BIM/FEA systems. The research by [4] operates under its conceptual review structure because it does not provide sufficient proof about robotic construction technologies. The research by [27] and [9] and [7] depends mostly on simulation and inspection research methods which do not provide sufficient time to track structural performance and decay through actual field testing. The research by [25] and [26] and [2] and current research advances but lacks full integration between field testing, long-term performance assessment, and combined design-maintenance systems for prefabricated infrastructure.

2.1 Research Gap and Motivation

Previous studies have addressed construction planning through conventional scheduling, BIM-based coordination, 4D simulation, and optimization techniques, but these approaches provide different capabilities and do not fully address the constrained erection-sequence planning problem in urban prefabricated segmental bridge construction. Conventional scheduling methods generally rely on predefined activity sequences and provide limited capability for systematically exploring alternative erection orders. BIM-based methods improve geometric coordination and construction visualization, while 4D simulation links construction activities with time and enables schedule-based assessment; however, these approaches do not inherently search for an optimized erection sequence among multiple alternatives. Genetic Algorithm (GA)-based approaches provide a mechanism for exploring alternative sequences and optimizing construction objectives, but when implemented independently they provide limited linkage with BIM-based spatial information and

time-dependent construction visualization. The urban bridge construction environment further increases the complexity of sequence planning because crane capacity, permitted working hours, traffic restrictions, construction time, cost, and traffic disruption must be considered simultaneously. Consequently, selecting an erection sequence requires both an optimization mechanism to identify suitable alternatives and a BIM-integrated 4D environment to represent, visualize, and assess their implementation within the construction context. A methodological gap therefore remains in the unified integration of WBS-based erection-sequence encoding, constrained GA optimization, and BIM-integrated 4D simulation for urban prefabricated segmental bridge construction. This study addresses this gap by using GA to optimize feasible erection sequences with respect to construction time, cost, and traffic disruption, while BIM-integrated 4D simulation links the optimized sequence with construction activities and provides time-based visualization and assessment under practical urban constraints.

3. Problem Statement

The research field exhibits key limitations that hinder the practical implementation of BIM-based structural design together with robotic construction systems and finite element modelling and methods for assessing seismic performance of prefabricated infrastructure systems. The study results of [20] show effective BIM/FEA design optimization which fails to deliver a comprehensive lifecycle system combining construction scheduling with resource management. The research conducted by [27] and [26] and [2] depends on laboratory experiments together with numerical testing which restricts their ability to assess actual field performance of their methods. The studies conducted by [7] and [18] lack comprehensive assessment of structural performance throughout extended periods of actual operational and environmental testing. The studies conducted by [10] and [4] lack generalizability because their researchers used case-specific or conceptual methods for their investigations [12]. The existing gaps demonstrate that there is no existing framework which integrates field testing with lifecycle assessment to monitor structural design and construction and operational performance of prefabricated infrastructure systems.

3.1 Research Objectives

- Develop a BIM-based 4D simulation environment for construction sequence planning.
- Optimize the sequences of erection for temporary structures based on time, cost, and traffic disruption using a Genetic Algorithm.
- Apply realistic construction constraints, resulting in feasible and effective solutions.
- Analyze the proposed framework exploit simulation-based analysis.
- Support visualization-based decisions by connecting 3D BIM models to time-based construction schedules.

Previous planning approaches for prefabricated segmental bridge construction provide useful capabilities but also present distinct limitations. Traditional planning methods mainly depend on predefined schedules and planner experience, which can make it difficult to evaluate alternative erection sequences and their effects on urban traffic and resource utilization. BIM-based approaches improve three-dimensional visualization and construction coordination, while 4D simulation further links construction activities with time; however, these approaches do not inherently determine an optimized erection sequence under multiple construction objectives. Conversely, genetic algorithm-based approaches can search alternative construction sequences efficiently, but when implemented independently, they provide limited integration with spatial BIM information and time-based construction visualization. These observations indicate a need for an integrated framework that combines BIM-based visualization, 4D simulation, WBS-based sequence representation, and GA optimization while simultaneously considering construction time, cost, traffic disruption, crane capacity, working-hour restrictions, and urban traffic constraints.

4. Methodology

The construction cost was formulated by considering labor, equipment, and operational expenses associated with each erection activity. Labor cost was calculated from the labor hours required for an activity and the corresponding hourly labor rate. Equipment cost was determined from the

equipment utilization duration and the applicable equipment hourly rate, with crane utilization linked to the start and finish times of the associated segment erection activities. Operational expenses were calculated according to the assumed operating period of the equipment and construction activities. For each candidate erection sequence, the activity schedule determined the corresponding labor and equipment utilization periods; therefore, changes in erection order or activity timing directly affected the calculated total construction cost. The same cost assumptions were applied to the conventional and GA-optimized schedules to maintain a consistent comparison. The methodology formulates bridge erection as a constrained engineering optimization problem involving structural components, resources, and temporal dependencies. BIM-integrated 4D simulation and GA optimization enable computational evaluation of alternative erection sequences.

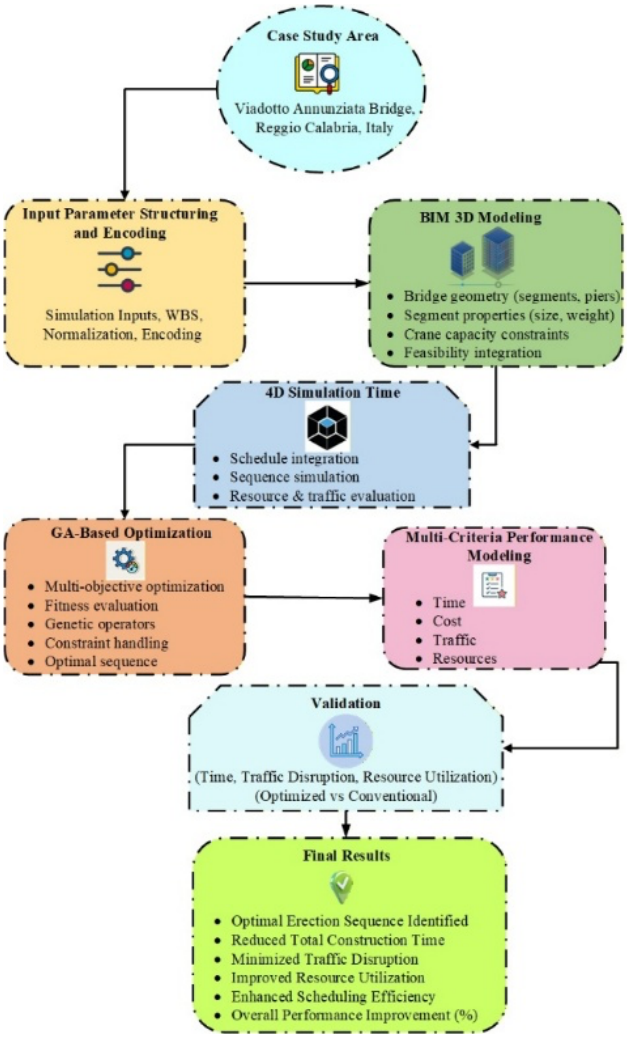


Fig. 1. Methodology flowchart of BIM-integrated 4D simulation and GA-Based optimization framework

The weighting scheme is used to represent the relative importance of the three optimization objectives in the urban bridge erection process. Construction time is assigned a higher weight ((W_1=0.4)) because erection duration directly affects the period of construction activities and associated urban interference. Construction cost and traffic disruption are assigned equal weights ((W_2=W_3=0.3)) to maintain balanced consideration of economic performance and traffic-related impacts. Thus, the adopted weights provide a time-oriented but balanced multi-objective formulation for evaluating alternative erection sequences. The proposed methodology integrates BIM with 4D simulation and GA based optimization for planning of erection sequence. Construction parameters and segment information are organized and encoded with WBS at the beginning. A comprehensive 3D BIM model is created and associated with scheduling information to allow real-time 4D visualization of a construction processes. The GA optimization module evaluates erection sequences to minimize project duration, cost, and traffic disruption, selecting the best sequence for

optimal efficiency and resource allocation. The flow of the proposed framework of BIM-based 4D simulation and GA for building components is presented in Figure 1. The case study links a 3D BIM model with a time-based schedule and uses GA-based optimization to enhance efficiency, cost, and resource utilization.

4.1 Case Study Area

The Annunziata Viaduct in the urban context of Reggio Calabria, a context characterized by a high density of population, closeness to a major university area, and the crossing of the Annunziata River by the viaduct. The study uses BIM-based 4D simulation to optimize prefabricated bridge construction, minimizing time, cost, and traffic disruption under urban constraints. The Annunziata Viaduct in Reggio Calabria was selected as the case study because its construction context provides a suitable environment for evaluating the proposed framework under the practical conditions considered in this study. The bridge construction involves prefabricated segmental erection activities that require coordinated sequencing, temporary resource utilization, and time-dependent planning. In addition, its urban setting provides a relevant context for considering traffic restrictions and construction-related disruption together with crane capacity and permitted working hours. These characteristics correspond directly to the constraints and optimization objectives incorporated into the proposed BIM-integrated 4D simulation and Genetic Algorithm (GA) framework. Therefore, the case study provides an appropriate basis for examining whether the proposed approach can generate feasible erection sequences while simultaneously evaluating construction time, cost, traffic disruption, resource utilization, and safety-related requirements within an urban bridge construction environment.

4.2 Input Parameter Structuring and Encoding

Each segment erection activity, the optimization input includes the segment lifting requirement and its associated crane operating condition. The crane-related parameters are linked to the segment location so that the applicable working radius and corresponding allowable capacity can be considered during sequence evaluation. These parameters are retained when an alternative erection sequence is generated, enabling crane feasibility to be reassessed for every candidate sequence. The precedence relationships were extracted from the bridge construction process and the corresponding work breakdown structure (WBS). These relationships define the required order between dependent erection activities, such that an activity can start only after all of its required predecessor activities have been completed. For example, segment erection activities are ordered according to the required construction sequence and completion of prerequisite supporting activities. During activity scheduling, these precedence relationships determine the earliest feasible start time of each dependent activity. They were also incorporated into the genetic optimization process so that candidate erection sequences violating the prescribed construction dependencies were treated as infeasible. Thus, the genetic algorithm searches for optimized erection sequences while preserving the practical construction order represented in the BIM-based schedule. Input parameters are deterministically generated, normalized, and structured for compatibility with the BIM-enabled 4D simulation and GA-based optimization framework, ensuring consistency and preventing bias is defined as in Eqn. (1):

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{1}$$

(x_i) denotes the original (unnormalized) value of the (i)-th construction parameter, while (x_i^{$norm$}) denotes its normalized value. The terms (x_i^{min}) and (x_i^{max}) represent the minimum and maximum values of the corresponding parameter used for min–max normalization, respectively. This notation explicitly distinguishes the original parameter value from its normalized representation and the associated normalization bounds.

4.3 BIM Modeling

The BIM-based 4D simulation workflow establishes an explicit relationship between BIM objects and their corresponding construction activities. Each bridge component represented in the BIM model was associated with a unique activity or WBS identifier corresponding to its erection

operation. The construction schedule generated from the defined erection activities was then mapped to these identifiers, allowing the start time, finish time, and sequence of each activity to control the corresponding BIM object during simulation. The GA-optimized erection sequence was subsequently applied to the activity schedule, and the updated schedule-object relationships were used to generate the complete 4D construction sequence. This workflow ensured that changes in activity order and timing were consistently reflected in the visualization of the associated bridge components. The BIM model, created with Autodesk Revit and Civil 3D, visualizes the bridge structure, including prefabricated segments, piers, and temporary supports, while incorporating construction parameters for feasibility analysis is given in Eqn. (2)

$$W = \rho \cdot V \tag{2}$$

where W is the segment weight, ρ is the material density, and V is the segment volume.

4.4 4D Simulation

Ensure consistency between construction planning and 4D visualization, crane capacity, permitted working hours, and traffic restrictions were synchronized with the BIM-based construction schedule. Each segment erection activity was assigned its required crane capacity, planned start and finish time, and applicable traffic condition. During schedule generation, an erection activity was considered feasible only when the required crane capacity was within the available crane limit, the activity duration fell within the permitted working-hour window, and the corresponding traffic condition satisfied the specified restriction. The feasible activity sequence generated by the genetic algorithm was then linked to the BIM model through the activity schedule, allowing the 4D simulation to represent the timing and sequence of erection operations under the specified construction constraints. The 4D implementation used Autodesk Navisworks to associate the BIM model with the construction activity schedule, while Autodesk Revit and Civil 3D were used for BIM model development. The activity identifiers defined in the WBS were used to establish correspondence between the modeled bridge components and their scheduled erection operations. The 4D simulation links BIM with project scheduling software to visualize construction sequences, crane operations, and traffic interactions, enabling efficient planning in space-constrained environments is expressed as in Eqn. (3)

$$T_{project} = max(t_1 + t_2 + \cdots + t_n) \tag{3}$$

where t_i represents the scheduled duration of individual construction activities considering precedence constraints.

4.5 Genetic Algorithm (GA) Optimization

The Work Breakdown Structure (WBS) is used not only to organize the construction activities but also to define the dependency relationships required for generating feasible erection sequences. Each WBS activity is assigned an activity identifier and associated with its predecessor activities based on the actual bridge construction process. For example, foundation and support-related activities must be completed before the corresponding segment erection activities, while segment erection and associated temporary works follow the defined construction order. These predecessor relationships are encoded together with the segment sequence representation and are used during initial population generation and subsequent genetic operations. A candidate sequence is considered feasible only when the required predecessor activities are completed before their dependent activities. Therefore, the WBS-based dependency structure directly restricts the search space of the GA and ensures that generated erection sequences remain consistent with the construction process. The crossover operation was implemented to exchange segment positions between two parent erection sequences while maintaining a valid permutation of the bridge segments. Two parent chromosomes were selected from the current population, and crossover positions were determined within the encoded sequence. The segment positions between the selected crossover points were transferred from one parent to generate a partial offspring sequence, while the remaining segment positions were filled according to the ordering information of the other parent. Duplicate segment assignments were removed and missing segments were inserted so that each offspring contained every required bridge segment exactly once. The resulting offspring were subsequently checked against the predefined construction precedence

relationships, and any sequence violating the required erection dependencies was repaired or treated as infeasible before fitness evaluation. This procedure enables segment positions to be exchanged between successive population generations while preserving the validity of the encoded erection sequence.

Handle infeasible candidate erection sequences, a severity-based penalty mechanism was incorporated into the fitness evaluation. For each candidate sequence, violations of crane capacity, permitted working hours, and traffic restrictions were identified separately. The severity of a violation was determined from the magnitude of the constraint exceedance, rather than treating all violations as identical. For example, a crane violation was related to the amount by which the required lifting load exceeded the allowable crane capacity, while temporal violations were related to the extent of the activity occurring outside the permitted working or traffic-restriction window. When multiple constraints were violated by the same candidate sequence, their individual penalty contributions were accumulated to obtain a total constraint penalty. This total penalty was added to the objective-based fitness value, thereby assigning poorer fitness to sequences with more severe or multiple constraint violations. Feasible sequences with no constraint violation received zero constraint penalty. Crane feasibility was evaluated by considering the relationship between the segment lifting requirement and the available crane capacity at the corresponding working radius. For each erection activity, the segment weight and lifting location were associated with the crane operating condition, and the allowable lifting capacity was determined for the corresponding working radius. A candidate erection activity was considered feasible when the required lifting load did not exceed the available crane capacity at that radius. During genetic optimization, this feasibility check was repeated whenever the segment erection order was changed, because a change in sequence can alter the associated lifting position, crane operating condition, and resource utilization period. Candidate sequences that violated the crane-capacity condition were therefore treated as infeasible or penalized during fitness evaluation.

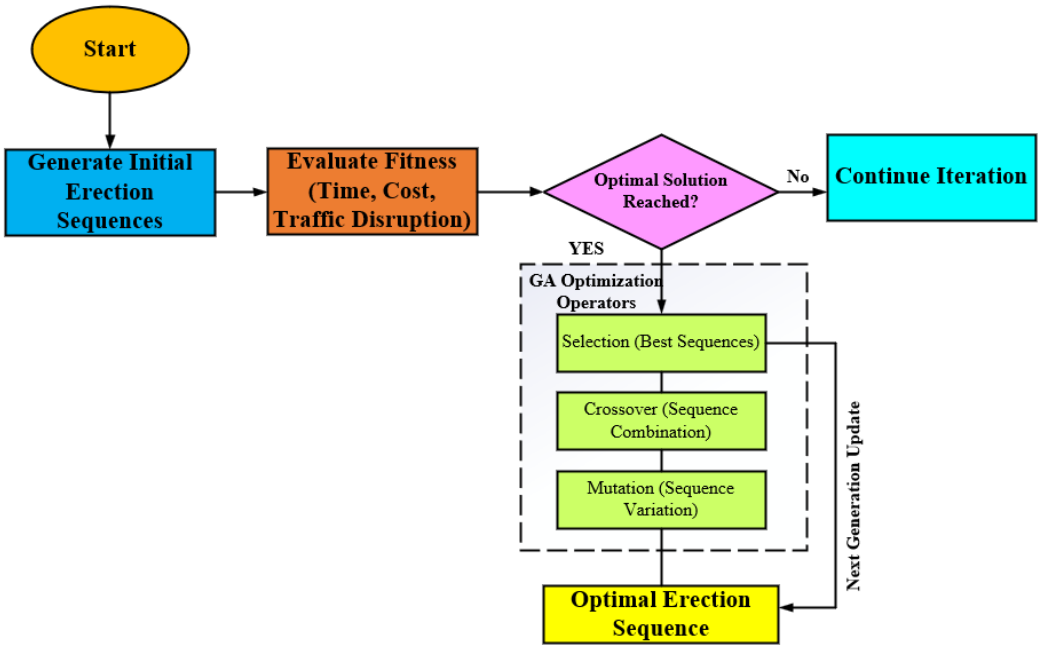


Fig. 2. GA-Based erection sequence optimization framework

During GA-based sequence optimization, the construction constraints were incorporated into the feasibility evaluation of each candidate erection sequence. For crane capacity, the required lifting load of each segment was compared with the available crane capacity, and sequences exceeding the allowable limit were treated as infeasible. Permitted working hours were applied as temporal constraints so that erection activities were scheduled only within the allowable operating periods. Traffic restrictions were incorporated as time-dependent constraints, preventing or penalizing erection activities that conflicted with restricted traffic periods. The resulting feasible schedule was subsequently synchronized with the BIM-based 4D model, ensuring that the optimized erection

sequence and its associated activity timings were consistently represented in the construction simulation. Precedence constraints were applied during the feasibility evaluation of each GA-generated erection sequence. A candidate activity was permitted to start only when all of its predecessor activities satisfied their completion requirements; therefore, sequences that violated the construction precedence relationships were excluded or penalized during fitness evaluation. The feasible sequence was subsequently transferred to the BIM-based schedule for 4D simulation. Figure 2 shows the GA-based optimization framework iteratively refines prefabricated bridge segment erection sequences to minimize construction time, cost, and traffic disruption, ensuring optimal efficiency and minimal urban impact.

4.5.1 Objective Function

The optimization aims to minimize project time, cost, and traffic disruption while considering urban impact and construction efficiency is represented as Eqn. (4).

$$minZ = w_1T + w_2C + w_3D \tag{4}$$

where T is the Total construction time required for completing all erection activities, C is the Total construction cost, including labor, equipment, and operational expenses, D denotes Traffic disruption index.

4.5.2 GA Procedure

The GA undergoes a disciplined evolutionary procedure to get the best erection order:

- Initialization: Generate an initial population of feasible erection sequences.
- Fitness Evaluation: Compute the fitness of each sequence using the defined objective function.
- Selection: Select high-performing sequences based on fitness values using selection strategies.
- Crossover: Combine selected parent sequences to generate new offspring by exchanging segment order information.
- Mutation: Introduce random variations in sequences to maintain diversity and avoid premature convergence.
- Iteration: Repeat the evaluation–selection–crossover–mutation cycle until convergence criteria are met or a maximum number of generations is reached.

The proposed framework integrates WBS-based activity representation, BIM modeling, 4D simulation, Genetic Algorithm (GA) optimization, and construction-constraint evaluation to develop a feasible and optimized erection sequence. Each component performs a specific function within the sequence-development process. The WBS first decomposes the bridge erection process into identifiable construction activities and establishes the precedence relationships required for feasible sequencing. BIM then represents the spatial configuration of bridge components and associates the construction activities with the corresponding BIM objects. The 4D simulation component links these activities with their scheduled time periods, enabling the temporal visualization and assessment of alternative erection sequences.

The GA optimization component explores alternative activity sequences by encoding the WBS-based erection activities as candidate solutions. For each candidate sequence, construction time, cost, and traffic disruption are evaluated, while crane capacity, permitted working hours, traffic restrictions, and precedence relationships are checked to maintain practical feasibility. Infeasible solutions are repaired where possible or penalized during fitness evaluation. Through selection, crossover, mutation, and iterative population updating, the GA searches for an improved sequence according to the defined objective function. The resulting optimized sequence is then incorporated into the BIM-integrated 4D environment, where its spatial and temporal implementation can be visualized and assessed. Thus, WBS provides the sequence structure, BIM provides spatial representation, 4D simulation provides time-based visualization, and GA provides the optimization mechanism, while the construction constraints ensure that the generated sequence remains practically feasible.

Algorithm 1. Genetic algorithm-based optimization of erection sequences

Input:
- Set of prefabricated segments
- Construction parameters (time, cost, traffic disruption)
- Constraint set (crane capacity, work-hour limits, traffic restrictions)
- GA parameters (population size, crossover rate, mutation rate, maximum generations)

Output:
- Optimal erection sequence
- Minimum objective value

Step 1: Initialization
- Generate an initial population of feasible erection sequences.
- Each sequence must include all segments without repetition.

Step 2: Fitness Evaluation
- Evaluate each sequence using the objective function:

$minZ = w_1T + w_2C + w_3D$
- Assign fitness values based on construction time, cost, and traffic impact.

Step 3: Constraint Handling

Check feasibility of each sequence using constraints such as:
- Crane lifting capacity:

$W_i \leq C_{max}(r)$
- Work-hour limitations
- Traffic restrictions

Penalize or discard infeasible sequences.

Step 4: Selection

Select high-quality sequences based on fitness using methods such as tournament or roulette wheel selection.

Step 5: Crossover
- Perform crossover between selected parent sequences to generate new offspring.
- Ensure that offspring maintain valid and non-repetitive segment sequences.

Step 6: Mutation
- Apply mutation by randomly altering segment positions.
- Maintain sequence feasibility after mutation.

Step 7: Population Update
- Form a new population by replacing fewer fit sequences with improved offspring.
- Retain the best-performing sequences (elitism).

Step 8: Termination Check

Repeat Steps 2–7 until:
- Maximum number of generations is reached, or
- Convergence is achieved (no significant improvement).

Step 9: Output

Select the best sequence with the minimum objective value as the optimal erection plan.

Algorithm 1 outlines the GA-based method for optimizing prefabricated bridge segment sequences, considering construction time, cost, and traffic disruption, while integrating realistic constraints for efficient, low-impact solutions. During the crossover operation, segment positions are exchanged between two parent erection sequences to generate new offspring while preserving the complete set of bridge segments. After crossover, the offspring sequence is checked for duplicated or missing segments, and a repair procedure restores the required one-to-one segment representation when necessary. The repaired sequence is then evaluated against the predefined construction precedence relationships to ensure that predecessor activities are completed before their dependent erection activities. Similarly, mutation modifies selected segment positions to introduce sequence diversity while maintaining the complete segment set. Each mutated sequence is subsequently checked for precedence, crane-capacity, working-hour, and traffic restrictions. If a generated sequence violates the applicable feasibility conditions, it is repaired where possible;

otherwise, it is treated as an infeasible candidate and assigned the corresponding constraint penalty before fitness evaluation. Thus, crossover and mutation preserve feasible sequence characteristics while allowing sufficient variation for genetic exploration.

4.5.3 Constraints

The optimization is subject to a practical construction and urban constraints so that all the sequences of erection generated are feasible, safe and consistent with actual situations.

Crane Lifting Capacity Constraint: Each segment is to be raised within the load-lifting capacity of the crane at the particular working radius is calculated from Eqn. (5)

$$W_i \leq C_{max}(r) \tag{5}$$

Where W_i is the Weight of the i^{th} segment, $C_{\max}(r)$ is the crane capacity at radius r.

Urban Traffic Constraint: Construction work shall be planned and conducted with a minimum interference of city traffic. Operations during the busy traffic hour are limited as per Eqn. (6)

$$t_i \notin T_{peak} \tag{6}$$

Where t_i is the Time of activity i, $T_{\text{peak:}}$ defined peak traffic time intervals.

Work-Hour Constraint: All construction activities must be executed within permissible working hours defined by local regulations is applied using Eqn. (7)

$$T_{work} \leq T_{allowed} \tag{7}$$

Where T_{work} represents total scheduled working time.

4.6 Multi-Criteria Performance Modelling

Resource Utilization Modeling: Resource Utilization Modeling compares active working time with available time to identify inefficiencies, with higher values indicating better resource allocation and productivity is applied using Eqn. (8)

$$RUE = \frac{\sum_{r=1}^{q} U_r}{\sum_{r=1}^{q} T_r} \tag{8}$$

Where RUE is the Resource Utilization Efficiency, U_r is the active utilization time,T_r is the total available time, q is the number of resources.

Resource Utilization Efficiency (RUE) is denoted consistently as RUE throughout the manuscript. RUE represents the efficiency of utilizing available construction resources during the bridge erection process and is evaluated as one of the performance indicators for comparing the conventional and GA-optimized erection schedules. The abbreviation RUE is retained without changes in capitalization or terminology in all subsequent performance evaluation and discussion sections.

Schedule Performance Evaluation: Schedule Performance Evaluation compares planned and actual durations to identify delays, with higher values indicating better adherence and coordination is given in Eqn. (9).

$$SAI = \frac{T_{planned}}{T_{actual}} \times 100 \tag{9}$$

Where SAI is the Schedule Adherence Index (%), T_{planned} is the planned duration, T_{actual} is the actual duration.

Construction Cost Model: The Construction Cost Model estimates project costs by factoring in labor, equipment, and operational expenses, with lower costs indicating more efficient planning is represented in Eqn. (10).

$$C_{total} = C_{labor} + C_{equipment} + C_{operation} \tag{10}$$

Where C_{total} is the total cost, C_{labor} is the labor cost, $C_{\text{equipment}}$ is the equipment cost, $C_{\text{operation}}$ is the operational cost, R_h is the hourly rate, T_h is the usage time.

Weight Selection Strategy: The Weight Selection Strategy balances construction time, cost, and traffic disruption based on project priorities and urban constraints for practical decision-making is given in Eqn. (11).

$$Z = W_1 T + W_2 C + W_3 D \tag{11}$$

Where Z is the objective value, W_1, W_2, W_3 is the weights, T, C, D is the normalized parameters.

Cumulative Construction Time Modeling: Cumulative Construction Time measures the total duration of all activities, accounting for sequencing and dependencies, with minimization ensuring efficient project completion is given in Eqn. (12).

$$T_{total} = \sum_{i=1}^{n} t_i + \sum_{(i,j)\in P} \delta_{ij} \tag{12}$$

Where T_{total} is the total construction time, t_i is the activity duration, P is the precedence relationships, δ_{ij} is the delay between activities. C_i is the completion time.

5. Experimental Setup

The experimental system tests the BIM-based 4D simulation and GA optimization for selecting an urban bridge erection sequence, considering construction parameters, constraints, and operational conditions. The GA-optimized solution is compared to traditional methods based on time, cost, traffic disruption, resource utilization, and schedule compliance.

Table 1. Software and hardware configuration

Specification	Details
Python Version	3.11.8
NumPy Version	1.26.4
Pandas Version	2.3.2
Matplotlib Version	3.10.6
Processor	12th Gen Intel Core i5-12400 (2.50 GHz)
Installed RAM	16.0 GB (15.7 GB usable)
System Type	64-bit OS, x64-based processor

The computational environment for realizing this study is described in Table 1. The software configuration includes Python 3.11.8 with NumPy, Pandas, and Matplotlib, running on a 12th Gen Intel Core i5 with 16 GB RAM for stable simulation and optimization performance.

5.1 Hyperparameter Configurations

Hyperparameter Settings define the behavior and performance of a Genetic Algorithm, influencing convergence, solution diversity, and the quality of optimization results. Preliminary trials were conducted to examine the effect of population size and generation count on the convergence behavior of the genetic algorithm under the specified bridge erection planning conditions. Different candidate population sizes were evaluated to assess the balance between solution diversity and computational effort, while the number of generations was examined by monitoring the best fitness value across successive iterations. The trials showed rapid fitness improvement during the early generations followed by progressively smaller changes as the optimization approached a stable region. Based on this convergence behavior and the computational requirements, a population size of 80 and a maximum generation count of 120 were selected for the final experiments. The maximum generation limit provides sufficient search capacity for alternative feasible erection sequences, while the observed convergence indicates that extending the optimization beyond the stabilized region provides limited additional improvement.

The population size of 80 and maximum generation count of 120 were selected based on a convergence assessment of the GA under the specified bridge erection planning conditions. The convergence behavior was evaluated by monitoring the best fitness value across successive generations. The fitness improved rapidly during the initial generations and subsequently

stabilized, with only marginal changes after the convergence region. Although the optimization reached a stable fitness level at approximately 20 generations, 120 generations were retained as the maximum generation limit to provide sufficient search capacity and prevent premature termination when exploring alternative feasible erection sequences. The selected population size of 80 provides a sufficiently diverse set of candidate erection sequences while maintaining reasonable computational requirements. Thus, the adopted settings provide a practical balance between solution diversity, convergence, and computational effort for the considered case study.

Table 2. Genetic algorithm hyperparameter settings

Parameter	Value	Description
POP_SIZE	80	Number of candidate solutions per generation
N_GEN	120	Total number of generations
CROSSOVER_R	0.8	Probability of crossover between parent solutions
MUTATION_R	0.15	Probability of mutation (segment swap)
ELITE_K	5	Number of elite solutions retained
W1 (Time)	0.4	Weight assigned to construction time
W2 (Cost)	0.3	Weight assigned to construction cost
W3(Disruption)	0.3	Weight assigned to traffic disruption

Table 2 presents the GA parameters used in the optimization experiments. The population size was set to 80, and the generation count was set to 120. The crossover rate and mutation rate were set to 0.8 and 0.15, respectively, while the elite count was set to 5. The objective weights were assigned as ($W_1 = 0.4$), ($W_2 = 0.3$), and ($W_3 = 0.3$) for construction time, construction cost, and traffic disruption, respectively. These parameter terms are used consistently throughout the subsequent optimization and performance evaluation discussions.

The GA hyperparameters were selected to provide a balance between search diversity, convergence behavior, and computational cost for the erection-sequence optimization problem. A population size of 80 was adopted to provide sufficient diversity among candidate erection sequences while maintaining a manageable computational burden. The crossover rate of 0.8 was selected to promote effective recombination of feasible segment-order characteristics between parent sequences, whereas the mutation rate of 0.15 was used to introduce additional sequence diversity and reduce premature convergence. A maximum generation count of 120 was selected to provide a sufficiently large search horizon for convergence. The convergence behavior presented in Section 6.5 indicates that the fitness improves rapidly during the initial generations and subsequently stabilizes, supporting the suitability of the adopted generation limit for the present case study.

5.2 Performance Evaluation

Performance Assessment processes construction results with respect to specific metrics such as time, cost and productivity etc. It evaluates the overall project performance enhancement brought by the submitted approach.

Total Construction Time Reduction: This measure quantifies the decrease in the length of make-span obtained by optimization. Smaller make span means the project finishes earlier and better scheduling is referred in Eqn. (13).

$$Time\ Improvement\ (\%) = \frac{T_{conv} - T_{opt}}{T_{conv}} \times 100 \tag{13}$$

Where T_{conv} is the Conventional construction time, T_{opt} is the Optimized construction time.

Total Construction Cost Reduction: The number represents how much the total project cost is reduced by the optimization. The reduction of cost due to better resources planning and less waste are illustrated in Eqn. (14)

$$Cost\ Improvement\ (\%) = \frac{C_{conv} - C_{opt}}{C_{conv}} \times 100 \tag{14}$$

Where C_{conv} is the Conventional construction cost, C_{opt} is the Optimized construction cost

Safety Compliance Improvement: This is a measure of improvement of safety during the building process. Higher values indicate better safety of workers, and the degree of regulatory compliance is given by Eqn. (15)

$$\textit{Safety Improvement}\ (\%) = \frac{S_{opt} - S_{conv}}{S_{conv}} \times 100 \tag{15}$$

Where S_{conv} is the Safety score (conventional), S_{opt} is the Safety score.

Resource Utilization Efficiency Improvement: This index is a reflection of the productive utilization of construction input resources. Better planning and coordination are signaled by a greater efficiency as given in Eqn. (16)

$$\textit{Efficiency Improvement}\ (\%) = \frac{R_{opt} - R_{conv}}{R_{conv}} \times 100 \tag{16}$$

Where R_{conv} is the Resource efficiency (conventional), R_{opt} is the Resource efficiency.

Average Segment Erection Time Reduction: This measurement assesses the time saving for segment installation. A smaller erection time implies a faster and more rational work given in Eqn. (17)

$$\textit{Time Reduction}\ (\%) = \frac{t_{conv} - t_{opt}}{t_{conv}} \times 100 \tag{17}$$

Where t_{conv} is the Conventional segment erection time, t_{opt} is the Optimized segment erection time

6. Results and Discussions

The results indicate that the proposed GA-based planning mechanism outperforms the traditional method in construction scheduling. The improved method not only shortens the total time of the project but also improves the efficiency of scheduling. This allows for improved cost control through better resource utilization and minimized work stoppages. Moreover, the framework greatly minimizes interruption to traffic, making the city life more comfortable while building. Indeed, the result is less resource utilization, improved safety performance, and a high probability of schedule reliability, which is consistent with these findings.

6.1 Optimization Performance Comparison

Optimization Performance Comparison evaluates multiple models or algorithms based on metrics like accuracy, speed, cost, and robustness to identify the best solution for a given problem.

Table 3. Performance comparison between conventional and GA-optimized approach

Metric	Conventional	GA-Optimized	Improvement (%)
Total Construction Time (hrs)	204.14	149.40	26.82
Total Construction Cost ($)	272287.63	174795.23	35.80
Total Traffic Disruption (units)	489.95	179.28	63.41
Peak Crane Utilisation (%)	72.40	91.80	26.80
Safety Compliance Score (0–100)	74.00	93.50	26.35
Resource Utilisation Efficiency (%)	68.00	88.50	30.15
Best GA Fitness Score	0.3506	0.3505	0.05
Schedule Adherence (%)	78.50	96.20	22.55
Carbon Emission Index	1.00	0.732	26.80
Average Segment Erection Time (hrs)	5.104	3.735	26.82

Table 3 shows The GA method outperforms traditional construction by reducing time, cost, traffic disturbance, carbon emissions, and erection time, while improving crane utilization, safety, schedule adherence, and resource efficiency.

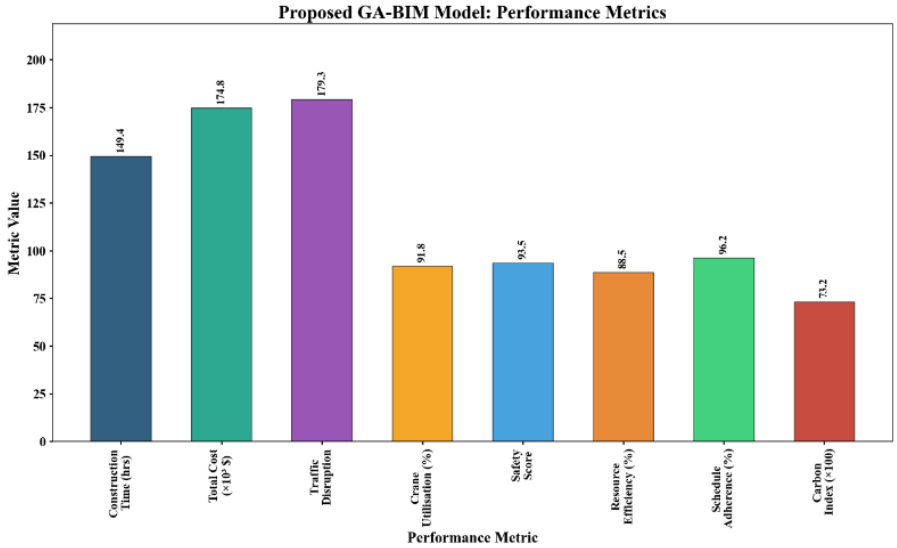


Fig. 3. Optimization performance metrics

Figure 3 shows the GA-BIM optimization model improves building time (149.4 hrs), cost ($174.8K), and traffic disruption (179.3 units), while enhancing crane utilization (91.8%), safety compliance (93.5%), and sustainability (carbon emission 0.732), proving its superiority in multi-criteria construction performance.

6.2 Ablation Study Analysis

Ablation Study Analysis is Ablation analysis evaluates the impact of individual components by selectively removing or altering them, helping optimize model design and understand each component's contribution.

Table 4. Ablation study of model components impact

Model Variant	Time (hrs)	Cost (×10^3 $)
Without GA	204.1	272.3
Without Traffic Constraint	162.3	181.4
Without Cost Objective	158.9	265.5
Full Model (Proposed)	149.4	174.8

Table 4 presents the ablation study shows that removing key components increases building time or cost, with the full model delivering the best performance and validating the importance of each component.

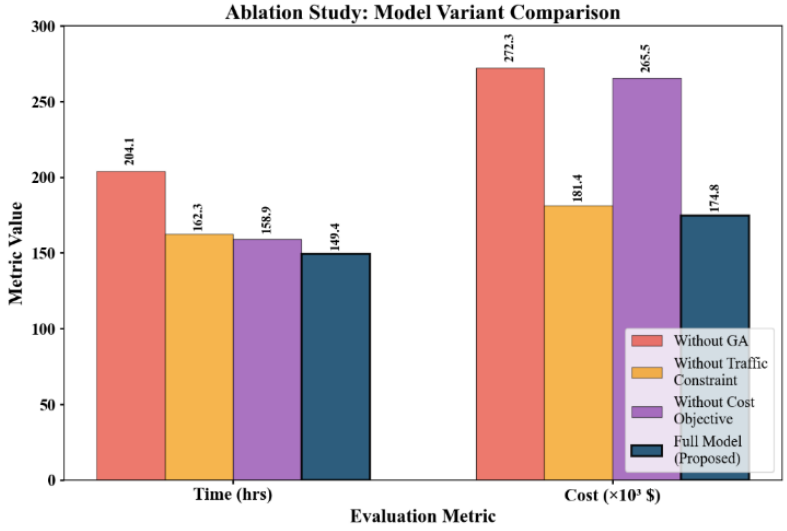


Fig. 4. Ablation study comparison

Figure 4 reports the ablation study shows the full GA model achieves the best performance, while other variants either increase time or cost, highlighting the importance of each module for optimal construction efficiency.

6.3 Cumulative Time Comparison

Cumulative Time Comparison evaluates total construction time across methods, highlighting scheduling effectiveness, delays, and the impact of sequence optimization on project duration.

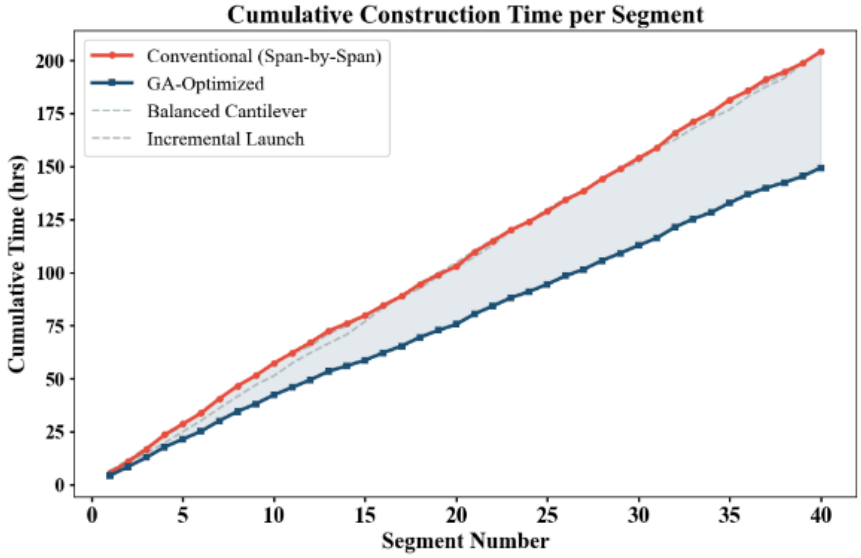


Fig. 5. Cumulative construction time per segment

Figure 5 presents the cumulative construction time per segment. Meanwhile, the traffic disruption analysis evaluates how well different methods control congestion, delays, and overall transportation disruption.

6.4 Traffic Disruption Comparison

Traffic Disruption Comparison analyses the impact of construction on urban traffic, evaluating how well different methods control congestion, delays, and overall transportation disruption.



Fig. 6. Traffic disruption per segment

Figure 6 to illustrate the GA-based method significantly reduces traffic disruption compared to the traditional approach, providing more stable and efficient scheduling across bridge segments.

6.5 GA Convergence Trend

GA Convergence Trend analyses how fitness values improve over generations, showcasing the algorithm's ability to stabilize and converge to an optimal solution.

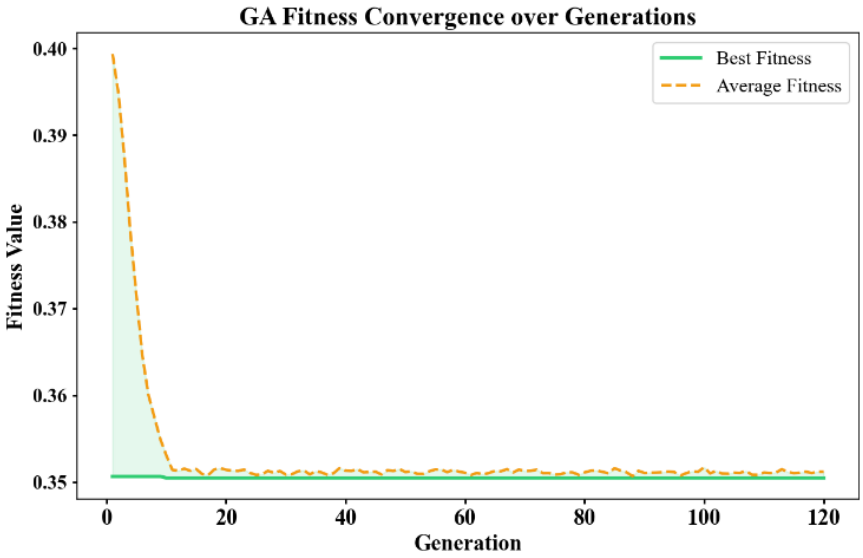


Fig. 7. GA fitness convergence over generations

Figure 7 illustrates the convergence behavior of the GA over the 120 generations. The best and average fitness values show rapid improvement during the initial generations, followed by progressively smaller changes as the optimization proceeds. The fitness values become nearly stable around the convergence region, with the best fitness remaining close to 0.351 in the later generations. This convergence behavior indicates that additional generations beyond the stabilized region provide only marginal optimization improvement under the specified construction conditions. Therefore, the maximum generation count of 120 was retained as a conservative termination limit to allow sufficient exploration while avoiding unnecessary computational iterations.

6.6 Strategy Performance Comparison

Strategy Performance Comparison evaluates alternative construction methods based on key indicators like time, cost, and disruption, highlighting the merits of optimized approaches over traditional methods.

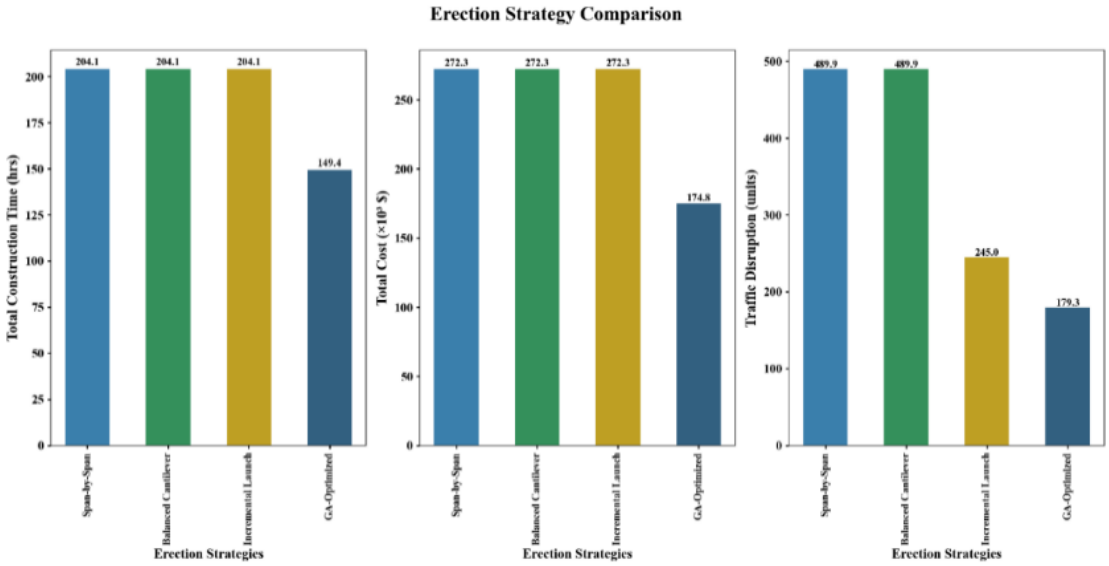


Fig. 8. Erection strategy comparison

Figure 8 shows the GA-based method significantly reduces construction time (149.4 hours), cost ($174.8K), and traffic disruption (179.3 units) compared to traditional methods, improving overall performance.

6.7 Cumulative Time Distribution

Cumulative Time Distribution analyzes time accumulation across construction segments, identifying trends, delays, and evaluating the efficiency of scheduling methods.

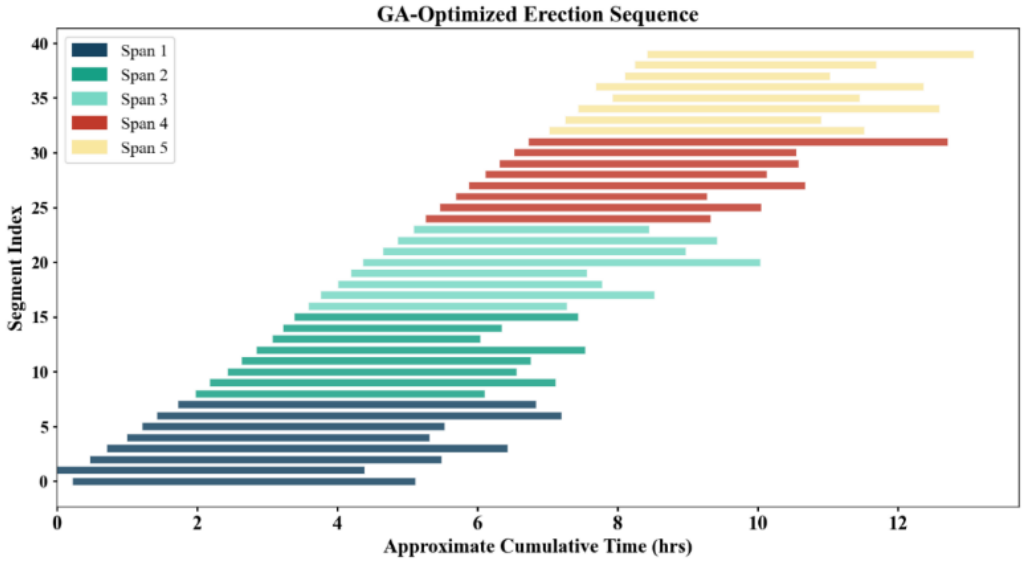


Fig. 9. Cumulative time analysis

Figure 9 shows the cumulative construction time distribution shows most segments take 4-7 hours, with a gradual increase in total time and noticeable scheduling overhead.

6.8 Multi-Criteria Performance

Multi-Criteria Performance Assessment (MCPA) evaluates solutions based on multiple indices, providing a holistic view to balance conflicting objectives like efficiency, cost, reliability, safety, and environmental impact.

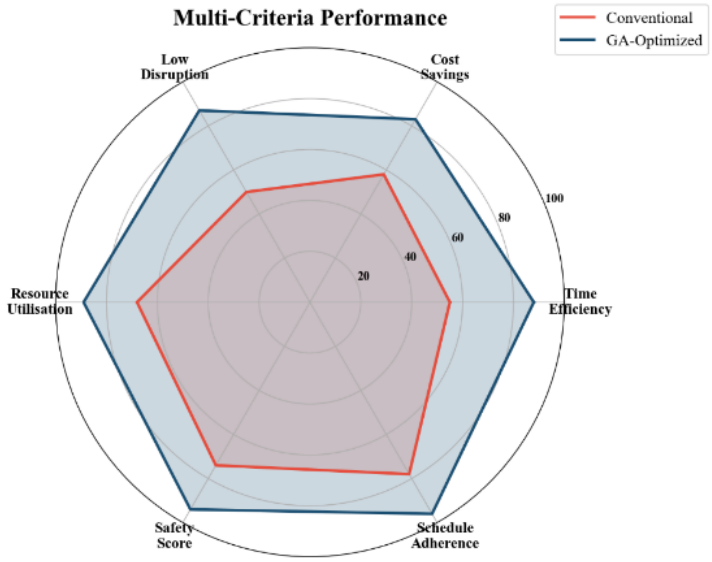


Fig. 10. Multi-criteria performance comparison

Figure 10 displays a radar plot showing that the GA-based method outperforms the traditional approach in time efficiency, cost, safety, traffic, resource use, and schedule compliance, highlighting a more optimized construction plan.

6.9 Sensitivity Analysis Results

Sensitivity analysis evaluates the robustness of the optimization scheme by assessing the impact of input parameter variations on construction time, cost, and traffic disruption.

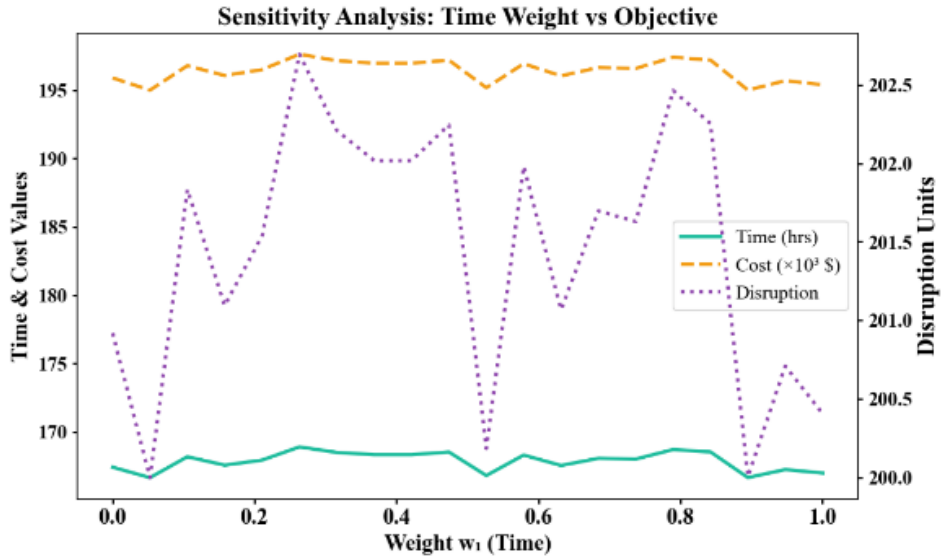


Fig. 11. Sensitivity analysis: Time weight vs objective

Figure 11 shows Changing the time weight has minimal impact on construction duration (167-169 hours), cost ($195-$198K), and traffic disruption (200-202.5 units), indicating stable optimization across objectives.

6.10 Crane Utilization Comparison

Crane Utilization Comparison assesses crane efficiency, highlighting better equipment use, less downtime, and improved schedule efficiency with optimized construction sequences.

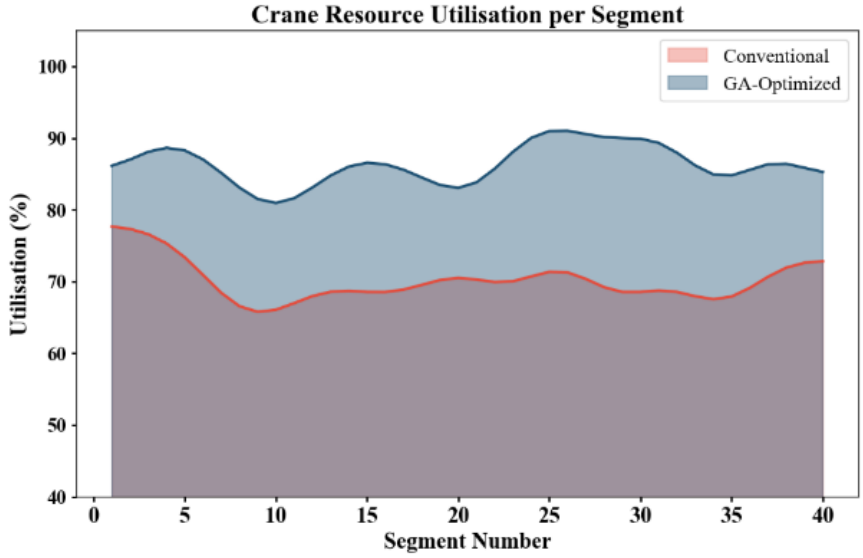


Fig. 12. Crane resource utilization per segment

Figure 12 presents the GA-based method increases crane utilization (82%-91%) compared to the conventional method (66%-73%), offering better efficiency and consistency across segments.

6.11 Safety Score Comparison

Safety Score Comparison evaluates construction methods' safety performance, showing that optimal planning and scheduling enhance operational safety and feasibility.

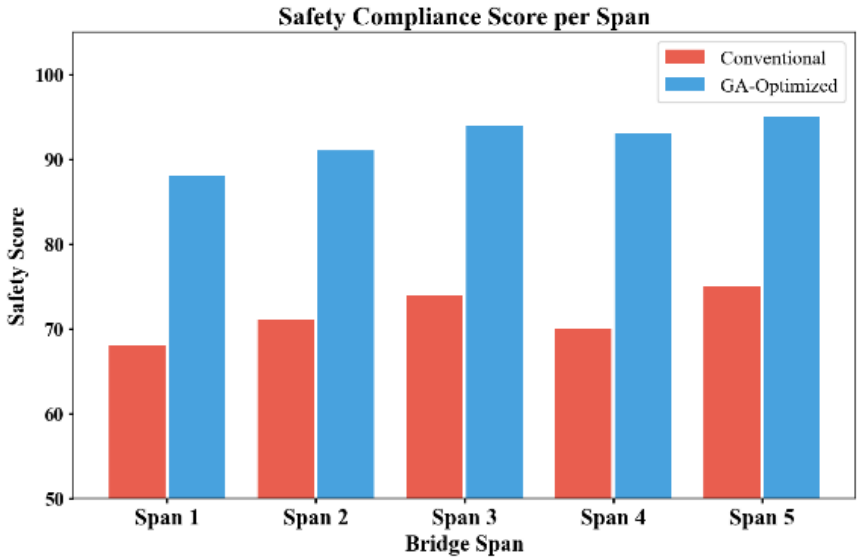


Fig. 13. Safety compliance score per span

Figure 13 shows the GA-based method improves safety compliance scores (88-95) by 15-20 points over the conventional method (68-75), demonstrating more reliable construction practices.

6.12 Optimized Erection Schedule and BIM-Based Visualization

The optimized erection schedule is obtained by transferring the sequence generated by the Genetic Algorithm (GA) into the construction planning environment and associating each optimized activity with its corresponding BIM object and scheduled time period. The GA determines the order of erection activities by evaluating construction time, cost, and traffic disruption while satisfying the defined precedence, crane-capacity, working-hour, and traffic constraints. The resulting sequence therefore represents the optimized planning output rather than an independent visualization result.

The BIM-integrated 4D environment subsequently provides the spatial and temporal representation of this optimized sequence. Each erection activity is linked to its corresponding bridge segment or construction component and positioned within its assigned start and completion period. The 4D simulation consequently visualizes the order in which the bridge components are erected and allows the optimized schedule to be examined in relation to the construction context. This establishes a direct correlation between algorithmic optimization and construction planning: the GA identifies the feasible sequence, the construction schedule assigns the optimized activities to time periods, and BIM-integrated 4D simulation visualizes the resulting sequence for schedule and constraint assessment. Thus, BIM visualization serves as the implementation and assessment layer for the optimized sequence, while GA provides the sequence-search and optimization mechanism.

6.13 Comparison Analysis

The proposed BIM-based 4D simulation and GA-optimization framework reveals a clear superiority in comparison to the others in the literature. For example, [20] were concentrated on BIM-based design optimization and structural safety evaluation, yet the herein proposed solution goes beyond design, combining construction scheduling, resource balancing and sequence optimization within a single framework. In the same vein, [4] introduced a conceptual framework of robotic construction technologies in Industry 4.0 with no practical results, while the current research offers a simulation-based, yet systematic and quantifiable approach towards construction performance. Regarding [27] The proposed method focuses on proactive planning, optimizing erection sequences, and integrating visualization, scheduling, and multi-objective decision-making to improve construction efficiency and reduce waste in urban environments.

The optimized erection sequence was checked against the adopted crane-capacity, permitted-working-hour, and traffic-restriction constraints before 4D simulation, ensuring that the visualized

construction schedule represented a feasible sequence under the specified urban construction conditions.

6.14 Discussion

The simulation-based results verify that the proposed BIM-based GA optimization model can effectively enhance the construction performance in terms of multiple performance indices. The proposed methodology concludes the total construction time as 149.40 hrs. as compared to 204.14 hrs. and the total construction cost as $174,795.23 as compared to $272,287.63 which signifies effective scheduling and resource allocation in simulated environment. Modelling results reveal a dramatic reduction in traffic disruptions from 489.95 to 179.28 (63.41%) units, demonstrating its power in minimizing urban impact for the adopted simulation setting. The performances of operational efficiency are improved with crane utilization from 72.40% to 91.80% and resource utilization efficiency from 68.00% to 88.50%. Safety compliance increases from 74.00 to 93.50 and schedule compliance from 78.50% to 96.20%, indicating more effective coordination. Furthermore, the decrease in the carbon emission index from 1.00 to 0.732 indicates of enhanced sustainability performance.

7. Conclusions

This paper proposes an integrated framework for optimizing the erection sequence planning of urban prefabricated bridges by combining Building Information Modeling (BIM), 4D simulation, and Genetic Algorithm (GA)-based optimization. The proposed approach addresses the challenges associated with planning bridge erection activities in complex and space-constrained urban environments, where construction operations must be carefully coordinated with traffic movement, available resources, site constraints, project duration, and construction costs. BIM provides a structured digital representation of the bridge components and construction activities, while 4D simulation integrates the temporal dimension with the three-dimensional construction model to visualize the planned erection sequence and identify potential activity conflicts.

The GA-based optimization component is employed to determine improved erection sequences by considering multiple construction objectives and practical constraints. These include construction efficiency, project duration, resource utilization, traffic disruption, equipment requirements, and overall construction cost. By integrating optimization with 4D simulation, the framework enables alternative erection strategies to be evaluated before their implementation at the construction site. This provides project planners with a decision-support mechanism for identifying feasible and efficient construction sequences while reducing potential scheduling conflicts and unnecessary resource consumption.

The results demonstrate that the optimized framework can improve the accuracy and reliability of erection planning compared with conventional planning approaches. The integration of BIM and 4D simulation facilitates better visualization and coordination of construction activities, allowing planners to identify spatial and temporal conflicts at an early stage. Meanwhile, GA-based optimization supports the systematic exploration of alternative erection sequences and provides solutions that satisfy real-world construction constraints. The framework also improves the interaction and coordination among construction activities, contributing to enhanced project performance in terms of scheduling, resource utilization, cost management, and traffic-related considerations. Furthermore, the proposed framework is designed to be flexible and scalable, allowing its application to different prefabricated bridge configurations and complex urban construction environments.

7.1 Limitations

- The study is entirely simulation-based and does not include real-world field validation, which may limit the direct applicability of results under actual construction conditions.
- The optimization framework accounts for a limited number of objectives, and it does not consider other real-world factors like weather, work variability, or unforeseen site uncertainties.

- The proposed framework is validated on a single case study, which may affect its generalizability across different bridge types, scales, and diverse urban environments.

7.2 Future Work

In the future, studies will focus on extending the proposed framework by means of incorporation of real-world construction data and enacting field validation to improve its practical significance and dependability. The model can be further enhanced by adding other dynamic elements, such as weather conditions, productivity changes of workers, machinery failure, and traffic data in real-time, so as to simulate more complex construction environments. The integration of other advanced techniques such as hybrid metaheuristic algorithms or machine learning based predictive models may result in improved quality of solution as well as convergence. In addition, future work could address the scalability to multi projects and the applicability in other types of infrastructure projects to increase the generalizability. Real-time monitoring system and digital twin technology can also be integrated to realize adaptive and autonomous construction planning for smarter and more sustainable infrastructure construction.

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