Optimizing construction project management via genetic algorithms – A state-of-the-art review

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Received:28 December 2023 ; Accepted: 15 January 2024

Abstract:

Construction projects involve complex trade-offs between conflicting objectives such as minimizing duration and costs while ensuring feasibility, safety, and quality. This paper reviews research on leveraging genetic algorithms (GAs)–adaptive bioinspired search techniques–to enhance decision-making in construction management spanning planning, scheduling, and control. The versatility of GAs in tackling combinatorial optimization problems is established through various applications optimizing workflows, resource allocation, and crew coordination for enhanced project performance. Empirical analyses validate GAs generating superior trade-off solutions regarding project timeline, budgetary compliance, profitability, and safety over conventional methods such as mathematical programming or regression. Challenges remain regarding further enhancing the solution quality and fine-tuning the GA parameters. Nonetheless, by efficiently exploring vast solution spaces, GAs enable the scientific translation of construction data into actionable insights for augmenting complex project decisions. Exciting innovation opportunities exist in synergistically hybridizing GAs with promising contemporaries, such as machine learning, simulation, and robotics. Collectively, the existing literature underscores GAs' immense and relatively untapped potential of GAs to develop next-generation AI-powered tools for optimizing construction productivity, cost efficiency, sustainability, and lean automation.

Keywords: Genetic algorithms; Construction project management; Project optimization.

1. Introduction

In the evolving landscape of construction project management, complexities arise from multifaceted challenges, such as cost overruns, schedule deviations, and maintaining high-quality standards. These challenges are not only persistent but also evolving with the scale and complexity of modern construction projects. This dynamic environment necessitates a paradigm shift in management strategies, prompting the search for more effective, adaptive, and innovative solutions.

Enter Genetic Algorithms (GAs), a beacon of hope in this complex scenario. According to the principles of natural selection and genetics, GAs are adaptive heuristic search algorithms that are particularly adept at solving complex optimization problems. In the realm of construction project management, GAs offer promising avenues for optimizing a wide range of processes, including but not limited to cost estimation, project planning, resource allocation, and scheduling. The ability of GAs to provide dynamic, efficient, and often novel solutions to complex problems makes them an invaluable tool in the arsenal of construction managers.

The objective of this review is to critically analyze and synthesize the current body of knowledge regarding the application of GAs in construction project management. This entails an exploration of how GAs have been employed to address various challenges in the field, the effectiveness of these applications, and their potential for future advancements in construction project management practices.

The scope of this review is broad, yet focused. It encompasses a wide range of applications of GAs in construction project management, but is particularly concentrated in areas where their impact has been most significant. These include project scheduling and planning, cost estimation and control, resource management, and risk analyses. Additionally, this review touches upon the adaptability of GAs to various types of construction projects, from small-scale residential buildings to large-scale infrastructure projects.

In terms of methodology, this review employed a systematic approach to literature collection and analysis. Studies were selected based on a set of predefined criteria aimed at ensuring relevance, quality, and comprehensiveness. The search encompassed multiple academic and professional databases, ensuring a broad and representative collection of seminal works in the field.

The structure of this paper is designed to provide readers with a comprehensive understanding of this subject. It begins with a theoretical background on GAs, exploring their origins, principles, and mechanisms. This was followed by an in-depth analysis of the applications of GAs in construction project management, highlighting case studies, comparative analyses with traditional methods, and discussions on the efficacy and limitations of these applications. The paper concludes with insights into future trends and potential areas of research for the application of GAs in construction project management.

2. Theoretical background of GAs

GAs are adaptive metaheuristic search methods inspired by Darwin's theory of natural evolution [1], [2]. They leverage evolutionary principles, such as reproduction, mutation, and selection, to arrive at optimal solutions for complex multidimensional problems. Just as genes evolve over generations to adapt, GA generates successive solutions, learns from them, refines the search process, and converges to near-global optimum outcomes.

The GA process involves randomly generating initial individuals and then applying genetic operators such as selection, crossover, and mutation to combine and alter parent individuals to produce offspring with higher fitness. Individuals with good fitness were retained to create the next generation. This is iterated until an optimal solution is found or the acceptable criteria are met.

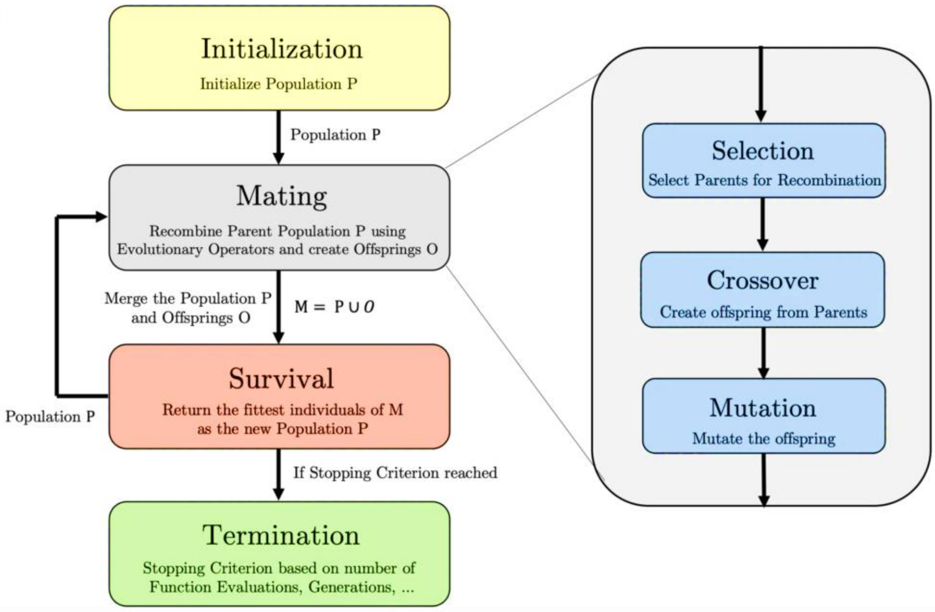

Figure 1. Principles of GA [3].

The iterative process of the GA (illustrated in Figure 1) is as follows:

- Initialization: The process starts by creating an initial population, P. This population consists of several individuals, which are potential solutions to the optimization problem.
- Mating: The individuals in the population P are recombined using evolutionary operators to create offspring O.
- Merge: The population P and offspring O are merged to form a new combined population M.
- Survival: From the combined population M, individuals are selected based on their fitness. The fittest individuals are chosen to form the new population P.
- Termination: The algorithm checks for a stopping criterion, which could be a certain number of generations reached, a satisfactory fitness level achieved, or the maximum number of function evaluations performed. If none of these criteria are met, the algorithm loops back to the mating step.
- Selection, Crossover, and Mutation (detailed on the right): These are the evolutionary operators mentioned in the mating step.
- Selection: Parents are selected from the population for recombination based on their fitness.
- Crossover: Combines the genetic information of the selected parents to create new offspring.
- Mutation: Random variations are introduced into the offspring, which provide genetic diversity and allow the algorithm to explore new parts of the solution space.

In construction project management, the application of GA has become increasingly popular, demonstrating its effectiveness in optimizing key factors such as time, cost, quality, and risk management.

3. Cost estimation

Cost estimation accuracy is vital for the success of any project. The current practice predominantly relies on the expertise of professionals. The utilization of computers becomes feasible with various statistical or machine learning methods, such as case-based reasoning, when historical data is available. GA enhances this process by enabling the creation of tools that ensure precise cost calculations for construction projects, thus augmenting the capabilities and accuracy of cost estimation procedures in a scientific context.

Kim et al. [4] selected eight input variables and applied three hybrid models of neural networks (NNs) and GAs projects built between 1997-2000. The models differ in determining the NN parameters by trial and error in Model I, by GA in Model II, and by training the NNs weights using GAs in Model III. The data were divided into training (80%), cross-validation (10%), and test (10%) sets. Training stops when the mean square error ceases to improve after 100 iterations. Model II was found to be the most effective.

Li et al. [5] propose integrating project selection and feature weighting with analogy-based estimation (ABE) to improve its accuracy. ABE suffers from skewed, outlier-ridden datasets and the exponential growth of historical data. Project selection refines the database into a small, representative subset, enhancing the quality and saving computation. Feature weighting assigns optimal relevance to the input metrics. Their framework combines these techniques. A GA searches for project subsets and feature weights that minimize the ABE error. The simultaneous optimization was tested as FWPSABE along with standalone versions. Extensive empirical analysis on real and artificial datasets shows that FWPSABE yields superior accuracy over ABE, feature-weighted ABE, machine learning models such as SVM, and manual project selection heuristics.

The integration of data point filtering and tailored feature tuning with case-based reasoning is the key insight that boosts ABE, a transparent but inaccurate estimation technique, to higher precision levels. This positions the optimized ABE as a simple yet robust methodology among complex modern approaches. This paper delivers an impactful data-driven solution to a critical software engineering problem: unreliable effort estimates. In summary, Li et al. successfully augmented a popular cost estimation method to better handle practical data issues, enhancing its viability. Their well-tested FWPSABE framework is a ready-to-apply tool for accurate real-world cost prediction using historical analogy.

To improve conceptual cost estimation accuracy, Cheng et al. [6] proposed the Evolutionary Fuzzy Neural Inference Model (EFNIM) combining GAs, fuzzy logic, and neural networks. GAs optimize the NN topology/weights and define the fuzzy membership functions. The two estimators produce overall and categorical costs from 10 inputs. However, only 23 training and five testing cases were used.

Jung et al. [7] present a novel model harnessing local search principles to boost case-based reasoning (CBR) analogical cost prediction. Their correlation-driven hybrid GA overcomes the blind randomness that limits the standalone GA search. Methodologically, they first computed inter-feature correlations in historical project data. The GA then evolves populations encoding CBR attribute weights while repeatedly assimilating these correlations via initialized genomes and iterative local searches. Relative correlations guide the descending feature priorities during evolutionary computations. By balancing exploitative local moves with exploratory GA mutations, poor local optima were avoided. Validated empirically on three building datasets, their optimized CBR framework reduces error rates by 3-6% over GA-CBR, uniform, and regression baselines, offering robust, accurate early benchmarks for bidding and planning. The model's integration of domain knowledge, combinatorial search, and automated machine learning provided an industry-ready toolbox for data-driven managerial decisions. Scientifically embedding explanatory local insights within a global randomized search successfully tackles the complexity in construction analogical reasoning. By interdisciplinarity synthesizing explanatory AI, Jung et al. enhanced automation, productivity, and asset usage. Their novel correlation-infused metaheuristic marks a valuable addition to the next-generation scientifically automated construction-estimation systems.

These studies collectively reflect a paradigm shift in construction project management, underlining the significant impact of GAs on enhancing cost estimation accuracy and reliability.

4. Project planning

In addition to being utilized in developing tools for cost estimation, GAs have been extensively applied in planning construction projects, as evidenced by multiple studies.

Yoo et al. [8] introduced the GARTS model to plan automated steel fabrication by robots in high-rise building construction. The model determines the optimal movement path for the bolting robot, schedules tasks, and estimates the steel erection duration. GARTS integrates GA, the line of balance method, and Monte Carlo simulation. It is applied to a 7-story pilot project using a robot-based construction automation (RCA) system. Compared to traditional methods, the results show that GARTS reduces the project duration of steel fabrication, while enhancing safety and decreasing the number of workers by approximately 30%.

Liu et al. [9] proposed a method combining SA (Simulated Annealing) and GA optimize the assembly sequence of prefabricated parts in construction. The evaluation criteria include the weight, quantity, interference constraints, and assembly time of the components. The comparative results for a residential project show that SA-GA has a better convergence speed and global search capability than traditional GA. Additionally, a mechanical simulation of the assembly process was performed to guide the actual construction. This study provides a potential solution towards automation in steel construction processes, contributing to improved productivity and efficiency in the construction industry.

Faghihi et al. [10] proposed a model that combines GA with 3D geometric information from BIM to automatically generate stable construction schedules. The algorithm reads 3D data, decodes stability rules into a connectivity matrix (DSM), and then GA optimizes schedules with the highest feasibility scores. The results of 21 different trials with various parameters and 3D models showed that the method always converged to the 100% feasibility objective. This demonstrates the effectiveness of the proposed model. This pioneering study exploits BIM data and GA to automatically generate schedules instead of simply optimizing existing ones. These highly promising results indicate great potential for application. Efficient construction site layout planning is fundamental for successful project execution, as it enhances productivity and safety on site. This task is a complex combinatorial optimization problem with multiple objectives that grows exponentially with increasing facilities and constraints.

Papadaki and Chassiakos [11] developed a multi-objective optimization model for the unequal area construction site layout problem, aiming to minimize transportation cost, construction cost of facilities, and safety concerns. The decision parameters include movement frequencies, distances, transportation costs, and construction costs. The model is solved by GAs owing to their capability to effectively search the vast solution space. Testing on benchmark cases showed that the proposed model provides cost-efficient and highly satisfactory solutions meeting the objectives and constraints.

Jang et al. [12] applied GAs to optimize the layout of construction materials at the floor level in high-rise building projects. They addressed the challenge of limited space at urban construction sites by developing a GA-based model. This model focuses on strategically positioning materials to minimize unnecessary movement and repositioning, thus enhancing efficiency. Their approach, validated through a case study, showed significant improvements in reducing material-handling distances, offering a robust solution for space management in dense urban construction environments.

In summary, the reviewed studies demonstrate the effectiveness of GAs in enhancing various aspects of construction project planning, from detailed scheduling and resource allocation to site layout optimization. By efficiently searching complex combinatorial spaces, GAs can inherently accommodate intricacies arising from constraints such as equipment capacities, safety requirements, and budget limits. The empirical results validate GAs' ability of GAs to automate planning decisions for productivity and efficiency improvements. As computing power continues to rise, substantial potential exists to further mature GA-based methodologies into next-generation integrated planning platforms. By incorporating real-time data analytics, simulations, and expert knowledge, such AI-powered systems could achieve leaner digital construction management via scientifically guided dynamic planning. Owing to their flexibility and scalability, genetic algorithms provide a crucial foundation for developing smart autonomous construction planning tools for the future.

5. Project scheduling

Scheduling is a crucial and complex task in construction project management. Projects often face multiple constraints regarding time, budget, and resources, as well as intricate relationships between activities. GA have emerged as an efficient optimization solution to handle this combinatorial challenge. In this section, we review the applications of GA in three main aspects of construction scheduling: resource-unconstrained scheduling, repetitive projects, and time-cost trade-off analysis. The simultaneous search capability of GAs has proven effective in tackling scheduling difficulties, resulting in superior schedules compared to conventional methods. This section provides an overview of the potential of GAs in automating and assisting construction scheduling decisions. By mimicking natural selection principles to efficiently explore vast solution spaces, GAs show great promise to enhance productivity, cost efficiency, and lean construction management through smarter automated scheduling.

5.1. Resource unconstrained scheduling

Liu et al. [13] address the emerging challenge of flexible scheduling for automated construction equipment in unstructured workzones. Such flexible earthwork scheduling problems (FESPs) require balancing mechanical capacities, automation techniques, and changing on-site constraints. Their key insight is the adaptation of the state-of-the-art multi-objective GA NSGA-III to handle the FESP complexity. Specifically, they modeled the Pareto-based tradeoffs between minimizing project duration, total equipment workload, and energy costs. Rigorously tested on a 22-equipment study, NSGA-III outperformed NSGA-II and SPEA in converging to diverse optimal schedule Pareto fronts. Further scrutiny across varied workloads and equipment counts validated the robustness of the model. The schedules balance assignments, timing, zonation, and sequences for uninterrupted and coordinated equipment workflow. The final analytic hierarchy processing selects single optimal schedules for field implementation via automation protocols. By scientifically integrating automation, optimization, and scheduling, Liu et al. demonstrated enhanced construction productivity and asset usage.

Their study delivered a significant, multifaceted decision support tool for streamlining real-world automated FESPs. In the broader context of GA-driven project scheduling, this work extends state-of-the-art multi-objective programming to automated, flexible construction environments. It expands evolutionary optimization capabilities to unconventional but increasingly pivotal scheduling domains.

5.2. Repetitive construction projects

Long and Ohsato [14] proposed a new GA-based method for scheduling repetitive construction projects with the objective of minimizing project duration, cost, or both. The method considers different activity types (allowing interruptions or not) and various cost-duration relationships (linear, non-linear, continuous, or discrete). Comparative results on examples show that the proposed method can provide good schedules while allowing the building of trade-off curves between project time and cost. This is an extension of previous methods that enhance the capability of planning repetitive construction projects. These promising results indicate a high potential for practical applications.

Huang et al. [15] developed an optimization model focused on workgroup-based repetitive scheduling was achieved, and this model was effectively solved through the use of a GA. The primary aim was to enhance the total net present value of the entire project. This was accomplished while ensuring adherence to the appropriate sequence of work across different workgroups, as well as maintaining a continuous flow in the utilization of resources. The model operates under the premise that each workgroup can be assigned work orders in a flexible manner. The structure of the model comprises chromosomes, each corresponding to the number of workgroups involved in a repetitive project. These chromosomes were further divided into segments, with each segment containing a pair of genes. These genes represent two critical aspects: the number of resources allocated, and the sequence number for each activity within a workgroup. The GA incorporates several key operators for its functionality, including external crossover, internal crossover, external mutation, internal mutation, and a roulette wheel selection process.

Essam et al. [16] developed a GA based optimization model for workgroup-based repetitive project scheduling. The model seeks to maximize the net present value (NPV) of the project while meeting work sequence constraints between workgroups and maintaining resource continuity. The work-group-based scheduling approach provides more flexibility in handling complex repetitive scheduling problems. It allows the use of multiple resources and different work order assignments for activities within workgroups. The GA-based optimization model supplements the scheduling method by enabling near-optimal solutions for repetitive project scheduling. The goal is to maximize project NPV, calculated from discounted cash inflows and outflows over the project lifecycle.

5.3. Time-cost tradeoff analysis

A time-cost tradeoff model using GA was developed by Sharma and Tiwari [17] to complete construction projects on time and at the lowest cost possible. The results from this model showcase the proficiency of GA in finding the best tradeoff between time and cost factors in project management.

Mungle et al. [18] proposed a multi-objective optimization model and FCGA algorithm to solve the complex time-cost-quality tradeoff problem in construction project management. The conflicting objectives are to minimize project time and cost and maximize quality. The FCGA integrates several established techniques such as NSGA-II, elite solution archive, fuzzy clustering, and fuzzy decision making to find the optimal Pareto set. The testing results on benchmark datasets showed that FCGA has superior performance over other algorithms. The study by Mungle et al. has demonstrated the great potential of GAs in effectively solving complex time-cost-quality tradeoff problems in project management. Further studies on more realistic and large-scale projects are warranted to validate the practicality of this approach. The study demonstrates the great potential of GAs in effectively tackling complex, multi-objective construction site layout planning problems. Further research is warranted to address more realistic layout issues.

Leu and Yang [19] present an integrated GA based framework that concurrently optimizes construction scheduling for time-cost tradeoffs, resource constraints and resource leveling. Previous analytical or heuristic approaches have focused largely on single objectives and have faced computational challenges in handling larger, multi-objective problems. The GA approach offers flexibility in modeling complex scheduling scenarios and efficiency in near-optimal solution searches. The integrated model is novel in unifying the time-cost tradeoff, resource allocation, and unlimited resource leveling problems that construction managers routinely encounter but cannot address holistically via existing methods. By generating non-dominated solutions and employing multi-criteria ranking, the model provides project decision-makers with valuable tradeoff information that is not available through conventional scheduling tools. The range of test cases validates the approach over problems involving up to nine activities and three resource types.

Ali et al. [20] address the critical real-world issue of resource constraints in discrete time-cost tradeoff optimization for project scheduling. They formulated a multi-mode model allowing alternate construction approaches, with differing resource needs and indirect cost dependencies, for each activity. A multi-objective GA using adjusted fuzzy dominance is proposed for concurrent cost, time, and resource optimization. Experiments on small and large test cases demonstrate the method's effectiveness in searching the Pareto frontier compared with leading algorithms. This study enhances the pragmatic applicability of scheduling solutions by incorporating key project complexities.

Afruzi et al. [21] present an innovative approach to solving the multi-mode resource-constrained discrete time-cost tradeoff problem in project scheduling. The authors introduce an “Adjusted Fuzzy Dominance GA” (AFDGA) to tackle the complexities of this problem. This paper is methodical in explaining the development and application of the AFDGA, providing a detailed mathematical model and a comprehensive algorithmic structure. The effectiveness of the AFDGA is demonstrated through a comparative analysis with four other well-known algorithms, showing its efficiency in both small- and large-scale problems. This study stands out for its thorough exploration of GAs in project management and provides a significant contribution to the field of operations research and project scheduling.

Hua et al. [22] propose an improved GA incorporating time window decomposition and novel strategies to solve the resource-constrained project scheduling problem (RCPSP). The RCPSP is computationally challenging, and metaheuristics offer a practical approach for large problem instances. Key contributions of this study include a new double-chain chromosome representation encoding the earliest and latest finish times, an extended serial schedule generation scheme respecting subsequential time windows, and three derivation methods to improve search diversity. Experiments on standard PSPLIB benchmarks demonstrated superior performance over the algorithm without added strategies. The approach also reliably solved two real-life construction cases, obtaining 100% success rates in finding optimal solutions. By continuously changing and narrowing the subspaces, the proposed technique offers promise in tackling RCPSP variants. The analysis of scheduling information provides insights into allocating computational efforts more effectively. Overall, the introduced improvements advance the search capability of evolutionary algorithms for addressing complex project scheduling optimization.

The development of MOSCOPEAs by El-Abbasy et al. [23] represents a significant leap in construction project management. This system, underpinned by the NSGA-II algorithm, excels in harmonizing various project objectives, such as cost efficiency, schedule optimization, and resource allocation. Unlike conventional models, MOSCOPEA demonstrates an enhanced capability to handle the complex, multidimensional scheduling challenges inherent in construction projects. Its rigorous testing reveals its robustness and superiority in optimizing construction schedules, setting a new benchmark in the field, and paving the way for more efficient project management methodologies.

5.4. Resource allocation

Liu et al. [24] propose an innovative late-mover GA (LMGA) for solving the resource-constrained project scheduling problem (RCPSP). The key novelty lies in incorporating a “1+1” evolution strategy within the GA framework, which requires only a single population member and eliminates the need for separate mutation steps. Additionally, the algorithm uses path representations and real-valued chromosomes, avoiding priority rules for schedule generation. Experiments on standard PSPLIB benchmarks demonstrated the method’s effectiveness and consistency across small-to-large test cases. Compared with state-of-the-art metaheuristics, LMGA achieves competitive solution quality and instance coverage without extensive parameter tuning. While further enhancing search capability remains a challenge, the simplicity, ease of use, and elimination of parameter dependencies suggest LMGA's promise as an alternative RCPSP solver. By limiting algorithm complexity, this study enhances the accessibility of optimization for practical project scheduling applications.

Bredael and Vanhoucke [25] proposed a novel GA incorporating resource-buffered scheduling strategies for solving the resource-constrained multi-project scheduling problem (RCMPSP). The RCMPSP remains an active area of study, given its complexity and NP-hard nature. Exact methods face computational challenges for realistically sized instances. Although metaheuristics demonstrate effectiveness, their relative performances vary across objectives and problem characteristics. The key distinction of the proposed approach lies in imposing artificial resource restrictions on projects to improve their utilization efficiency and distribute workloads more evenly. The algorithm integrates the most effective evolutionary operators from the literature and outperforms prior metaheuristics for ~20% of the test instances. In addition to demonstrating benchmark results across objectives and due dates, this study also offers insights through a new metric quantifying the project prioritization level of schedules. The proposed algorithm and analyses contribute to a better understanding of how to address complex project scheduling scenarios.

6. Comparative Analysis GA vs traditional optimization

To demonstrate the competitive advantages offered by GA, a comparative analysis against prevalent conventional optimization methods for infrastructure project management is presented below:

Complexity handling: Traditional mathematical models have limited scalability. GA inherently handles problem complexity through evolutionary learning across generations. This enables the optimization of real-world scale public projects with thousands of dynamic interacting variables [26].

Global optimization: Traditional techniques are often trapped in local optima. GA avoids suboptimal convergence through mutation-driven innovation and maintains a parallel set of solutions with crossover breeding. This focuses the search towards finding globally best configurations [20].

Flexibility: Conventional optimization relies on rigid mathematical assumptions that seldom hold perfectly in practice. GA’s metaheuristic approach provides the flexibility to adapt the solution methodology for any problem condition or constraint [27].

Combinatorial spaces: Problems with vast permutations of parameters, such as infrastructure design and contractor bid evaluation, quickly become infeasible using exact methods owing to exploding solution search spaces. GA is designed to effectively traverse huge combinatorial possibilities [28].

Hybrid models: Mathematical modeling limitations, such as linearity or derivability constraints, mean that conventional methods cannot incorporate real-world complexities. GA's operability of GA with any analytical, statistical, or computational model facilitates the development of hybrid problem-specific optimizations [29].

Black box integration: Many real-world phenomena relevant to construction projects may be too intricate to model mathematically. GA allows seamlessly integrating empirical data or proprietary predictive 'black box' modules into the end-to-end solution methodology [30].

Automation enablement: Conventional optimization is tailored for specific problems. Automating optimization workflows requires parameterizing the methodology components. GA's inherently parameterized architecture enables the configuration of automated flows [31].

In summary, GA provides a versatile, scalable, and integrative optimization technology well suited for unleashing the full potential of emerging digital transformation initiatives for managing construction projects. Investments in further maturing this technology combined with adopting GA-driven intelligent project management promises significant future improvements across public sector infrastructure quality, budgetary, and social outcomes over prevailing approaches.

7. Conclusion and Discussion

7.1. Conclusion

This paper presented a comprehensive review on leveraging GAs to optimize key aspects of construction project management, spanning cost estimation, planning, scheduling, and resource allocation, among others. The versatility of GAs enables addressing numerous project complexities such as extended timelines, budget constraints, resource limitations, and complex interdependencies. By efficiently exploring vast combinatorial search spaces, GAs facilitate superior solutions over conventional optimization methods regarding minimizing time and costs while maximizing feasibility, quality, and profitability trade-offs. Case studies and empirical results validated GAs' effectiveness of GAs across small-to large-scale construction projects of varying types, such as buildings, highways, and factories. GAs consistently demonstrate capabilities to automate and enhance planning, scheduling, and control, transforming construction management to be proactive rather than reactive.

7.2. Discussion

Challenges remain regarding further enhancing solution quality, balancing computational expense, and calibrating GA components such as population size, crossover, and mutation rates for problem-specific convergence. Nonetheless, GAs have cemented themselves as an established and indispensable technique for leveraging construction data. The comprehensive technical advances and success stories covered in this review underscore ample headroom to push construction optimization frontiers using GAs. Exciting innovation opportunities abound in exploring synergistic GA hybridization with promising contemporaries, such as deep reinforcement learning, digital twins, robotics, and virtual prototyping. By scientifically embedding project complexities within biomimetic search, GA-based decision support systems can transform scattered construction data into actionable insights, bringing augmented intelligence for construction projects closer to reality. Overall, GAs provide a versatile technological foundation for developing the next generation of AI-powered tools to optimize construction management efficiency to unprecedented levels.

References

[1] A. Ashkzari and A. Azizi, "Introducing Genetic Algorithm as an Intelligent Optimization Technique," *Appl. Mech. Mater.*,

vol. 568–570, pp. 793–797, 2014, doi: 10.4028/www.scientific.net/AMM.568-570.793.

[2] C. A. Murthy, "Genetic Algorithms: Basic principles and applications," 2012 2nd Nat.vConf. Comput. Intell. Sig. Process. (CISP), Guwahati, India, 2012, pp. 22-22, doi: 10.1109/NCCISP.2012.6189670.

[3] J. Blank, "An Introduction to Genetic Algorithms: The Concept of Biological Evolution in Optimization," Towards Data Science, Aug. 2020. [Online]. Available: https://towardsdatascience.com/an-introduction-to-genetic-algorithms-the-concept-of-biological-evolution-in-optimization-fc96e78fa6db.

[4] G. H. Kim, D. S. Seo, and K. I. Kang, "Hybrid models of neural networks and genetic algorithms for predicting preliminary cost estimates," *J. Comput. Civ. Eng.*, vol. 19, no. 2, pp. 208–211, Apr. 2005, doi: 10.1061/(ASCE)0887-3801(2005)19:2(208).

[5] Y. F. Li, M. Xie, and T. N. Goh, "A study of project selection and feature weighting for analogy based software cost estimation," *J. Syst. Softw.*, vol. 82, no. 2, pp. 241–252, Feb. 2009, doi: 10.1016/j.jss.2008.06.001.

[6] M. -Y. Cheng, H. -C. Tsai, and W.-S. Hsieh, "Web-based conceptual cost estimates for construction projects using evolutionary fuzzy neural inference model," *Autom. Constr.*, vol. 18, no. 2, pp. 164–172, Mar. 2009, doi: 10.1016/j.autcon.2008.07.001.

[7] S. Jung, J. -H. Pyeon, H. -S. Lee, M. Park, I. Yoon, and J. Rho, "Construction Cost estimation using a case-based reasoning hybrid genetic algorithm based on local search method," *Sustainability*, vol. 12, no. 19, Sep. 2020, Art. no. 7920, doi: 10.3390/su12197920.

[8] W. S. Yoo, H. -J. Lee, D. -I. Kim, K. -I. Kang, and H. Cho, "Genetic algorithm-based steel erection planning model for a construction automation system," *Autom. Constr.*, vol. 24, pp. 30–39, Jul. 2012, doi: 10.1016/j.autcon.2012.02.007.

[9] C. Liu, F. Zhang, H. Zhang, Z. Shi, and H. Zhu, "Optimization of assembly sequence of building components based on simulated annealing genetic algorithm," *Alex. Eng. J.*, vol. 62, pp. 257–268, Jan. 2023, doi: 10.1016/j.aej.2022.07.025.

[10] V. Faghihi, K. F. Reinschmidt, and J. H. Kang, "Construction scheduling using genetic algorithm based on building information model," *Expert Syst. Appl.*, vol. 41, no. 16, pp. 7565–7578, Nov. 2014, doi: 10.1016/j.eswa.2014.05.047.

[11] I. N. Papadaki and A. P. Chassiakos, "Multi-objective construction site layout planning using genetic algorithms," *Procedia Eng.*, vol. 164, pp. 20–27, 2016, doi: 10.1016/j.proeng.2016.11.587.

[12] H. Jang, S. Lee, and S. Choi, "Optimization of floor-level construction material layout using genetic algorithms," *Autom. Constr.*, vol. 16, no. 4, pp. 531–545, Jul. 2007, doi: 10.1016/j.autcon.2006.09.006.

[13] Y. Liu et al., "Multi-objective optimal scheduling of automated construction equipment using non-dominated sorting genetic algorithm (NSGA-III)," *Autom. Constr.*, vol. 143, p. 104587, Nov. 2022, doi: 10.1016/j.autcon.2022.104587.

[14] L. D. Long and A. Ohsato, "A genetic algorithm-based method for scheduling repetitive construction projects," *Autom. Constr.*, vol. 18, no. 4, pp. 499–511, Jul. 2009, doi: 10.1016/j.autcon.2008.11.005.

[15] R. Huang and K. -S. Sun, "A GA optimization model for workgroup-based repetitive scheduling (WoRSM)," *Adv. Eng. Softw.*, vol. 40, no. 3, pp. 212–228, Mar. 2009, doi: 10.1016/j.advengsoft.2008.01.010.

[16] N. Essam, L. Khodeir, and F. Fathy, "Approaches for BIM-based multi-objective optimization in construction scheduling," *Ain Shams Eng. J.*, vol. 14, no. 6, p. 102114, Jun. 2023, doi: 10.1016/j.asej.2023.102114.

[17] D. Sharma and S. Tiwari, "Genetic Algorithm Based Optimization Model for Time-Cost Trade-Off for Construction Project," *Int. J.*

Res. Appl. Sci. Eng. Technol., vol. 11, no. 1, pp. 565–574, Jan. 2023, doi: 10.22214/ijraset.2023.48621.

[18] S. Mungle, L. Benyoucef, Y.-J. Son, and M. K. Tiwari, "A fuzzy clustering-based genetic algorithm approach for time–cost–quality trade-off problems: A case study of highway construction project," *Eng. Appl. Artif. Intell.*, vol. 26, no. 8, pp. 1953–1966, Sep. 2013, doi: 10.1016/j.engappai.2013.05.006.

[19] S.-S. Leu and C.-H. Yang, "GA-Based Multicriteria Optimal Model for Construction Scheduling," *J. Constr. Eng. Manag.*, vol. 125, no. 6, pp. 420–427, Dec. 1999, doi: 10.1061/(ASCE)0733-9364(1999)125:6(420).

[20] K. M. Ali, M. H. Kotb, and A. S. Saleh, "Optimizing the Schedule of Resource - Constrained Construction Projects using Genetic Algorithms," *J. Environ. Sci.*, vol. 47, no. 3, pp. 17–29, Sep. 2019, doi: 10.21608/jes.2019.130000.

[21] E. Nabipoor Afruzi, E. Roghanian, A. A. Najafi, and M. Mazinani, "A multi-mode resource-constrained discrete time–cost tradeoff problem solving using an adjusted fuzzy dominance genetic algorithm," *Sci. Iran.*, p. S1026309812003070, Jan. 2013, doi: 10.1016/j.scient.2012.12.024.

[22] Z. Hua, Z. Liu, L. Yang, and L. Yang, "Improved genetic algorithm based on time windows decomposition for solving resource-constrained project scheduling problem," *Autom. Constr.*, vol. 142, Oct. 2022, Art. no. 104503, doi: 10.1016/j.autcon.2022.104503.

[23] M. S. El-Abbasy, A. Elazouni, and T. Zayed, "MOSCOPEA: Multi-objective construction scheduling optimization using elitist non-dominated sorting genetic algorithm," *Autom. Constr.*, vol. 71, pp. 153–170, Nov. 2016, doi: 10.1016/j.autcon.2016.08.038.

[24] Y. Liu, L. Huang, X. Liu, G. Ji, X. Cheng, and E. Onstein, "A late-mover genetic algorithm for resource-constrained project-scheduling problems," *Inf. Sci.*, vol. 642, p. 119164, Sep. 2023, doi: 10.1016/j.ins.2023.119164.

[25] D. Bredael and M. Vanhoucke, "A genetic algorithm with resource buffers for the resource-constrained multi-project scheduling problem," *Eur. J. Oper. Res.*, p. S0377221723008482, Nov. 2023, doi: 10.1016/j.ejor.2023.11.009.

[26] Y. Duan, K. Zhou, W. Dong, and Q. Fu, "Improved genetic algorithm to optimization pattern in traffic network layout problem," in *Bio-Inspired Computing - Theories and Applications*, M. Gong, P. Linqiang, S. Tao, K. Tang, and X. Zhang, Eds., Berlin, Heidelberg: Springer, 2015, pp. 138–149.

[27] S. Bourhnane et al., "A parallelized genetic algorithms approach to community energy systems planning," in *2022 14th Int.Conf. on Comput. Intell. Commun. Netw. (CICN)*, Dec. 2022, pp. 266–272, doi: 10.1109/CICN56167.2022.10008362.

[28] G. Gui, H. Pan, Z. Lin, Y. Li, and Z. Yuan, "Data-driven support vector machine with optimization techniques for structural health monitoring and damage detection," *KSCE J. Civ. Eng.*, vol. 21, no. 2, pp. 523–534, Feb. 2017, doi: 10.1007/s12205-017-1518-5.

[29] M. Marzouk, S. Azab, and M. Metawie, "BIM-based approach for optimizing life cycle costs of sustainable buildings," *J. Clean. Prod.*, vol. 188, pp. 217–226, Jul. 2018, doi: 10.1016/j.jclepro.2018.03.280.

[30] A. Kumar, S. Jain, and D. Yadav, "A novel simulation-annealing enabled ranking and scaling statistical simulation constrained optimization algorithm for Internet-of-things (IoTs)," *Smart Sustain. Built Environ.*, vol. 9, no. 4, pp. 675–693, Jan. 2020, doi: 10.1108/SASBE-06-2019-0073.

[31] C. Akcay and S. Işikyildiz, "Multi-objective optimization of time-cost-quality in construction projects using genetic algorithm," *Rev. Constr. J. Constr.*, vol. 19, no. 3, pp. 335–346, Dec. 2020, doi: 10.7764/rdlc.19.3.335-346.