Data Engineering and Applications

Review Paper

Towards Data-Enabled Intelligent Road Construction: A Review of Hybrid Algorithms and Applications

Stencel Krzysztof[1,*], Joanna Baran[2]

[1] Faculty of Computer Science and Information Technology, Wrocaw University of Science and Technology, Wrocaw 50-370, Poland
[2] Faculty of Electronics and Information Technology, Silesian University of Technology, Gliwice 44-100, Poland
*Corresponding author: s.krzysztof@wpias.edu.pl

Abstract. Contemporary road building projects are becoming increasingly complex, requiring advanced project management solutions to address challenges such as risk management, resource optimization, Adaptive scheduling, and real-time decision-making. Traditional deterministic methods are difficult to adapt to the complex constraints and uncertainties of large infrastructure projects. To achieve this goal, hybrid algorithms—including machine learning, meta-heuristic algorithms, and simulation-based optimization techniques—have emerged as a key method in intelligent road construction management. This paper provides a detailed discussion of the theoretical foundations, classification, and practical applications of hybrid computational intelligence models. Through research in key areas such as quality control, resource allocation, project scheduling, and real-time monitoring, this paper highlights the significant advantages of hybrid frameworks in terms of adaptability, efficiency, and robustness. Based on comparative studies and benchmarking, hybrid algorithms demonstrate outstanding performance in addressing uncertainty, improving resource utilization, and reducing overall project duration. Despite these developments, issues such as data quality, model generalization capabilities, interoperability with intelligent construction platforms, and consistency in benchmarking practices remain to be addressed. This review concludes that hybrid algorithms form the foundation for the digital transformation of road construction management. Continued efforts to standardize data, innovate methods, and achieve seamless integration between intelligent algorithms and evolving construction technologies will determine future development. The research findings provide valuable insights for researchers and practitioners dedicated to designing more efficient, adaptive, and resilient modern road construction project management solutions.

Keywords: *Computer intelligence, Data-Driven Engineering, Hybrid algorithms, Road construction management, Resource optimization, Project scheduling*

Received on 12 September 2024, Accepted on 2 November 2024, Published on 6 November 2024

Introduction

As the scale and complexity of modern road construction continue to increase, project management is facing unprecedented challenges. In critical areas such as risk management, dynamic decision-making, resource allocation, and schedule coordination, traditional static management models based on deterministic assumptions are no longer sufficient to address the widespread uncertainty and dynamic changes inherent throughout the project lifecycle [1]. Especially in the current industry context where quality control standards are becoming stricter, green construction requirements are increasing, and production efficiency urgently needs to be improved, the limitations of traditional methods are becoming increasingly evident. In recent years, computational intelligence technology has been rapidly penetrating the construction management field. The system provides an innovative solution for constructing more dynamically adaptive management strategies by integrating meta-heuristic algorithms, machine learning, and mathematical optimization models into a hybrid

DOI:

algorithm system [2]. It also effectively addresses the shortcomings of traditional methods in handling complex problems.

Hybrid algorithms can solve important problems in intelligent road construction and management, such as risk assessment, multi-objective optimization, project scheduling, and resource allocation [3]. Research shows that hybrid algorithms are more scalable, higher quality, and more robust than single methods [4]. Hybrid models such as data-driven optimization frameworks, multi-agent systems, and the integration of meta-heuristic algorithms and machine learning have shown outstanding performance in dealing with the complexity management of road construction projects. Although the relevant research has made phased progress, there are still obvious gaps in the generalization ability, interpretability and benchmark testing practice of the model, which also highlights the importance of carrying out a comprehensive analysis of the current research progress and continuous challenges [5].

This paper reviews the application of hybrid algorithms in intelligent road construction management, with a focus on the application of computational intelligence methods in solving key management issues. This study clarifies the current state of research by analyzing various hybrid models and evaluating their performance, and points out the path for future research and progress. Its goal is to provide researchers and practitioners with an authoritative reference for designing more efficient, adaptive, and intelligent management solutions to meet the ever-changing requirements of road construction projects.

Theoretical Foundations

Intelligent road construction management relies on hybrid algorithms. It connects computational theory with engineering practice. The integration of multiple computational paradigms forms the theoretical basis of these algorithms. These computational paradigms offer the ability to solve problems. to address the inherent complexity of construction projects.

Hybrid Algorithms: Concepts and Classification

Genetic algorithms; neural networks; ant colony optimization; fuzzy logic systems; and other computational intelligence methods form the basis of hybrid algorithms. The limitations of single-algorithm approaches, particularly in balancing convergence speed, solution diversity, and robustness across different application scenarios, underpin the principles of hybrid algorithms [6]. Research indicates that combining meta-heuristic algorithms with data-driven models can improve project scheduling and resource optimization tasks, as these hybrid systems can dynamically adjust constraints and heterogeneous objectives [7]. In the field of construction management, hybrid algorithms can be classified based on their integration level and depth. These classifications include loosely coupled systems and tightly coupled systems, sequential frameworks and parallel frameworks, as well as knowledge-based architectures and data-driven architectures. Table 1 categorizes road construction hybrid algorithms and lists their structural characteristics and main application areas.

Table 1. Classification of Hybrid Algorithms in Road Construction Management

Hybridization Type	Constituent Methods	Integration Mode	Application Domain	Key References
Metaheuristic-ML	Genetic algorithms （GA）+ANN PSO+SVM	Parallel Sequential	Scheduling, Cost Estimation	[6,7]
Metaheuristic-Fuzzy	GA + Fuzzy Logic ACO +Fuzzy	Embedded	Resource Allocation, Risk Analysis	[8]
Simulation-Optimization	DES +GA Monte Carlo + PSO	Loosely Coupled	Time-Cost Tradeoff, Logistics	[9]
Multi-Agent Systems	MAS + Evolutionary Algorithms	Distributed	Collaborative Planning	[10]

Computational Intelligence Techniques in Construction

Computational intelligence has completely transformed the way construction projects are managed. In road construction projects, genetic algorithms (GA), particle swarm optimization (PSO), and neural networks (NN) have demonstrated outstanding performance, achieving significant results in addressing common NP-hard problems such as cost optimization, resource balancing, and scheduling [8]. Specifically, PSO can converge quickly in multi-dimensional optimization scenarios, which is one of its major advantages; GA has adaptive search capabilities, which can help efficiently explore large solution spaces. As for neural networks, typical models such as self-organizing maps and multilayer perceptron's are often used for prediction modeling and classification tasks, and cost estimation and quality assessment work cannot do without their support [9]. Fuzzy logic systems provide a reliable foundation for addressing common data and language uncertainties in construction environments. Table 2 lists the primary computational intelligence methods used in road construction management, highlighting their advantages and typical application scenarios.

Table 2. Computational Intelligence Technologies in Road Construction

Method	Theoretical Basis	Application Area	Strengths	Limitation	Key References
Genetic Algorithm	Computation via evolution	Scheduling, Resource	Global search, Flexibility	Premature Convergence	[8]
PSO	Swarm Intelligence	Cost Optimization	Fast Convergence	Local Optima Risk	[9]
Neural Networks	Connectionist Models	Prediction Classification	Nonlinear Mapping	Interpretability	[10]
Fuzzy Logic	Approximate Reasoning	Risk Analysis, Quality	Uncertainty Handling	Rule Design	[11]

Key Challenges in Road Construction Management

The application of hybrid algorithms in road construction management faces numerous complex challenges. The decision-making space for road construction projects is multidimensional, resource supply is highly random, and various project constraints interact with one another. This requires algorithms to maintain stability in uncertain environments and respond swiftly to dynamic changes [10]. The widespread adoption of algorithms in real-world engineering operational environments is still hindered by challenges related to computational efficiency, scalability, and model interpretability [11]. Additionally, data heterogeneity hinders the full realization of hybrid algorithms' potential. To achieve deep integration of diverse data types—from structured sensor real-time data to unstructured expert judgment—efficient integration mechanisms are required. On the other hand, the absence of standardized benchmarking protocols makes it challenging to conduct unified, objective evaluations of algorithm performance. This not only increases the variability in contrasting several studies outcomes but also complicates the effective application of algorithms in real-world engineering scenarios.

Hybrid Algorithm Types and Features

A comprehensive review of published research reveals significant trends in hybrid algorithm design and application. Comprehensive frameworks that combine meta-heuristic algorithms with machine learning or fuzzy systems are consistently more stable and adaptive than single models [12]. Table 1 and Table 2 demonstrate the structural and functional diversity of these algorithms, highlighting the breadth of innovation in this field. The domain focuses on modular and data-driven architectures while emphasizing interpretable results and operational reliability.

Application scope in the field of intelligent road construction

Using the program of hybrid algorithms, significant progress has been made in intelligent road construction management. These computational frameworks have redefined the boundaries of quality control, project scheduling, resource allocation, and real-time decision support, providing powerful solutions to previously intractable problems. In-depth research in these areas has demonstrated that the methodology of combining computational intelligence with domain-specific expertise is both innovative and practical.

Project Scheduling and Optimization

Hybrid algorithms offer a new approach to project scheduling and optimization for road construction projects. By combining metaheuristic algorithms and machine learning models, multiple scheduling schemes can be studied simultaneously while dynamically adjusting to changes in project constraints. Under conditions of uncertainty, the ant colony optimization-fuzzy logic framework, particle swarm optimization-support vector machine system, and genetic algorithm-neural network hybrid model all demonstrate high robustness and scheduling efficiency [13]. These hybrid systems address multi-objective trade-offs, including time-cost minimization, resource leveling, and robustness against stochastic disruptions, which are critical in large-scale infrastructure projects [14]. Table 3 summarizes prevalent hybrid algorithmic frameworks, mapping their technical structure to specialized scheduling scenarios.

Table 3. Road Construction Management Application Scenarios and Typical Hybrid Algorithms

Application Scenario	Representative Hybrid Algorithms	Key Functionalities	References
Multi-objective scheduling	GA +ANN PSO+SVM	Time-Cost Optimization	[13,14]
Stochastic project networks	ACO+Fuzzy Logic	Robustness under Uncertainty	[15]
Resource-constrained planning	GA+Fuzzy	Resource Leveling	[16]

Case Studies

Empirical studies confirm the efficacy of hybrid frameworks in real-world scheduling environments. Execution of Genetic Algorithm–Neural Network systems in highway construction projects has resulted in marked reductions in project duration and enhanced adaptability to variable resource availability [13]. According to the analysis of project results, the adaptive search and learning included in these hybrid models improved project progress efficiency and reduced deviation from the baseline plan.

Comparative Analysis

A comparative evaluation of the performance differences between hybrid algorithms and single algorithms was conducted. The particle swarm optimization and support vector machine (PSO-SVM) algorithm is more suitable than traditional meta-heuristic algorithms for handling high-dimensional constraint spaces and dynamic project updates [14]. The ant colony optimization with fuzzy logic (ACO-FL) system is more effective than deterministic scheduling models in addressing resource supply fluctuations and environmental uncertainties. It also exhibits higher computational efficiency and robustness [15]. Table 4 presents the quantitative benchmarking results, demonstrating the hybrid algorithm's advantages in key scheduling performance metrics.

Table 4. Comparative Performance of Hybrid Algorithms on Scheduling and Optimization Tasks

Algorithm Type	Scheduling Accuracy	Adaptability	Computational Efficiency	References
GA ,ANN	High	Strong	Moderate	[13]
PSO ,SVM	Very High	Excellent	High	[14]
ACO ,Fuzzy Logic	High	Very Strong	High	[15]
Standalone Metaheuristic	Moderate	Moderate	High	[16]
Deterministic Model	Low	Weak	Very High	[17]

Resource Allocation and Logistics

Hybrid models have changed resource allocation and logistics management in road construction. They introduce computational strategies capable of optimizing resource flows under conditions of uncertainty. Multi-agent systems incorporating evolutionary algorithms can manage dispersed resource pools and dynamically adjust project requirements [18]. An optimization framework based on fuzzy logic can improve the efficiency of labor, machinery, and material resource allocation while integrating qualitative judgments and incomplete information. Research indicates that hybrid methods outperform traditional deterministic models in reducing resource idleness, addressing operational issues, and enhancing resource utilization across project phases [19].

Quality Control and Risk Management

The application of computational intelligence is critical for quality control and hybrid risk management, especially in situations with high variability and incomplete information. Models based on neural networks and fuzzy logic can assess construction quality indicators in real time, enabling the early detection of non-conforming or erroneous projects [20]. Probabilistic risk assessment uses simulation models and genetic algorithms to mitigate the impact of material performance and environmental uncertainties on projects. Research indicates that integrating these systems enables more accurate risk predictions and supports proactive risk mitigation methods, thereby enhancing project reliability [21].

Real-time Monitoring and Decision Support

The real-time monitoring and decision support system for road construction uses hybrid algorithms to integrate heterogeneous data streams to enable timely intervention measures based on information. By combining sensor data analysis and machine learning-meta heuristic hybrid algorithms, it is possible to support continuous assessment of project status and anomaly detection [19]. Multi-agent optimization frameworks facilitate decentralized decision-making by distributing control authority to project nodes, enhancing the ability to address new issues. According to empirical research, such systems can improve intervention accuracy, reduce information latency, and support adaptive project control, thereby elevating the standards of intelligent construction management [22].

Classification and Comparative Analysis of Hybrid Models

In intelligent road construction management, hybrid models are a combination of algorithmic paradigms, each optimized for performance bottlenecks in complex project environments. By conducting a critical classification analysis of these hybrid frameworks, it is possible to identify their methodological innovations, operational trade-offs, and experiential advantages. This demonstrates how they are still evolving as essential computational tools for construction management.

Metaheuristic-Machine Learning Hybrids

A hybrid model combining machine learning and heuristic algorithms, utilizing global search heuristic algorithms and data-driven pattern recognition techniques to improve the quality of solutions in areas such as predictive analytics, resource optimization, and scheduling. By leveraging the global exploration capabilities of evolutionary strategies and the nonlinear mapping advantages of neural network architectures, the genetic algorithm–artificial neural network (GA–ANN) hybrid model demonstrates outstanding performance in high-dimensional scheduling and cost estimation tasks [23]. The particle swarm optimization–support vector machine (PSO–SVM) framework is highly adaptable to dynamic constraint environments. Empirical studies indicate that the PSO-SVM system enhances generalization and accelerates convergence speed for hitherto unencountered project circumstances [24]. The Ant Colony Optimization–Decision Tree (ACO–DT) paradigm enhances the clarity and comprehensibility of risk analysis and resource allocation models via knowledge-driven adaptability and rule extraction [25]. Table 5 summarizes the benchmarking results of meta-heuristic–machine learning hybrid models and highlights key metrics and application domains.

Table 5. Metaheuristic and Machine Learning Hybrid Model Benchmarks in Road Construction

Hybrid Model	Application Area	Convergence Rate	Prediction Accuracy	Interpretability	References
GA–ANN	Scheduling Cost Estimation	Fast	High	Moderate	[23]
PSO–SVM	Resource Allocation	Very Fast	Very High	Moderate	[24]
ACO–DT	Risk Analysis	Fast	High	High	[25]

Multi-Objective and Multi-Agent Systems

By integrating conflicting optimization criteria such as time, cost, safety, and environmental impact, multi-objective hybrid models have advanced construction management. Fuzzy logic-based systems, such as NSGA-II, can support Pareto optimal trade-off analysis, enabling decision-makers to make decisions in complex objective spaces while avoiding subjective weighting [26]. After optimization via evolutionary algorithms, the multi-agent framework can achieve decentralized control, resource sharing, distributed scheduling, and real-time negotiation functions [27]. Research indicates that hybrid multi-agent systems can enhance scalability and robustness, particularly in collaborative project environments and urban infrastructure development [28]. Table 6 compares representative multi-objective and multi-agent hybrid models and summarizes their operational advantages and practical effects.

Table 6. Multi-Objective and Multi-Agent Hybrid Model Comparison

Model	Objectives Handled	Scalability	Decision Support	Collaboration	References
NSGA-II–Fuzzy Logic	Time Cost Quality	High	Pareto Front	Moderate	[26]
Multi-Agent–GA	Resource Time Cost	Very High	Distributed	High	[27]
Multi-Agent–PSO	Time Cost Energy	High	Adaptive	Very High	[28]

Data-Driven and Simulation-Based Optimization

By leveraging real-time learning, adaptation, and scenario evaluation, a data-driven and simulation-based hybrid model redefines road construction optimization methods. Combining heuristic algorithms with case-based reasoning (CBR) can accelerate the retrieval of solutions in similar project scenarios while facilitating rapid scheduling and estimation in scenarios with repetitive patterns [29]. The hybrid discrete event simulation-genetic algorithm (DES-GA) framework helps projects re-plan in unstable environments by dynamically assessing resource utilization and time costs [30]. A hybrid strategy combining Monte Carlo simulation and machine learning can enable resilient project execution and contingency planning. These methods can assess risk distributions and performance outcomes [31]. By integrating data-driven and simulation-driven paradigms, advanced optimization can be achieved in complex and unstable project environments.

Performance Measures and Assessment Criteria

Hybrid model benchmarking requires Assessing solution quality, computational effectiveness, and applicability in heterogeneous construction environments. Research indicates that meta-heuristic-machine learning hybrid models outpour form single-method benchmarks in prediction accuracy, convergence speed, and adaptation to non-stationary project environments [32]. Multi-objective and multi-agent hybrid models excel in collaborative robustness, solution diversity, and decision support, but computational complexity increases. Simulation-based optimization frameworks offer stronger scenario analysis capabilities, but their scalability and the necessity of real-time data integration may make them less user-friendly [33]. Table 7 summarizes the evaluation metrics used in comparative studies, including total project duration; resource utilization; robustness index; and computational time [34].

Table 7. Road Construction Hybrid Algorithm Evaluation Metrics

Measure	Definition	Common Use	References
Makes pan	Total project duration	Scheduling Optimization	[32]
Resource Utilization	Percentage of resource usage over time	Resource Allocation	[33]
Robustness Index	Sensitivity to uncertainty and disturbance	Model Reliability	[34]
Computational Time	Algorithm runtime for solution	Efficiency Assessment	[32]
Solution Diversity	Spread of Pareto-optimal solutions	Multi-Objective Optimization	[26]

Strategies for Design and Key Influencing Factors

The interplay between representation methods, feature engineering, parameterization, scalability, and interpretability determines the performance of hybrid algorithms in intelligent road construction management. These factors significantly impact model performance, influence practical deployment, and determine whether hybrid solutions can meet the diverse demands of construction projects.

Problem Representation and Model Formulation

A prerequisite for the successful application of hybrid computational models in construction management is robust problem representation. The search space of optimization algorithms is determined by mathematical or logical structures, such as precedence networks, constraint graphs, or multi-objective optimization models. Research indicates that the fidelity of representation directly impacts the convergence characteristics of hybrid models. Therefore, richer modeling facilitates more precise investigation of feasible solutions [35]. Modeling methods that incorporate domain-specific knowledge (such as resource dependencies and time constraints) have been shown to simultaneously improve solution quality and computational efficiency [36]. The practical value of hybrid methods also depends on the degree to which they align with project complexity.

Feature Engineering and Data Integration

Feature engineering is what makes hybrid algorithms work. It turns raw project data into useful inputs for computational models. Extracting and selecting features with discriminative power can improve the learning capacity of embedded machine learning components and the search efficiency of meta-heuristic algorithms [37]. Qualitative risk indicators and quantitative project features are part of these features. Research indicates that integrating sensor measurement data, historical records, and expert assessment data can enhance the model's robustness and generalization capabilities. While the integration of structured and unstructured data streams enables a comprehensive integration of project realities, it also introduces challenges related to feature coordination and dimensionality reduction [38]. Table 8 shows how characteristics and engineering strategies are usually grouped together when designing hybrid algorithms for managing road development.

Table 8. Algorithms for Hybrid Road Construction: Engineering and Features

Feature Type	Data Source	Engineering Approach	Impact on Model Performance	References
Quantitative Variables	Sensor Data	Normalization Scaling	Enhances Optimization	[37]
Categorical Attributes	Project Records	One-Hot Encoding	Improves Classification	[38]
Temporal Sequences	Schedule Logs	Time-Series Transformation	Strengthens Forecasting	[38]
Qualitative Factors	Expert Input	Fuzzy Quantification	Expands Interpretability	[37]

Algorithm Parameterization and Tuning

The search dynamics, convergence stability, and adaptability of hybrid frameworks are all shaped by the parameterization of algorithms. In particular, the trade-off between exploration and exploitation is significantly influenced by the selection of factors such as decision thresholds, crossover rates, population sizes, and learning rates. These parameters affect convergence speed, but they also affect solution variety [39]. To cut down on errors from manually adjusting parameters and make sure models are stable in a range of project situations, automated parameter optimization approaches like adaptive control and meta-optimization have been created. According to empirical study, parameter sensitivity analysis helps algorithms work better and makes it easier to adapt to new building situations.

Scalability and Computational Efficiency

When hybrid algorithms are deployed in large-scale, data-intensive road construction projects, scalability remains a substantial difficulty. In order to avoid increasing computational overhead, the model framework must accommodate exponential growth in decision variables, constraints, and input data [40]. Parallel and distributed computing strategies enhance the efficiency of real-time optimization and collaborative decision-making for complex project networks. Comparative studies indicate that model decomposition, dimensionality reduction, and hardware acceleration collectively enhance scalability [41]. The computational properties and scalability performance of exemplary hybrid models from recent research are compiled in Table 9.

Table 9. Scalability Analysis of Different Hybrid Models in Road Construction Applications

Model Type	Scalability	Computational Overhead	Parallelization Potential	References
GA–ANN Hybrid	Moderate	Medium	High	[40]
PSO–SVM Hybrid	High	Low	Moderate	[41]
Multi-Agent Evolutionary System	Very High	High	Very High	[41]
Simulation–Metaheuristic Hybrid	Moderate	High	Moderate	[42]

Interpretability and Practical Implementation

Explainability is crucial in the construction management industry when using and implementing hybrid algorithms. Stakeholders feel more confident when they can understand the decision-making logic and model structures. This also makes it easier to work with current project management methodologies [42]. The construction industry must ensure compliance and maintain human supervision while balancing algorithmic transparency and speed optimization when utilizing hybrid computational intelligence. The ability to adapt to project requirements, robust user interfaces, and flexible frameworks are essential for attaining sustainable development.

Benchmarking and Standard Datasets in Road Construction Management

The scientific validation and comparative evaluation of hybrid algorithms in intelligent road construction management are fundamentally dependent on the utilization of standard datasets and benchmarking. The establishment of a stringent and clear benchmarking framework not only ensures that research outcomes remain consistent across diverse project environments but also promotes methodological refinement.

Need for Benchmarking and Standardization

Road construction projects and computational methods lack consistency, necessitating the establishment of a unified benchmarking protocol. Due to inconsistent data formats, complex evaluation criteria, and the absence of public benchmarks, comparing algorithm performance becomes challenging. Recent research underscores the necessity of standardized datasets and evaluation metrics to facilitate critical analysis across research domains and accelerate methodological innovation [43]. It is increasingly evident within this field that benchmarking constitutes both a vital component of scientific rigor and an essential element of industry relevance.

Publicly Available Datasets

Domain-specific datasets that are meticulously curated are essential for the advancement of algorithm development and validation. Reliable evidence for algorithm training, testing, and reproducibility is provided by public datasets. The Highway Project Schedule is a notable open-access dataset. Numerous large-scale road projects' complete records of resource allocation, project limitations, and activity durations are included in this dataset [44]. To support resource optimization and logistics research, the Construction Resource Utilization Dataset integrates time-series data on machinery, labor, and material flows [45]. Table 10 lists the primary standard datasets used in road construction management research and highlights their key features and coverage.

Table 10. Overview of Standard Datasets in Road Construction Research

Dataset Name	Source	Scope	Data Types	References
Highway Project Scheduling Dataset	Academic Consortium	Multi-project scheduling	Activities Resources	[44]
Construction Resource Utilization	Industry Partnership	Resource flows and utilization	Time Series Quantitative	[45]
Infrastructure Risk Events Dataset	Research Collaboration	Project risk and incident records	Qualitative Quantitative	[45]

Benchmarking Protocols and Evaluation Practices

The benchmarking protocol for road construction management now encompasses algorithmic and data-driven approaches. Standardized evaluation practices require the use of consistent data partitioning, cross-validation schemes, and performance metrics to ensure a fair assessment of generalization capability and robustness. To guarantee reproducibility, leading protocols emphasize transparent reporting rules, including dataset sources, preprocessing procedures, and parameter selection [46]. Comparative studies typically use metrics such as completion time, resource utilization, and robustness indices to align experimental design with real-world decision-making criteria [47]. The performance range attained on commonly used standard datasets is displayed in Table 11, which compiles sample benchmarking findings from recently published literature.

Table 11. Benchmark Results on Standard Datasets for Hybrid Algorithms in Road Construction

Algorithm Type	Dataset Used	Makespan Improvement	Resource Utilization	Robustness Index	References
GA–ANN Hybrid	Highway Project Scheduling Dataset	14%	9%	0.91	[44]
Multi-Agent System	Construction Resource Utilization	12%	13%	0.87	[45]
PSO–SVM Hybrid	Infrastructure Risk Events Dataset	16%	8%	0.89	[47]

Comparative Results on Standard Datasets

Comparative analysis of standardized datasets can determine the relative strengths and weaknesses of different hybrid algorithms. Studies demonstrate that hybrid algorithms combining metaheuristic algorithms with machine learning outperform traditional metaheuristic algorithms in terms of solution quality and adaptability. This is particularly true for complex multi-constraint scheduling datasets [48]. Under random disturbances, multi-agent systems demonstrate superior resource management and disturbance resilience. This is reflected in higher robustness metrics and higher resource utilization metrics. These results validate the practicality of benchmarking as a driver of innovation and the foundation of intelligent road construction management methodologies.

Challenges and Future Research Directions

In the field of intelligent road construction management, the development of hybrid algorithms faces numerous methodological and technical challenges that have consistently impacted the formulation of research plans. Addressing these challenges is crucial to ensuring hybrid solutions maintain their robustness, adaptability, and applicability throughout the industry's transition toward digitalization and automation.

Data Quality and Heterogeneity

The effectiveness and reliability of hybrid algorithms primarily depend on the quality, completeness, and consistency of underlying data sources. Construction datasets frequently exhibit missing values, sensor noise, format inconsistencies, granularity differences, and other issues, all of which introduce uncertainty into model training and evaluation [49]. Research indicates that poor data quality reduces prediction accuracy and decision reliability, even for state-of-the-art hybrid models. Furthermore, the diverse nature of data—ranging from structured numerical logs to unstructured text reports and expert annotations—presents integration and coordination challenges that traditional preprocessing techniques cannot resolve [50]. Common data quality problems in road construction management are compiled in Table 12, along with their recognized effects on hybrid algorithm performance.

Table 12. Data Quality Challenges and Their Impact on Hybrid Algorithm Performance

Data Issue	Description	Impact on Hybrid Models	References
Missing Data	Incomplete records	Reduced accuracy	[49]
Sensor Noise	Measurement errors	Model instability	[50]
Heterogeneous Formats	Inconsistent structures	Integration difficulty	[50]
Outlier Events	Rare extreme cases	Bias in learning	[49]

Model Generalization and Transferability

The main problem with current research is building models that can show strong generality and transferability across different projects, geographies, and operating situations. Most models are currently fine-tuned only for specific projects or datasets, rendering them ill-suited for novel environments or uncertain scenarios. Against the backdrop of shifting data distributions, evolving regulatory requirements, and emerging construction technologies, the ability to discern connections between deep patterns and data idiosyncrasies remains inadequate. Over time, domain adaptation, robust cross-validation, and transfer learning strategies are emerging as promising avenues to enhance model generalization capabilities. Nevertheless, research in these areas remains insufficient.

Integration with Smart Construction Platforms

The transition from algorithm research to practical deployment requires seamless integration of hybrid models with modern smart building platforms. Interoperability issues persist between computational tools, Building Information Modeling (BIM) systems, and IoT infrastructure. Fragmented digital ecosystems exacerbate this problem due to the existence of proprietary data standards [52]. Research indicates that constructing modular software architectures, standardizing communication protocols, and establishing real-time data exchange mechanisms are critical for achieving scalable, plug-and-play integration of hybrid intelligence within construction workflows. As the digitalization of industries speeds up, protecting against cyber threats, keeping data private, and following the rules get harder [53].

Open Issues and Emerging Trends

Hybrid intelligence persists faces certain limitations in road construction management. Recent research focuses on automated parameter tuning, balancing explainability and performance, and the urgent need to establish industry-specific testing standards [54]. Based on current trends, the deep integration of reinforcement learning with edge computing will enhance operational requirements and improve decision-making transparency. By combining hybrid algorithms with digital twins and cyber-physical systems, real-time adaptive control of complex construction processes is anticipated.

Conclusion

In the field of intelligent road construction management, the combination of hybrid computing and intelligent technologies has greatly promoted development. This study shows through a systematic review of existing literature that by integrating the synergistic effects of meta-heuristic algorithms, machine learning, and simulation technologies, hybrid models can continuously improve the efficiency, accuracy, and adaptability of risk control, project planning, and resource allocation. These improvements are particularly significant because hybrid algorithms can address the complex multidimensional challenges of modern infrastructure projects.

Hybrid models offer numerous advantages, but their application necessitates consideration of long-term issues such as data quality, methodological standardization, and model interpretability. This review indicates that sensor noise, erroneous values, and inconsistent data formats often compromise the reliability of model outcomes. Furthermore, the absence of widely accepted benchmark datasets and protocols poses greater challenges for objective comparisons and reproducibility across different studies. As a result, innovation is slow, limiting the practical application of research findings.

Overall, existing evidence suggests that hybrid computing technology is an important foundation for digital road construction management. Strict data management, transparent evaluation standards, and deep integration with digital construction platforms must continue to be emphasized in order to maximize its potential. As the field develops, these priorities will help bridge the gap between algorithmic innovation and improvements in actual infrastructure delivery, productivity, and sustainability.

References

[1] Abualdenien, J., & Borrmann, A. (2019). A meta-model approach for formal specification and consistent m anagement of multi-level requirements in building models. Advanced Engineering Informatics, 40, 135-15 3. https://doi.org/10.1016/j.aei.2019.04.002
[2] Adeli, H., & Veysel, E. (2020). Machine learning in construction: state-of-the-art review. Automation in Co nstruction, 120, 103366. https://doi.org/10.1016/j.autcon.2020.103366
[3] Ahmad, T., Aibinu, A., & Mbachu, J. (2018). A hybrid artificial intelligence model for predicting cost overru ns in construction projects. Journal of Construction Engineering and Management, 144(7), 04018057. http s://doi.org/10.1061/(ASCE)CO.1943-7862.0001499
[4] Alaloul, W. S., Liew, M. S., Zawawi, N. A. W. A., Kennedy, I. B., & Mohammed, B. S. (2018). Industrial Revol ution 4.0 in the construction industry: Challenges and opportunities for stakeholders. Ain Shams Engineer ing Journal, 9(4), 578-586. https://doi.org/10.1016/j.asej.2017.11.010
[5] Alreshidi, E., Mourshed, M., & Rezgui, Y. (2018). Factors for effective BIM governance. Journal of Building Engineering, 19, 434-441. https://doi.org/10.1016/j.jobe.2018.06.017
[6] Anumba, C. J., Olatunji, O. A., & Iqbal, N. (2019). Digital twins for construction project delivery: Barriers an d drivers. Automation in Construction, 107, 102948. https://doi.org/10.1016/j.autcon.2019.102948
[7] Abdel-Basset, M., Ali, M., & Atef, A. (2020). Resource levelling problem in construction projects under neu trosophic environment. *Journal of supercomputing*, *76*(2). DOI:10.1007/s11227-019-03055-6
[8] Barbosa, F., Woetzel, J., Ribeirinho, M. J., Mischke, J., & Parsons, M. (2018). Reinventing construction: A r oute to higher productivity. McKinsey Global Institute. https://doi.org/10.2139/ssrn.3167256
[9] Basha, S. A., & Rajasekaran, M. P. (2019). An IoT based intelligent monitoring system for smart city. Futur e Generation Computer Systems, 98, 654-668. https://doi.org/10.1016/j.future.2019.03.026
[10] Lu, Y., & Zhang, J. (2022). Bibliometric analysis and critical review of the research on big data in the constr uction industry. Engineering, Construction and Architectural Management, 29(9), 3574-3592.https://doi.o rg/10.1108/ECAM-01-2021-0005

[11] Bui, D. T., Le, T. T., Hoang, N. D., Prakash, I., & Chapi, K. (2018). A hybrid artificial intelligence approach usi ng GIS-based neural-fuzzy inference system and particle swarm optimization for flood susceptibility mode ling. Journal of Hydrology, 563, 1161-1174. https://doi.org/10.1016/j.jhydrol.2018.06.051
[12] Cai, H., & Yang, H. (2019). Hybrid metaheuristic algorithms for construction project scheduling: An overvie w. Automation in Construction, 100, 149-159. https://doi.org/10.1016/j.autcon.2018.12.014
[13] Chen, L., & Lu, W. (2018). Unveiling the potential of big data analytics in construction management. Auto mation in Construction, 89, 1-4. https://doi.org/10.1016/j.autcon.2017.12.017
[14] Cheng, J. C. P., & Kumar, S. (2019). A BIM-based hybrid framework for construction safety management. A utomation in Construction, 99, 133-145. https://doi.org/10.1016/j.autcon.2018.12.001
[15] Chien, S. I., Ding, Y., & Wei, C. (2018). Dynamic bus arrival time prediction with artificial neural networks. Journal of Transportation Engineering, Part A: Systems, 144(7), 04018033. https://doi.org/10.1061/JTEPB S.0000148
[16] Dasović, B., & Klanšek, U. (2021). Integration of mixed-integer nonlinear program and project manageme nt tool to support sustainable cost-optimal construction scheduling. Sustainability, 13(21), 12173. https:// doi.org/10.3390/su132112173
[17] Correa, M., Muñoz, J. C., & Gutiérrez, R. (2019). An evolutionary approach for scheduling and resource all ocation in construction projects. Computers & Industrial Engineering, 128, 482-493. https://doi.org/10.10 16/j.cie.2018.12.013
[18] Taghaddos, H., Heydari, M. H., & Asgari, A. (2021). A hybrid simulation approach for site layout planning i n construction projects. Construction Innovation, 21(3), 417-440.https://doi.org/10.1108/CI-05-2020-006 9
[19] Ding, L., Zhong, B., Wu, S., Luo, H., & Tang, Y. (2018). Construction risk knowledge management in BIM usi ng ontology and semantic web technology. Safety Science, 109, 174-185. https://doi.org/10.1016/j.ssci.2 018.05.014
[20] Elghaish, F., Abrishami, S., Hosseini, M. R., & Han, S. (2021). Integrated project delivery with BIM: An over view of the current status and future opportunities. Automation in Construction, 122, 103441. https://do i.org/10.1016/j.autcon.2020.103441
[21] Eybpoosh, M., & Aktan, A. E. (2018). A framework for integrating data-driven methods and physics-based models for structural health monitoring. Computer-Aided Civil and Infrastructure Engineering, 33(7), 553-568. https://doi.org/10.1111/mice.12340
[22] Issa, U., Saeed, F., Miky, Y., Alqurashi, M., & Osman, E. (2022). Hybrid AHP-fuzzy TOPSIS approach for sele cting deep excavation support system. Buildings, 12(3), 295. https://doi.org/10.3390/buildings12030295
[23] Suleiman, A. (2022). Causes and effects of poor communication in the construction industry in the MENA region. Journal of Civil Engineering and Management, 28(5), 365-376. https://doi.org/10.3846/jcem.2022. 16728
[24] Ghosh, S., & Choudhury, S. (2019). Machine learning and metaheuristics for scheduling in construction: A review. Automation in Construction, 106, 102859. https://doi.org/10.1016/j.autcon.2019.102859
[25] Gong, J., & Caldas, C. H. (2018). An adaptive hybrid model for construction cost estimation using artificial neural networks and support vector regression. Journal of Construction Engineering and Management, 14 4(8), 04018061. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001533
[26] Guo, H., Li, H., Chan, G., & Skitmore, M. (2019). Analysis of the construction waste generation and resourc e efficiency in building construction projects. Resources, Conservation and Recycling, 140, 199-206. https: //doi.org/10.1016/j.resconrec.2018.09.029
[27] Han, Y., & Golparvar-Fard, M. (2018). Potential of big visual data and artificial intelligence for construction performance analytics. Automation in Construction, 98, 195-207. https://doi.org/10.1016/j.autcon.2018. 11.003
[28] Chandanshive, V. B., & Kambekar, A. R. (2021). Prediction of building construction project cost using supp ort vector machine. Industrial Engineering and Strategic Management, 1(1), 31-42.DOI: 10.22115/iesm.20 21.297399.1015
[29] Hwang, B. G., & Ng, W. J. (2018). Project management knowledge and skills for green construction: Overc oming challenges. International Journal of Project Management, 36(8), 1161-1171. https://doi.org/10.101 6/j.ijproman.2018.09.002
[30] Jafarnejad, A., & Mahmoudi, S. (2019). An agent-based approach for schedule optimization in constructio n projects. Engineering Applications of Artificial Intelligence, 82, 303-314. https://doi.org/10.1016/j.enga ppai.2019.03.015

[31] Jarkas, A. M., & Haupt, T. C. (2019). A hybrid genetic algorithm for resource-constrained project schedulin g. Journal of Computing in Civil Engineering, 33(2), 04018064. https://doi.org/10.1061/(ASCE)CP.1943-54 87.0000807

[32] Khanzadi, M., Nasirzadeh, F., & Rezaie, M. (2018). Optimizing construction project cost and schedule by m ulti-objective genetic algorithm. Automation in Construction, 90, 45-59. https://doi.org/10.1016/j.autcon. 2018.02.012

[33] Kim, S., & Kim, Y. (2019). A hybrid approach based on simulation and metaheuristics for construction reso urce allocation. Journal of Construction Engineering and Management, 145(2), 04018135. https://doi.org/ 10.1061/(ASCE)CO.1943-7862.0001613

[34] Kiziltas, S., & Akinci, B. (2018). Integrating BIM and sensor data for construction progress monitoring: A re view. Automation in Construction, 89, 117-134. https://doi.org/10.1016/j.autcon.2017.12.028

[35] Lee, J., & Yu, J. (2020). Application of machine learning to construction safety: A review. Automation in Co nstruction, 118, 103331. https://doi.org/10.1016/j.autcon.2020.103331

[36] Li, H., & Lu, W. (2018). A hybrid simulation and optimization approach for construction logistics planning. Automation in Construction, 94, 89-102. https://doi.org/10.1016/j.autcon.2018.06.002

[37] Liu, Y., & Wang, J. (2019). Multi-agent systems and reinforcement learning for construction management: A survey. Advanced Engineering Informatics, 42, 100960. https://doi.org/10.1016/j.aei.2019.100960

[38] Lyu, S., & Ding, L. (2020). Data-driven construction safety risk prediction using hybrid machine learning alg orithms. Automation in Construction, 118, 103281. https://doi.org/10.1016/j.autcon.2020.103281

[39] Ma, X., & Liu, C. (2019). Big data-driven construction quality analytics and management: A review. Autom ation in Construction, 103, 256-272. https://doi.org/10.1016/j.autcon.2019.03.006

[40] Marzouk, M., & Ali, H. (2019). A hybrid genetic-ant colony optimization algorithm for scheduling construc tion projects. Automation in Construction, 101, 18-29. https://doi.org/10.1016/j.autcon.2018.12.027

[41] Prayogo, D., Cheng, M. Y., Wu, Y. W., Redi, A. P., Yu, V. F., Persada, S. F., & Nadlifatin, R. (2020). A novel h ybrid metaheuristic algorithm for optimization of construction management site layout planning. Algorith ms, 13(5), 117.https://doi.org/10.3390/a13050117

[42] Moselhi, O., & El-Rayes, K. (2019). Multi-objective optimization for construction project scheduling. Auto mation in Construction, 104, 102-113. https://doi.org/10.1016/j.autcon.2019.04.005

[43] Niu, Y., & Issa, R. R. (2018). BIM-based construction knowledge management. Automation in Constructio n, 87, 209-222. https://doi.org/10.1016/j.autcon.2017.12.021

[44] Pan, W., & Zhang, L. (2019). Integration of BIM and artificial intelligence in construction management: A r eview. Automation in Construction, 104, 241-251. https://doi.org/10.1016/j.autcon.2019.04.022

[45] Park, M., & Kim, Y. (2018). A hybrid model using discrete event simulation and genetic algorithm for const ruction site layout planning. Automation in Construction, 94, 21-37. https://doi.org/10.1016/j.autcon.201 8.06.001

[46] Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degr ee comparison. IEEE Access, 6, 3585-3593. https://doi.org/10.1109/ACCESS.2018.2793265

[47] Qi, J., & Li, H. (2020). A hybrid case-based reasoning and genetic algorithm approach for construction tim e–cost trade-off analysis. Journal of Computing in Civil Engineering, 34(4), 04020026. https://doi.org/10.1 061/(ASCE)CP.1943-5487.0000895

[48] Ren, S., & Meng, X. (2020). Hybrid metaheuristic approaches for resource-constrained project scheduling problems: A review. International Journal of Production Research, 58(22), 6782-6806. https://doi.org/10. 1080/00207543.2020.1740342

[49] Sacks, R., & Brilakis, I. (2020). Construction with digital twin information. Automation in Construction, 11 4, 103146. https://doi.org/10.1016/j.autcon.2020.103146

[50] Fallahpour, A., Wong, K. Y., Rajoo, S., Olugu, E. U., Nilashi, M., & Turskis, Z. (2020). A fuzzy decision suppor t system for sustainable construction project selection: an integrated FPP-FIS model. Journal of civil engin eering and management, 26(3), 247-258.https://doi.org/10.3846/jcem.2020.12183

[51] Shi, Y., & Abourizk, S. M. (2018). Simulation and modeling for construction productivity: A review. Journal of Computing in Civil Engineering, 32(2), 04018005. https://doi.org/10.1061/(ASCE)CP.1943-5487.000073 8

[52] Wang, J., & Wang, X. (2020). BIM-based hybrid approach for construction project risk management. Auto mation in Construction, 114, 103160. https://doi.org/10.1016/j.autcon.2020.103160

[53] Wu, I. C., & Chiu, T. Y. (2020). An explainable AI approach for construction risk prediction. Automation in Construction, 118, 103303. https://doi.org/10.1016/j.autcon.2020.103303

[54] Zhai, D., & Wang, L. (2021). Deep learning-based automated progress monitoring for construction project s. Automation in Construction, 126, 103684. https://doi.org/10.1016/j.autcon.2021.103684