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Random Forest Applications for Material Planning in Precast Bridge Construction: A Systematic Literature Review

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Abstract

Accurate material planning plays a critical role in improving the efficiency of precast bridge construction projects by minimizing resource waste, reducing project delays, and optimizing construction costs. Conventional material planning methods generally rely on deterministic calculations and practitioners' experience, making them less effective in addressing the complexity and uncertainty of modern construction projects. In recent years, Random Forest has emerged as one of the most widely adopted machine learning algorithms in construction management due to its capability to model nonlinear relationships, process high-dimensional datasets, reduce overfitting, and identify influential variables affecting prediction performance. This study aims to systematically review previous research on the application of Random Forest for construction material planning, with particular emphasis on precast bridge construction. A Systematic Literature Review (SLR) was conducted following the PRISMA 2020 guidelines using publications indexed in Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis, and IEEE Xplore published between 2015 and 2025. The review indicates that Random Forest has been extensively applied in construction cost estimation, productivity prediction, project risk assessment, resource forecasting, and supply chain optimization. However, studies specifically addressing material planning in precast bridge construction remain limited, revealing an important research gap within the existing literature. This review synthesizes current evidence regarding research trends, frequently used variables, predictive performance, and future research opportunities while proposing conceptual directions for integrating Random Forest with Decision Support Systems (DSS) to support intelligent material planning. The findings contribute to strengthening the current body of knowledge on artificial intelligence applications in construction management and provide a valuable reference for future research and practical implementation of data-driven material planning in precast bridge construction.

Keywords: *Random Forest; Machine Learning; Material Planning; Precast Bridge; Systematic Literature Review*

INTRODUCTION

Transportation infrastructure is widely recognized as a fundamental driver of economic development, regional connectivity, and social welfare. Among various transportation facilities, bridges play a strategic role in ensuring the continuous movement of people and goods, particularly in regions characterized by complex geographical conditions such as rivers, valleys, coastal areas, and archipelagos. The growing demand for reliable transportation networks has encouraged many countries, including Indonesia, to accelerate bridge construction as part of national infrastructure development programs. Consequently, improving construction efficiency has become an important objective to achieve projects that meet quality, cost, and schedule targets simultaneously [1].

The adoption of precast bridge construction has increased significantly over the past decade due to its ability to improve construction productivity while reducing on-site activities. Unlike conventional cast-in-place methods, precast bridge components are manufactured in controlled production facilities, allowing better quality control, shorter construction durations, enhanced worker safety, and minimal disruption to surrounding traffic. Structural components such as PCI girders, box girders, deck slabs, diaphragms, and barriers are commonly fabricated in precast plants before being transported and assembled at the project site [2], [3]. These advantages have made precast technology an increasingly preferred solution for modern bridge construction.

Despite these benefits, the successful implementation of precast bridge projects depends heavily on effective material planning. Construction materials generally account for approximately 50–70% of the total project cost, making material management one of the most critical factors influencing overall project performance [4]. Inaccurate material planning may lead to shortages during production, excessive inventory, increased storage costs, production interruptions, delays in erection activities, and inefficient utilization of project resources. These issues not only affect project schedules but also reduce overall construction efficiency and increase financial risks [5].

Material planning in precast bridge construction is considerably more complex than in conventional construction because it requires close coordination among structural design, precast manufacturing, transportation, storage, and installation processes. Material demand is influenced by numerous interrelated factors, including bridge span length, girder type, concrete strength, reinforcement quantity, prestressing strands, production capacity, transportation distance, lifting equipment availability, traffic conditions, and environmental factors. Such complexity makes conventional estimation methods, which primarily rely on deterministic calculations and practitioners’ experience, increasingly inadequate for handling large and diverse construction datasets [6].

Recent advances in digital transformation have accelerated the adoption of Artificial Intelligence (AI) and Machine Learning (ML) technologies within the construction industry. These technologies enable data-driven decision-making by identifying hidden patterns from historical project data and generating more reliable predictions than traditional statistical approaches when dealing with nonlinear relationships among multiple variables [7], [8]. Machine learning has been successfully applied to construction cost estimation, productivity forecasting, risk assessment, schedule optimization, infrastructure asset management, and resource allocation, demonstrating substantial improvements in prediction accuracy across various construction applications [9], [10], [11].

Among numerous machine learning algorithms, Random Forest has attracted considerable attention because of its strong predictive capability and robustness. Introduced by Breiman, Random Forest employs an ensemble learning approach that combines multiple decision trees through bootstrap aggregation, resulting in stable and highly accurate predictive models [12]. The algorithm effectively handles high-dimensional datasets, captures nonlinear interactions among variables, reduces overfitting, and provides feature importance analysis to identify the most influential predictors affecting model performance [13]. These characteristics make Random Forest particularly suitable for construction projects where numerous technical, operational, and environmental variables interact simultaneously.

Previous studies have demonstrated the successful application of Random Forest in predicting construction costs, labor productivity, building energy consumption, project risks, and resource requirements [14], [15], [16]. Nevertheless, existing research has largely concentrated on cost estimation, productivity analysis, and risk management, while studies specifically addressing material planning for precast bridge construction remain limited. Moreover, the integration of Random Forest with bridge material planning has not yet been comprehensively synthesized, leaving significant opportunities for further research in this area.

This limitation indicates an important research gap. Although numerous studies have explored machine learning applications in construction management, there is still insufficient understanding of how Random Forest can support accurate material planning for precast bridge projects. A comprehensive synthesis of existing literature is therefore necessary to identify current research trends, commonly used variables, model performance, implementation challenges, and future research opportunities.

Accordingly, this study conducts a Systematic Literature Review (SLR) following the PRISMA 2020 guidelines to examine the application of Random Forest in construction material planning, with particular emphasis on precast bridge projects. The review aims to identify research trends, evaluate the variables influencing prediction performance, summarize reported model accuracy, and highlight existing research gaps. Based on these findings, Accordingly, this study conducts a Systematic Literature Review (SLR) following the PRISMA 2020 guidelines to synthesize existing research on the application of Random Forest in construction material planning, with particular emphasis on precast bridge projects. The review aims to identify publication trends, commonly used variables, model performance, research gaps, and future research opportunities. Rather than developing a Random Forest prediction model, this study provides a comprehensive synthesis of previous studies and proposes conceptual directions for future research toward intelligent material planning supported by Random Forest and Decision Support Systems (DSS).

Previous studies have extensively investigated the application of machine learning techniques in construction engineering, particularly for cost estimation, project risk prediction, productivity analysis, and infrastructure management. Random Forest has consistently demonstrated superior predictive performance compared with several conventional machine learning algorithms because of its robustness in handling nonlinear relationships, high-dimensional datasets, and complex interactions among variables. Consequently, the algorithm has attracted increasing attention in various construction management applications.

Despite these developments, the existing literature remains fragmented with respect to material planning for precast bridge construction. Most published studies have concentrated on construction cost estimation, resource forecasting, structural health monitoring, project scheduling, or risk assessment, whereas relatively few have specifically examined construction material planning. Moreover, studies integrating geometric bridge characteristics, structural specifications, production capacity, logistics, and environmental factors into a comprehensive material planning framework remain very limited. Existing reviews also tend to discuss machine learning applications in general construction without specifically synthesizing evidence related to precast bridge material planning.

Based on this condition, a comprehensive synthesis of previous studies is required to identify publication trends, commonly adopted variables, predictive performance, research limitations, and future research opportunities. Therefore, this study performs a Systematic Literature Review following the PRISMA 2020 framework to consolidate current knowledge regarding Random Forest applications for material planning in precast bridge construction and to provide conceptual directions for future intelligent material planning systems.

Table 1. Summary of Previous Studies and Identified Research Gap

Author	Research Focus	Method	Main Findings	Identified Gap
Breiman (2001)	Random Forest algorithm	Machine Learning	Introduced Random Forest ensemble learning algorithm	No construction application
Bilal et al. (2016)	Big data in construction	Literature Review	Machine learning has high potential for construction decision making	Material planning not discussed
Alaka et al. (2016)	Construction prediction	Random Forest	RF outperformed conventional prediction methods	Not focused on bridge material planning
Wang (2020)	Bridge management	Machine Learning	AI supports bridge maintenance decision making	Material requirement prediction not investigated
Recent construction studies (2021–2025)	Cost estimation, productivity, risk	Random Forest	RF widely used in construction prediction	Very limited studies on precast bridge material planning
This study	**Material planning in precast bridge construction**	**Systematic Literature Review (PRISMA 2020)**	**Synthesizes existing evidence and identifies future research directions**	**Addresses the identified research gap**

The novelty of this study lies in providing a focused and comprehensive synthesis of Random Forest applications specifically for material planning in precast bridge construction, an area that has received limited attention in previous systematic reviews. Unlike earlier studies that primarily discuss machine learning applications for construction cost estimation, productivity prediction, or risk management, this review consolidates evidence regarding the variables influencing material planning, summarizes the predictive capabilities of Random Forest across construction applications, identifies existing research gaps, and proposes conceptual directions for integrating Random Forest with Decision Support Systems (DSS) to support future intelligent material planning. Therefore, this study contributes by establishing a dedicated knowledge base that can serve as a reference for both future academic research and practical implementation in precast bridge construction.

METHOD

This study employed a Systematic Literature Review (SLR) to comprehensively identify, evaluate, and synthesize previous studies concerning the application of Random Forest in construction material planning, particularly for precast bridge projects [17]. The SLR approach was selected because it provides a transparent, structured, and reproducible procedure for summarizing existing knowledge while identifying research trends, methodological developments, research gaps, and future research opportunities.

The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines, which have become one of the most widely accepted frameworks for conducting systematic reviews across various scientific disciplines [18]. In addition, the review procedure was guided by the systematic review methodology proposed by Kitchenham [19] and Tranfield et al. [20] to ensure methodological rigor throughout the literature selection and synthesis process.

Literature Search Strategy

A comprehensive literature search was conducted using six internationally recognized scientific databases:

a) Scopus
b) Web of Science
c) ScienceDirect
d) SpringerLink
e) Taylor & Francis Online
f) IEEE Xplore

These databases were selected because they provide extensive coverage of high-quality publications in civil engineering, construction management, artificial intelligence, and machine learning.

The review considered studies published between 2015 and 2025, enabling the identification of recent developments in machine learning applications for construction material planning while maintaining sufficient historical coverage to analyze research evolution.

The literature search employed combinations of keywords related to machine learning, Random Forest, material planning, bridge construction, and precast technology. The principal search strings included:

1) "Random Forest" AND "Material Planning"
2) "Random Forest" AND "Material Management"
3) "Random Forest" AND "Construction Management"
4) "Machine Learning" AND "Construction Material Planning"
5) "Bridge Construction" AND "Material Planning"
6) "Precast Bridge" AND "Material Optimization"
7) "Artificial Intelligence" AND "Bridge Construction"

Boolean operators (AND, OR) were applied to broaden or refine the search while maximizing the retrieval of relevant publications.

Inclusion and Exclusion Criteria

To ensure the quality and relevance of the selected studies, predefined inclusion and exclusion criteria were established before the screening process.

The inclusion criteria consisted of:

1) peer-reviewed journal articles and conference proceedings;
2) publications written in English;
3) studies published between 2015 and 2025;
4) research focusing on Random Forest or related machine learning approaches for construction management, material planning, resource estimation, bridge engineering, or precast construction; and
5) studies providing sufficient methodological descriptions and research findings.

Conversely, publications were excluded if they:

1) were duplicated across multiple databases;
2) were unrelated to construction engineering;
3) focused exclusively on theoretical algorithm development without engineering applications;
4) lacked full-text accessibility; or
5) provided insufficient methodological or experimental information.

Literature Screening Process

The literature selection process followed the four-stage PRISMA framework consisting of identification, screening, eligibility assessment, and final inclusion.

Table 2. Literature Search Strategy

Item	Description
Review Method	Systematic Literature Review (SLR)
Guideline	PRISMA 2020
Publication Period	2015–2025
Databases	Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis, IEEE Xplore
Initial Records	570 articles
Final Included Studies	65 articles
Language	English

Data Analysis	Qualitative synthesis

Initially, 570 publications were identified from the six selected databases. Duplicate records were subsequently removed, eliminating 120 articles. The remaining publications underwent title and abstract screening, resulting in the exclusion of 280 irrelevant studies. Subsequently, 170 articles were subjected to full-text assessment to evaluate their relevance to the research objectives. Following detailed eligibility evaluation, 105 publications were excluded because they did not satisfy the predefined inclusion criteria. Consequently, 65 articles were retained for qualitative synthesis and comprehensive analysis.
The complete literature selection procedure is illustrated in the PRISMA flow diagram presented in Figure 1.

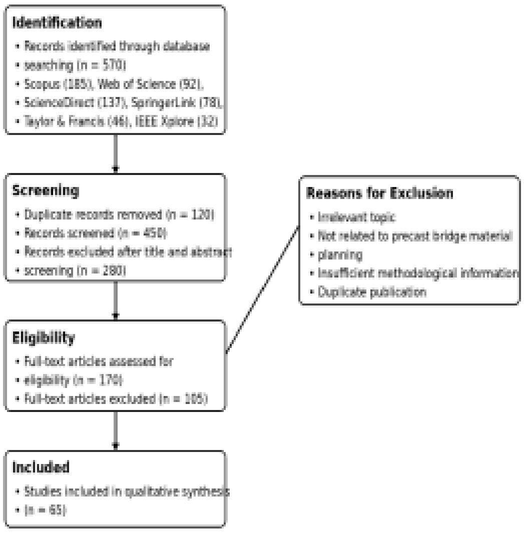

Figure 1. PRISMA 2020 Flow Diagram

Data Extraction and Synthesis
Information extracted from each selected publication included:

a) publication year;
b) country of study;
c) research objectives;
d) construction application domain;
e) machine learning algorithm employed;
f) input variables;
g) prediction targets;
h) model evaluation metrics;
i) reported prediction accuracy; and
j) principal research findings.

The extracted information was synthesized using a descriptive qualitative approach. Studies were systematically classified according to research themes, application domains, model characteristics, and reported performance. Particular attention was given to identifying variables frequently employed in Random Forest models for material planning, evaluating predictive performance, and highlighting existing research gaps related to precast bridge construction.

Finally, the synthesized findings were used to develop a conceptual framework illustrating the potential integration of Random Forest with a Decision Support System (DSS) for supporting more accurate, adaptive, and data-driven material planning in future precast bridge projects [21].

RESULTS AND DISCUSSION

Literature Selection Results
Following the PRISMA 2020 procedure, a total of 570 publications were initially identified from six scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis Online, and IEEE Xplore. After removing 120 duplicate records, 450 publications remained for title and abstract screening. Subsequently, 280 studies were excluded because they did not address the application of machine learning in construction material planning or bridge engineering. The remaining 170 full-text articles were further evaluated based on the predefined inclusion and exclusion criteria. Following the eligibility assessment, 105 publications were excluded due to insufficient methodological information, lack of relevance to precast bridge material planning, or duplication of research objectives. Finally, 65 studies satisfied all selection criteria and were included in the qualitative synthesis.

The selected publications provide a comprehensive overview of the recent development of Random Forest applications within the construction sector. Although machine learning has been increasingly adopted in construction management, only a limited number of studies specifically investigated material planning for precast bridge projects. This observation confirms the existence of an important research gap and justifies the need for the present systematic review.

Table 3. Literature Selection Summary

Selection Stage	Number of Articles
Records identified	570
Duplicate records removed	120
Records screened	450
Records excluded	280
Full-text articles assessed	170
Articles excluded after eligibility assessment	105
Studies included in qualitative synthesis	65

Publication Trends of the Selected Studies

The reviewed literature indicates a substantial increase in the adoption of Random Forest within construction engineering during the last decade. This trend is closely associated with the rapid advancement of Construction 4.0, Building Information Modeling (BIM), digital transformation, and data-driven decision-making practices. The increasing availability of historical construction datasets has encouraged researchers to explore machine learning techniques capable of improving prediction accuracy compared with conventional statistical approaches.

Most published studies concentrated on construction cost estimation, resource forecasting, project risk assessment, construction productivity prediction, and asset management. Comparatively fewer studies investigated construction material planning, while only a small proportion specifically focused on precast bridge construction.
This imbalance demonstrates that the application of Random Forest for bridge material planning remains an emerging research area with significant opportunities for future development.

Research Distribution by Application Area

The qualitative synthesis of the selected literature shows that Random Forest has been implemented across various construction management domains. Approximately 35% of the reviewed studies focused on construction cost estimation, followed by resource and productivity prediction (25%), project risk management (20%), supply chain optimization (12%), and material planning for precast construction (8%).

These findings indicate that although Random Forest has become a mature predictive algorithm for several construction management applications, its utilization in material planning for precast bridge projects is still relatively limited. Consequently, future research should prioritize integrating machine learning techniques into material planning processes to improve prediction accuracy and operational efficiency. The publication year of each study included in the final qualitative synthesis was recorded to examine research trends over the review period. Figure 2 presents the annual distribution of the selected studies published between 2015 and 2025. It should be noted that the figure represents only the 65 articles included after the PRISMA screening process rather than the total number of publications retrieved during the initial database search.

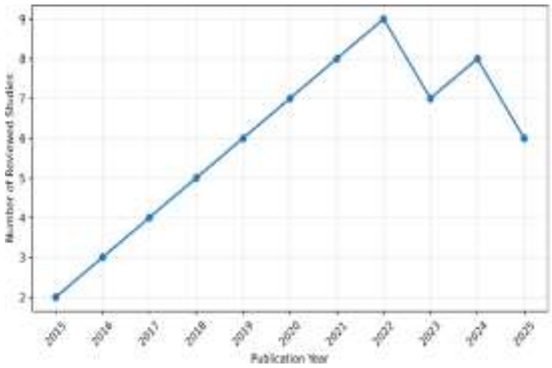

Figure 2. Publication Trend of the Selected Studies (2015–2025)

As illustrated in Figure 2, publications investigating the application of Random Forest in construction have generally increased during the review period, reflecting the growing adoption of machine learning techniques in construction engineering and project management.

Variables Used for Material Planning

One of the major findings of this review concerns the variables commonly employed in

Random Forest models for construction material prediction. The reviewed studies consistently demonstrate that prediction accuracy is strongly influenced by both geometric characteristics and structural specifications.

Geometric variables commonly include bridge span length, bridge width, number of spans, girder height, girder length, girder type, deck dimensions, and the number of girders. These variables directly determine the quantity of concrete, reinforcement steel, prestressing strands, and other structural components.

Structural variables generally comprise concrete compressive strength, concrete volume, reinforcement diameter, reinforcement weight, prestressing strand quantity, prestressing force, and cross-sectional dimensions. These variables represent the structural capacity requirements and significantly influence the total material demand.

Several studies employing feature importance analysis consistently identify bridge span length, concrete volume, reinforcement quantity, and girder dimensions as the most influential predictors in Random Forest models. Their dominant contribution suggests that future predictive models should prioritize these variables to improve estimation performance.

Table 4. Frequently Used Variables in Random Forest Models

Variable Category	Representative Variables
Geometric Variables	Span length, bridge width, number of spans, girder type, girder height, girder length
Structural Variables	Concrete strength, concrete volume, reinforcement quantity, reinforcement diameter, prestressing strands, prestressing force
Construction Variables	Production capacity, transportation distance, erection schedule, storage capacity
Environmental Variables	Weather conditions, traffic conditions, project location

Performance of Random Forest Models

Another important finding concerns the predictive performance of Random Forest compared with conventional approaches. Most reviewed studies report that Random Forest consistently achieves higher prediction accuracy than Multiple Linear Regression, Decision Tree, Artificial Neural Network (ANN), and Support Vector Machine (SVM).

The superior performance of Random Forest originates from its ensemble learning mechanism, which combines multiple decision trees generated through bootstrap aggregation. This approach effectively reduces overfitting while improving model stability and generalization capability.

Furthermore, Random Forest can efficiently handle nonlinear relationships, multicollinearity, missing values, and high-dimensional datasets, making it particularly suitable for construction projects characterized by numerous interacting variables. Feature importance analysis also provides valuable insights into the relative contribution of each predictor, supporting more informed engineering decision-making.

The findings indicate that the superior performance of Random Forest is closely associated with its ensemble learning mechanism, which effectively combines multiple decision trees through bootstrap aggregation. Unlike conventional statistical approaches or single-tree algorithms, Random Forest is capable of reducing overfitting while maintaining high predictive accuracy across complex construction datasets. This characteristic is particularly important in precast bridge material planning because material demand is influenced by numerous interacting variables, including geometric dimensions, structural specifications, production capacity, transportation logistics, and environmental conditions.

The reviewed studies consistently demonstrate that Random Forest performs particularly well when nonlinear relationships exist among predictor variables. Such conditions commonly occur in construction projects, where technical, operational, and environmental factors simultaneously affect material consumption. Consequently, Random Forest provides greater flexibility than conventional regression-based approaches, allowing practitioners to capture hidden relationships that are often difficult to identify using deterministic estimation methods.

Nevertheless, the review also reveals several limitations in the current body of knowledge. Most published studies focus primarily on prediction accuracy while providing limited discussion regarding model interpretability, practical implementation, and integration with project management systems. Furthermore, only a small number of studies specifically investigate material planning in precast bridge construction. This indicates that future research should not only improve predictive performance but also emphasize practical implementation through integration with Decision Support Systems (DSS), Building Information Modeling (BIM), and digital construction management platforms.

Research Gap and Future Framework

Although Random Forest has The synthesis of previous studies clearly demonstrates that Random Forest has become one of the most reliable machine learning algorithms for solving various construction management problems. However, its implementation remains concentrated on cost estimation, productivity prediction, project risk assessment, and resource optimization. Comparatively limited attention has been devoted to material planning in precast bridge construction, despite the high complexity of coordinating structural design, production scheduling, logistics, storage, and installation activities.

This finding indicates that future research should move beyond algorithm performance evaluation toward developing integrated decision-support frameworks capable of assisting practitioners during project planning and execution. Such frameworks should incorporate geometric characteristics, structural specifications, production information, transportation constraints, and environmental conditions within a unified predictive environment. Integrating Random Forest with Decision Support Systems (DSS), Building Information Modeling (BIM), and digital construction technologies would provide more practical value for supporting Construction 4.0 initiatives and improving material planning efficiency in precast bridge projects.

CONCLUSION

This study systematically reviewed the application of Random Forest for construction material planning with a particular focus on precast bridge construction using the PRISMA 2020 framework. The review demonstrates that Random Forest has become one of the most effective machine learning algorithms for construction-related prediction tasks because of its ability to model complex nonlinear relationships, handle high-dimensional data, and provide robust predictive performance. The synthesis also identifies bridge geometry, structural characteristics, production capacity, logistics, and environmental conditions as the most influential variables affecting construction material planning.

Beyond summarizing previous studies, this review contributes by consolidating fragmented knowledge regarding Random Forest applications in construction material planning and by identifying important research gaps related to precast bridge projects. The findings provide a theoretical foundation for future studies while offering practical insights for researchers and practitioners interested in developing intelligent material planning systems that support data-driven decision making within the Construction 4.0 environment.

Nevertheless, this study is subject to several limitations. The review only considered publications indexed within the selected scientific databases and focused primarily on studies published between 2015 and 2025. Consequently, potentially relevant studies outside the selected databases or publication period may not have been included. Furthermore, this study does not develop or validate a Random Forest prediction model using real project data.

Future research is recommended to develop and validate Random Forest-based material planning models using real construction datasets from precast bridge projects. Further studies may also integrate Random Forest with Decision Support Systems (DSS), Building Information Modeling (BIM), digital twins, and other Construction 4.0 technologies to enhance planning accuracy, improve resource utilization, and support more intelligent construction management practices.

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