

A Systematic Taxonomic Review of Risk Modelling and Assessment Methods in Construction Projects (1990–2025)

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Abstract

This study presents a systematic taxonomic review of risk modelling and assessment methods in construction projects over the past 35 years (1990–2025). Through a structured four-stage process, 91 peer-reviewed articles from 15 leading journals were analysed. The taxonomic approach enabled the classification and mapping of methods according to chronological evolution, study type, authorship patterns, and focus areas, while thematic analysis was employed to synthesise key themes, trends, and research gaps. The review examines publication trends, geographical distribution of research contributions, and methodological developments. The findings reveal that the probability-impact (P-I) model remains the dominant approach, despite its well-documented limitations in capturing risk interdependencies and their cascading effects on project quality and overall performance. Fuzzy Set Theory (FST), Analytic Hierarchy Process (AHP), and Monte Carlo Simulation (MCS) emerged as the most frequently adopted techniques. The analysis demonstrates a clear evolution in the field: from predominantly basic probabilistic methods in the 1990s to increasingly sophisticated hybrid, fuzzy logic-based, and AI-enhanced approaches after 2010. Notwithstanding these advancements, significant gaps persist, particularly the lack of integrated frameworks capable of simultaneously addressing risks across multiple project objectives—cost, time, quality, and performance. This review synthesises the state of knowledge in the field, identifies persistent theoretical and practical shortcomings, and offers a comprehensive roadmap for future research. Key directions include the development of machine learning applications, dynamic modelling techniques, and holistic multi-objective risk assessment frameworks to better align risk management theory with the complex realities of modern construction projects.

Keywords: taxonomic review; project management; risk assessment; risk modelling; construction industry

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1. Introduction

The construction industry is inherently exposed to risks arising from the involvement of multiple stakeholders, including owners, designers, contractors, suppliers, and regulatory authorities [1,2]. The unique characteristics of construction projects, such as site-specific conditions, technical complexity, and increasing scale, further amplify these risks [3]. External factors, including political, social, economic, and cultural influences, add additional layers of uncertainty. According to the Project Management Institute (PMI) [4], project risk encompasses uncertainties that can positively or negatively affect key

project objectives, including cost, scope, time, and quality. When left unaddressed, such risks frequently result in delays and cost overruns [5,6]. Despite the critical importance of effective risk management, the construction industry continues to lag behind more mature sectors such as finance and insurance in the development and application of advanced risk modelling techniques (e.g., [7,8]). While financial institutions routinely employ sophisticated stochastic models, Value-at-Risk frameworks, and real-time predictive analytics [9], construction risk practices remain dominated by relatively basic tools. This gap contributes to persistent project overruns, delays, and disputes.

Contemporary construction projects are defined by intrinsic complexities and dynamic interdependencies across multiple dimensions, including environmental, financial, sustainability, and legal factors [10]. Traditional intuition-based forecasting methods have proven inadequate for managing the sophisticated risk profiles characteristic of modern projects [11]. A persistent gap exists between theoretical advancements in risk management frameworks and their effective implementation in practice [12]. For instance, while stochastic models offer probabilistic insights into project duration, their practical adoption remains limited, underscoring the need for broader validation across diverse contexts [13]. The evolution of risk modelling techniques, from conventional approaches toward more advanced quantitative and hybrid methods, reflects a growing recognition of these challenges [14–16]. Nevertheless, integrating these methodologies into cohesive, practical risk management systems remains difficult amid rapidly evolving technologies and project environments [17,18].

This critical juncture necessitates a comprehensive synthesis of existing knowledge to identify methodological trends and bridge the divide between theory and practice [19]. To this end, the present study conducts a systematic taxonomic review of risk modelling and assessment methods in construction projects. Focusing on their application in international construction and infrastructure contexts, the review analyses methodological trends across leading academic journals over the past 35 years. The review covers the period 1990–2025 for two main reasons. First, although foundational concepts in project risk management emerged in the 1980s (e.g., [20]), systematic empirical studies focused specifically on risk modelling and assessment methods in construction began to proliferate from the early 1990s onward. Second, this timeframe captures the transition from traditional probabilistic approaches to more sophisticated hybrid and digital methods, providing a comprehensive view of the field's evolution over three and a half decades. Specifically, the review addresses the following research questions:

1. What are the dominant risk assessment and modelling methodologies in the construction industry?
2. What are the key limitations of current risk assessment methods, and how can they be addressed to better align theory with practice?

Drawing on 91 peer-reviewed articles published in 15 top-tier journals spanning construction management, project management, and risk analysis, this study provides a temporal and methodological examination of the field. By highlighting prevailing trends, persistent gaps, and emerging opportunities, it offers valuable insights for both researchers and practitioners. Ultimately, this review aims to advance the integration of theoretical developments with practical applications, serving as a foundation for future studies in construction risk management.

2. Literature Review

The construction industry is inherently complex and multifaceted, involving large-scale projects with numerous stakeholders, including owners, contractors, suppliers, designers, and regulatory bodies. This complexity, combined with the unique, site-specific

nature of each project, renders the sector particularly vulnerable to risks [2]. Risks emerge from diverse sources, encompassing technical challenges, financial uncertainties, external pressures such as political instability, and internal factors including poor stakeholder communication [3].

Effective risk management is therefore essential for project success, as it minimises adverse impacts on key objectives relating to cost, time, scope, and quality [4]. Risk management encompasses a systematic process of identifying, assessing, mitigating, and monitoring potential risks to address uncertainties that may affect project outcomes. As Fink [21] notes, robust risk management not only reduces potential losses but also enhances decision-making by offering a structured framework for evaluating strategic alternatives. Central to this process is risk assessment, which evaluates the probability and potential impact of adverse events. Established approaches, such as the probability-impact (P-I) model and quantitative techniques like Monte Carlo Simulation (MCS), have been developed to support this evaluation [22]. However, these methods frequently fall short in capturing the interdependencies among risk factors—a critical limitation widely acknowledged in the literature [23].

Comparative studies highlight that the financial and insurance industries have benefited from decades of regulatory-driven innovation and abundant data, resulting in more mature risk quantification practices (e.g., [24,25]). In contrast, construction risk management has been slower to adopt similar advancements due to project uniqueness, data fragmentation, and industry fragmentation. Many projects continue to rely on informal, experience-based approaches, resulting in inconsistent and suboptimal outcomes [9]. Moreover, while cost and schedule risks receive considerable attention, the impact of risks on project quality and overall performance remains underexplored in both research and practice [26]. This imbalance underscores the need for a more holistic perspective that simultaneously considers all project objectives.

Risk management in construction is also highly context-specific. Political, economic, and cultural factors significantly shape the nature and extent of risks, particularly in international projects. Regulatory frameworks, labour market conditions, and local customs often present distinctive challenges for project teams [1]. As the industry becomes increasingly globalised, understanding these contextual variables has emerged as a priority for both researchers and practitioners.

Despite notable advances in tools and methodologies, significant gaps remain in the implementation of comprehensive risk management frameworks. Few models adequately represent the interconnected nature of risk factors and their cumulative effects across multiple project goals [4,23]. These shortcomings highlight the need for integrated approaches capable of addressing the dynamic and multifaceted risk landscape of contemporary construction projects.

3. Research Methodology

A literature review extends beyond a mere compilation of references. It offers a comprehensive review, critical evaluation, and synthesis of existing scholarship on a specific topic [27]. According to Fink [21], such studies integrate findings from individual investigations to construct a coherent and integrated argument, while simultaneously identifying avenues for future research. Literature reviews occupy a central position in scholarly endeavour, as scientific progress is inherently cumulative and relies on the generation of new knowledge through the systematic interpretation and synthesis of prior work [28,29].

This study adopts a systematic and replicable approach to reviewing the literature. Figure 1 illustrates the multi-stage process employed. In the initial phase, relevant articles addressing risk modelling and assessment in construction were identified. A targeted selection of 15 leading journals was then undertaken for in-depth analysis, based on the

following rigorous criteria to ensure quality, relevance, and comprehensiveness: (1) Indexing and Ranking: Journals were drawn from reputable databases such as Scopus and Web of Science (WoS), confirming high academic standards; (2) Relevance to the Field: Priority was given to journals with a strong emphasis on construction management, project management, and risk analysis; (3) Impact Factor and Citation Metrics: Journals demonstrating significant influence within the academic community, as measured by impact factors and citation records, were prioritised; and (4) Stability and Longevity: Only journals with a consistent publication record spanning the review period were included to capture long-term trends and developments in the field.

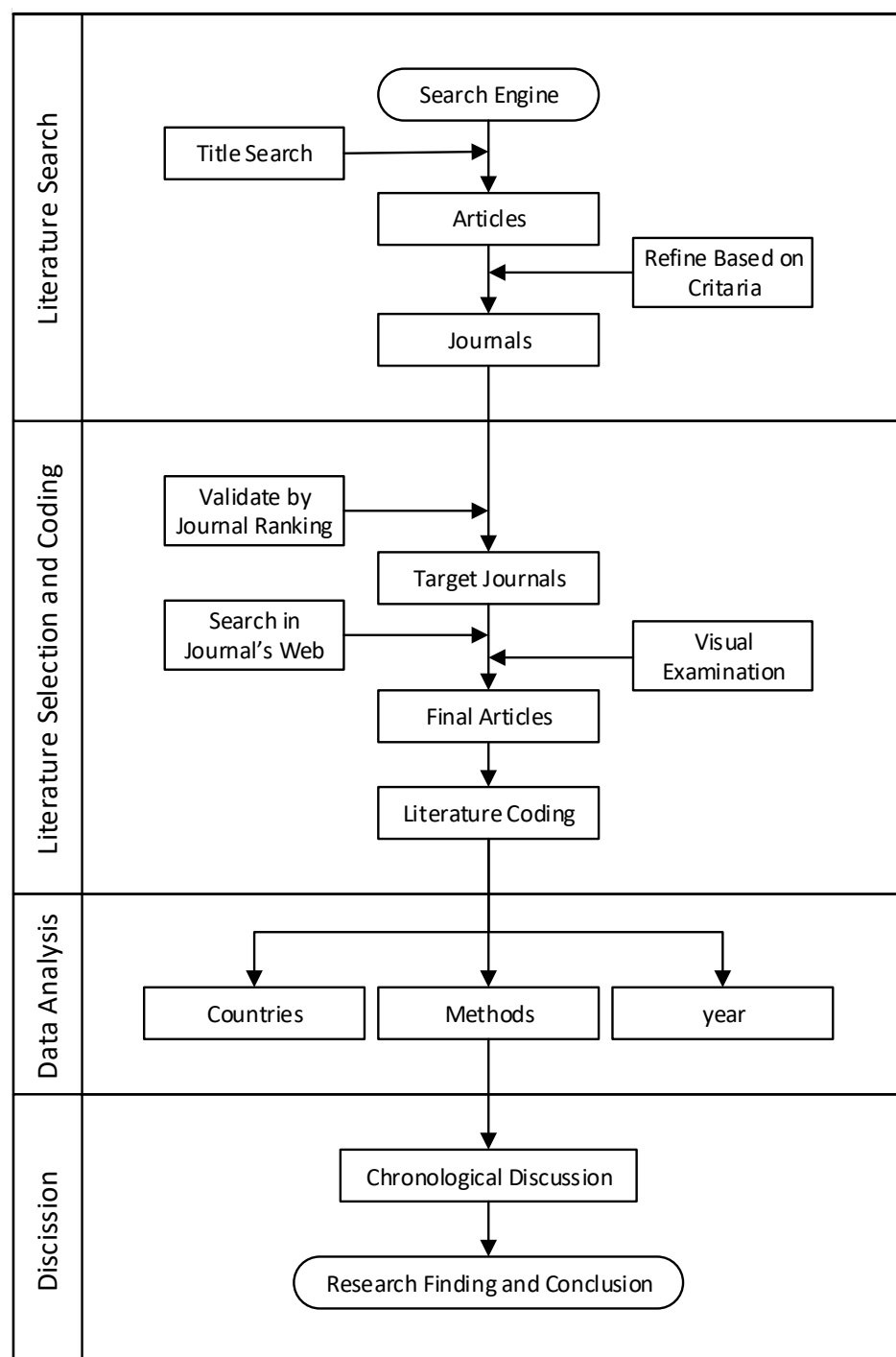


Figure 1. Research framework for the study.

This structured selection process ensures the robustness and representativeness of the reviewed literature, forming a reliable foundation for subsequent analysis.

4. Data Collection

4.1. Literature Search

The literature review was conducted in four distinct stages to ensure a comprehensive and systematic understanding of risk modelling and assessment practices in construction. The literature search was limited to publications from 1990 to 2025. While important conceptual foundations were established in the 1980s (e.g., [20]), the systematic development and empirical application of risk modelling and assessment methods in construction gained momentum from 1990 onwards. This starting point therefore enables a focused analysis of the field's methodological evolution while acknowledging the influence of earlier foundational works.

A comprehensive search was performed in the Scopus database, targeting the 'title', 'abstract', and 'keyword' fields. Search terms included combinations of 'risk assessment', 'risk evaluation', 'assessment of risk', 'evaluation of risk', 'risk analysis', 'risk modelling', 'construction', and 'infrastructure', with exclusions applied for 'health' and 'safety'. The search was restricted to peer-reviewed articles in English, published after 1989, within the subject areas of engineering and business. The custom query employed was as follows: TITLE-ABS-KEY((risk assessment OR risk evaluation OR assessment of risk OR evaluation of risk OR risk analysis OR risk modelling) AND (construction OR infrastructure) AND NOT(health OR safety)) LANGUAGE(English) PUBYEAR > 1989 SUBJAREA(ENGI).

Scopus was selected as the primary database for this review because of its particularly strong and extensive coverage of high-quality construction management, project management, and civil engineering literature, including a broader range of international and interdisciplinary journals compared with alternative databases [30,31]. Its comprehensive indexing of titles, abstracts, and keywords, together with its inclusion of a higher number of relevant journals in the built environment, made it the most suitable source for identifying the core literature on construction risk modelling and assessment. This choice is consistent with recent high-impact systematic reviews in the field (e.g., [11,32,33]).

Nevertheless, the authors acknowledge that reliance on a single database may introduce a degree of coverage bias by potentially omitting studies indexed exclusively in other major databases such as WoS. Although the overlap between Scopus and WoS is substantial, particularly within engineering and management disciplines [34], some high-quality or highly cited works may have been missed. To mitigate this limitation, the review focused on 15 leading journals that are well-represented in both databases, supplemented by rigorous manual screening of titles, abstracts, keywords, and reference lists.

Although the search parameters were rigorously defined, some articles that partially deviated from the criteria but contained relevant keywords were retained following manual screening. The final selection prioritised publications from leading journals and considered the annual volume of relevant risk assessment articles. Subsequent refinement identified the 15 journals with the highest number of pertinent publications on construction risk management, as detailed in Table 1. Among these, six are recognised as top-ranked outlets in construction engineering and management [35]: Construction Management and Economics (CME), Journal of Construction Engineering and Management (JCEM), Engineering, Construction and Architectural Management (ECAM), Journal of Management in Engineering (JME), International Journal of Project Management (IJPM), and Automation in Construction (AIC). These journals were prioritised for their strong focus on international construction trends and their prominent positions in the 2025 Scientific Journal Ranking (SJR).

Table 1. Number of relevant 91 articles on construction risk management in the 15 selected journals.

Journal Title	Journal Abbreviations	Number of Relevant Papers
International Journal of Project Management	IJPM	24
Journal of Construction Engineering and Management	JCEM	22
Construction Management and Economics	CME	8
Automation in Construction	AIC	6
International Journal of Construction Management	IJCM	5
Journal of Management in Engineering	JME	4
Engineering Construction and Architectural Management	ECAM	4
Journal of Computing in Civil Engineering	JCCE	3
Sustainability	SU	3
Safety Science	SS	3
Reliability Engineering and System Safety	RESS	2
Journal of Cleaner Production	JCP	2
Journal of Civil Engineering and Management	JoCEM	2
KSCE Journal of Civil Engineering	KSCE	2
Expert Systems with Applications	ESWA	2
Total number		91

A targeted selection of 15 leading journals in construction management, project management, and civil engineering was made based on their established reputation, high impact factors, and substantial contribution to the risk management literature. These 15 journals accounted for approximately 68% of the 717 initially retrieved documents in the Scopus search, demonstrating strong representativeness of the core field. Journals with very low publication volumes on the topic were also omitted to maintain analytical depth and feasibility. The decision to focus the in-depth analysis on these 15 high-impact journals, while ensuring quality and relevance, may introduce a degree of selection bias by prioritising influential outlets over studies in lower-tier or more specialised venues. This boundary was deliberate, however, to capture the most influential contributions that have shaped the field, as evidenced by their strong citation records and prominence in prior reviews (e.g., [35,36]).

To assess the potential impact of this limitation, the authors note that the identified methodological trends and persistent gaps are broadly consistent with the wider literature. Nevertheless, studies published outside these 15 journals could offer additional context-specific insights or emerging methods from niche or regional perspectives. Overall, the rigorous selection criteria and comprehensive coding process ensure that the core findings remain representative of the field's primary scholarly discourse.

The search query was constructed using a combination of Boolean operators and targeted keywords to capture relevant studies on risk modelling and assessment in construction. To ensure the reliability and robustness of the results, several statistical and analytical criteria were applied. These included preliminary filtering based on publication type (peer-reviewed journal articles only), language (English), and date range, followed by structured title, abstract, and keyword screening using a checklist derived from the inclusion/exclusion criteria. The final sample size was deemed statistically sufficient for taxonomic synthesis, as it exceeded the thresholds commonly recommended for reliable qualitative and quantitative pattern identification in systematic literature reviews (e.g., >50–70 articles for thematic saturation in construction management research; see [36]). These steps collectively ensured analytical rigour, minimised selection bias, and enhanced the replicability of the review process.

4.2. Literature Selection

Guidance from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was followed to ensure transparency, rigour, and replicability in the literature search, screening, and selection processes [37]. This involved a structured protocol covering identification of records, screening, eligibility assessment, and inclusion, as detailed in the PRISMA flow diagram (Figure 2). The completed PRISMA 2020 checklist is provided as Supplementary Material. Similar PRISMA-guided approaches have been successfully employed in related construction and safety research (e.g., [38,39]), further validating the methodological framework adopted in the present study.

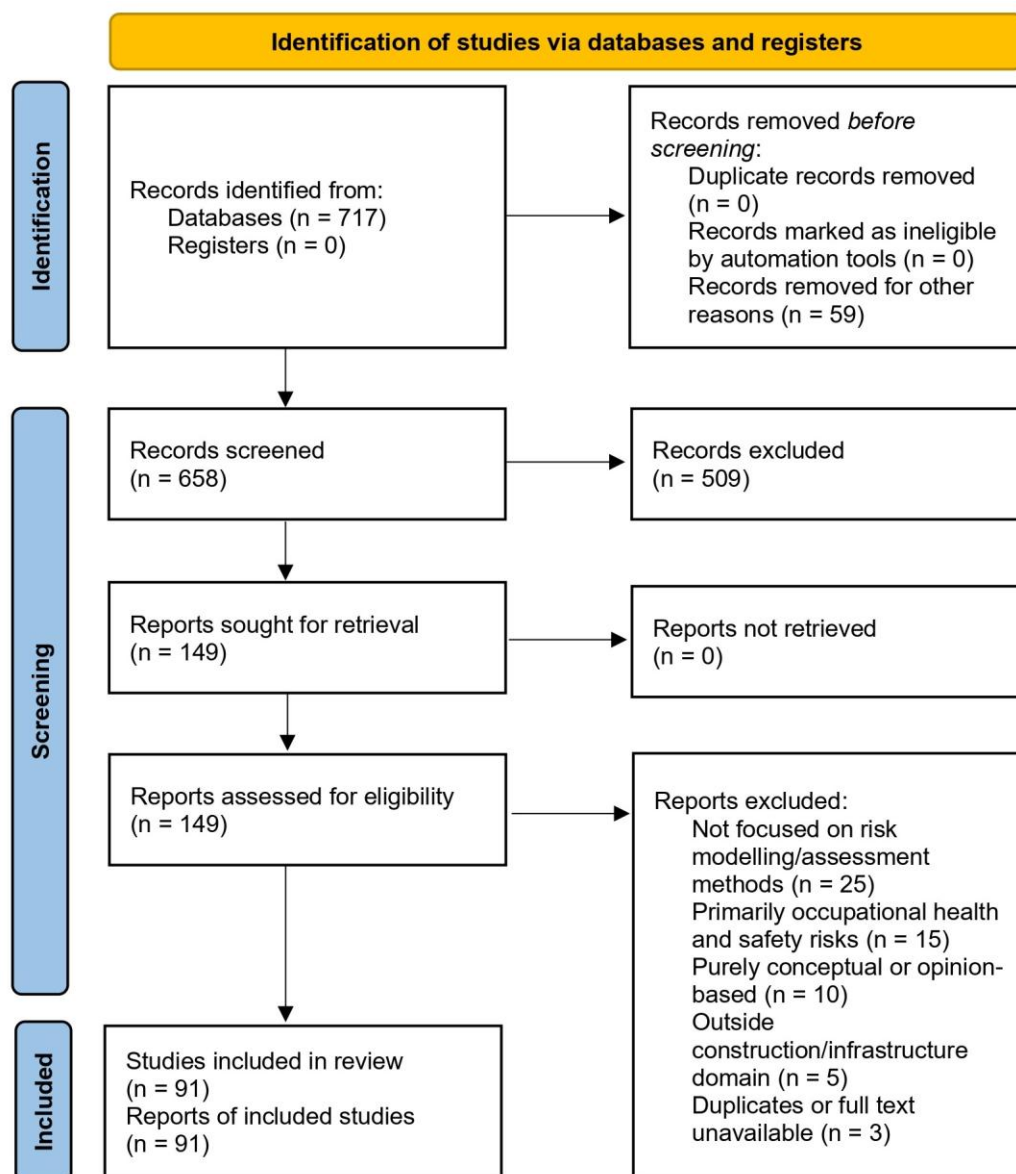


Figure 2. PRISMA diagram describing the flow of decision to review literature and categorising its content.

The initial Scopus search yielded 717 publications between 1990 and 2025 within the 15 selected journals listed in Table 1. While some relevant works may have been inadvertently excluded, this review does not aim to provide an exhaustive catalogue of all related articles. Instead, it focuses on identifying underlying trends and addressing key knowledge gaps.

The literature selection process followed a structured, multi-stage approach, as illustrated in Figure 2. The initial Scopus search yielded 717 publications between 1990 and 2025 within the 15 selected journals. After removing non-research items and applying preliminary filters, 658 documents remained for detailed title, abstract, and keyword screening.

In the next stage, clearly defined inclusion and exclusion criteria were applied. Articles were retained if they were peer-reviewed English-language journal articles with an explicit focus on risk modelling, assessment, or analysis methods applied to construction or infrastructure projects. Studies were excluded if they primarily addressed occupational health and safety risks, were purely conceptual or opinion-based without a clear methodological contribution, fell outside the construction or infrastructure domain, or were duplicates or inaccessible. This process reduced the pool to 149 publications for full-text review. During full-text assessment, a further 58 articles were excluded for the following specific reasons: (1) the primary focus was not on risk modelling or assessment methods (e.g., general risk identification or qualitative perception studies without methodological advancement); (2) the work centred on occupational health and safety rather than project-level risk modelling/assessment; (3) the article lacked a clear methodological framework; (4) the study was outside the construction or infrastructure domain; or (5) the full text was unavailable or duplicated. The final sample comprised 91 articles that fully satisfied all inclusion criteria and were included in the taxonomic analysis. The complete selection pathway is summarised in the flow diagram (Figure 2).

As shown in Table 1, the International Journal of Project Management (IJPM) and the Journal of Construction Engineering and Management (JCEM) contributed the largest share of relevant papers, together accounting for approximately 60% of the final sample. These two journals have played a particularly influential role in shaping the literature on risk modelling and assessment in construction.

Notwithstanding the rigorous selection process, certain biases inherent to any literature review cannot be eliminated. This study relies exclusively on the data retrieved through the described methodology. The review was conducted by a single reviewer, adhering to principles of selectivity, neutrality, and transparency [40]. This approach enhances the replicability and consistency of the process.

4.3. Literature Coding and Taxonomy Framework

The analysis adopted a systematic taxonomic approach combined with thematic synthesis. A clear taxonomy framework was developed based on four primary classification dimensions to organize and map the literature:

1. Chronological Evolution: Articles were categorized into four periods (1990s, 2000s, 2010–2020, and post-2020) to trace the development of risk modelling and assessment methods over time.
2. Geographical Patterns: Country contributions were analysed to identify research productivity and regional trends.
3. Methodological Type: Studies were classified according to the primary risk assessment approach used (e.g., P-I model, Fuzzy Set Theory (FST), Bayesian Belief Networks (BBN), MCS, AI and ML techniques, and hybrid methods).

This structured taxonomy enabled a systematic mapping of the field, identification of dominant approaches, emerging trends, and persistent gaps. Thematic analysis was then applied within this taxonomic structure to synthesize recurring themes, strengths, limitations, and future research directions. The combination of a clearly defined taxonomy with thematic synthesis provides both a structured overview and deeper interpretive insights, distinguishing this review from conventional narrative or purely thematic literature reviews.

The literature coding process was systematic and iterative to ensure comprehensive data extraction and thematic accuracy. Initially, the selected articles' titles, abstracts, and keywords were reviewed to determine their relevance to the study's objectives. When these sections did not provide sufficient information, the full text of the articles was carefully examined to facilitate detailed coding. As the sole author, taxonomic classification and coding were performed by the researcher. To promote consistency, each article was reviewed and coded on two separate occasions, with a time interval between rounds. Any ambiguous cases were revisited and resolved. This self-checking process supported the reliability of the classification.

The coding process specifically focuses on key aspects of each study, including its methodology and conclusions. To enhance transparency and replicability, the following information was systematically collected and documented during the coding process: (i) Title of the Article: To identify the specific study; (ii) Year of Publication: To track temporal trends in the research field (iii) Journal Name: To analyze the dissemination patterns and credibility of sources; (iv) Author Name(s): To recognize individual and collaborative contributions; (v) Country or Region: This refers to the authors' origin rather than the location of the study, providing insights into regional research focuses; and (vi) Primary Tools and Theories include the main analytical frameworks, models, or methodologies for evaluating and assessing risk.

By systematically collecting this information, we organized the dataset in a way that not only facilitated coding but also provided a foundation for thematization. This approach ensures that the study's findings are transparent and replicable, meeting the highest standards of qualitative research.

5. Data Analysis

5.1. Publications Distributed by Country

This section presents the key findings from the taxonomic analysis of the 91 selected articles. The results are organised according to the main classification dimensions: publication trends over time, geographical distribution of authorship, and methodological approaches.

Among all the selected papers, the earliest to be published appeared in the International Journal of Project Management in August 1990. It presented risk analysis techniques related to the application of proposal assessment in the construction industry [41]. As shown in Figure 3, the annual number of publications remained relatively low in the early years.

In contrast to Zhou et al. [42], who analyzed the country/region distribution concentrated on the study location, this review is based on authors or institutions. A similar criterion was also considered by Junjia et al. [43]. For those works with authors from different countries, each country was considered once. It was observed that many of the works involved the United Kingdom. As shown in Figure 4, 25 nations spanning six continents were included. The United Kingdom accounted for more than 20% of the works. Other nations of note are the United States, South Korea, Singapore, China, Canada, and Australia. In particular, Singapore produced six publications despite its small construction industry. Other countries published only five or fewer articles. As a region, Asia accounted for 40 articles, demonstrating an increase in construction safety in developing nations. However, it is worth noting that many European journals that publish in languages other than English were excluded.

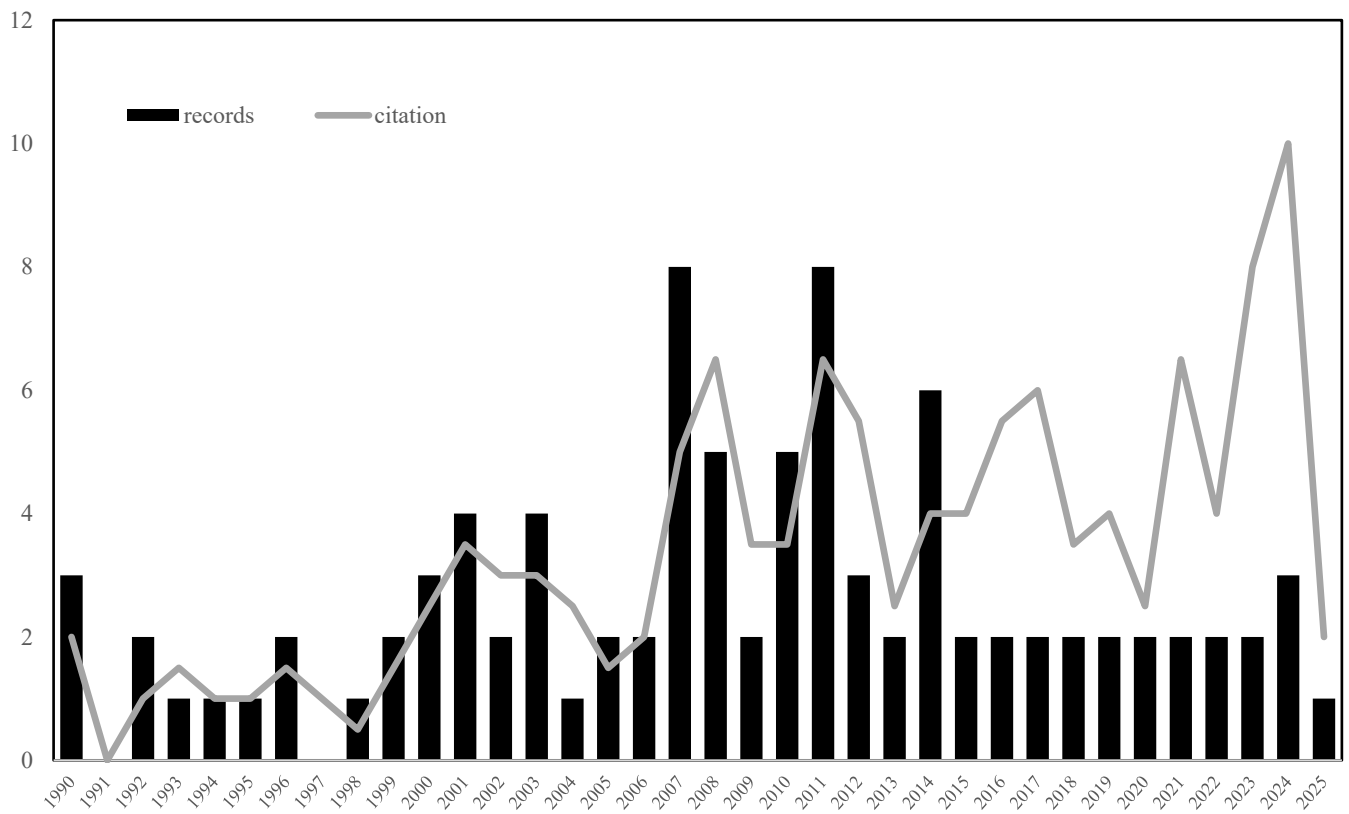


Figure 3. Number of annual risk assessment publications in the 15 selected journals.

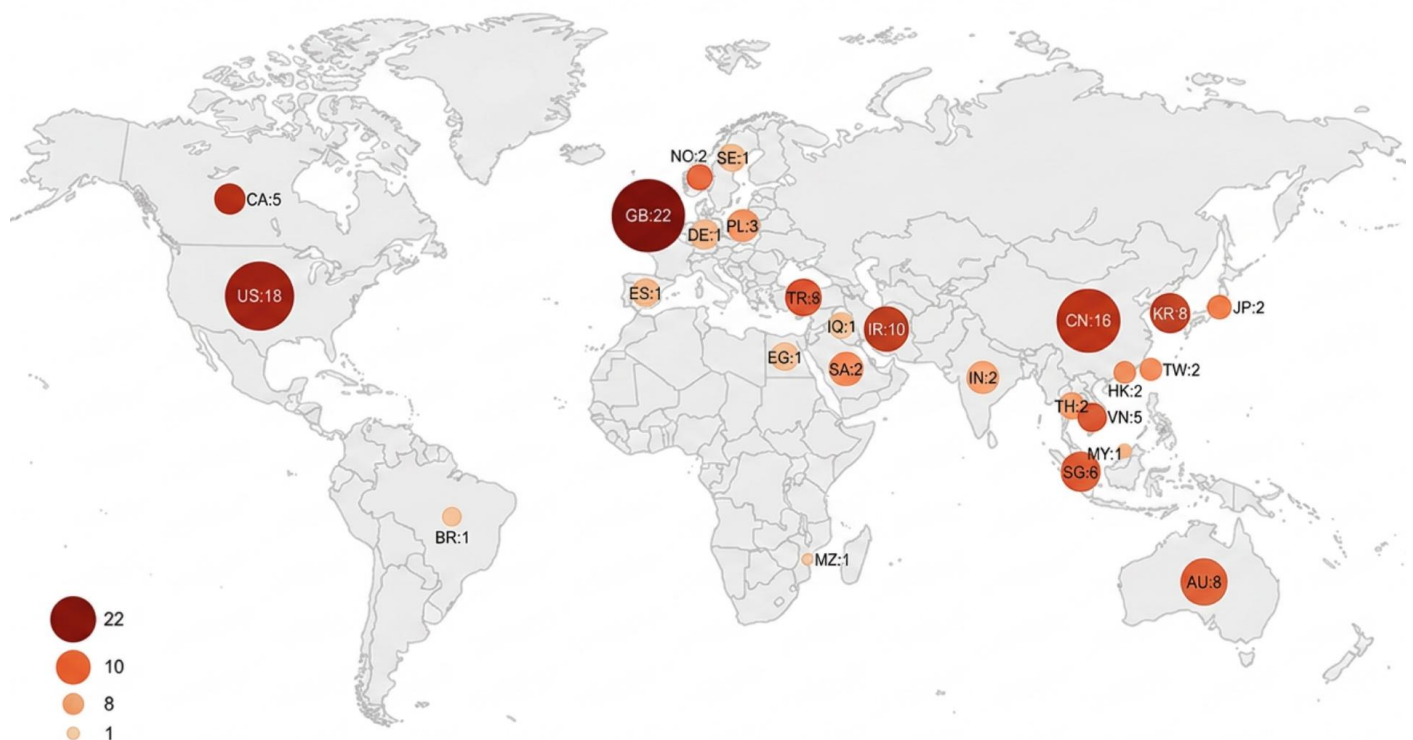


Figure 4. Publication distribution by countries.

5.2. Assessment Methods Distribution

Previous studies have examined construction risk assessment from various perspectives. For the purpose of this analysis, the 91 selected papers were classified according to their primary risk assessment methods. The coding process identified 23 distinct methods, reflecting the methodological diversity in the field. These include FST, Analytic Hierarchy Process (AHP), MCS, and others. Table 2 presents a detailed distribution of these methods.

Table 2. Distribution of construction risk assessment methods.

Assessment Method	Abbreviation	Number (%)
Influence diagramming	ID	5 (3.97)
Monte Carlo simulation	MCS	9 (7.14)
Project evaluation and review technique	PERT	4 (3.17)
Fuzzy set theory	FST	32 (25.40)
Analytic hierarchy process	AHP	12 (9.52)
Literature review—cognitive argument	LR	14 (11.11)
Risk assessment matrix	RAM	7 (5.56)
Stochastic programming	SP	1 (0.79)
Fault tree analysis	FTA	3 (2.38)
Case-based reasoning	CBR	1 (0.79)
Utility theory	UT	3 (2.38)
Bayesian belief networks	BBN	8 (6.35)
Failure modes and effects analysis	FMEA	3 (2.38)
System dynamics	SD	3 (2.38)
Microsoft Excel	MSE	1 (0.79)
GTOPSIS	GTO	1 (0.79)
Genetic Algorithm	GA	2 (1.59)
Bootstrap	BOO	1 (0.79)
Multi-attribute direct rating & consistent fuzzy preference relations	MADR & CFPR	1 (0.79)
Neural networks	NN	3 (2.38)
Sensitivity analysis	SS	1 (0.79)
Questionnaire	QU	2 (1.59)
Probability theory	PT	2 (1.59)
DEMATEL	DEMATEL	1 (0.79)
Artificial Intelligence	AI	2 (1.59)
SWARA	SWARA	1 (0.79)
Machine Learning	ML	2 (1.59)
WASPAS	WASPAS	1 (0.79)

Note: Percentages may not sum to 100% due to rounding to two decimal places.

FST, AHP, MCS, and Literature review—cognitive argument (LR) emerged as the most frequently adopted approaches, collectively accounting for approximately 55% of the studies. Other commonly employed methods include influence diagramming (ID), the Project Evaluation and Review Technique (PERT), and the Risk Assessment Matrix (RAM).

Figure 5 illustrates the evolution of assessment methods across these periods. Research in the 1990s was relatively fragmented and primarily relied on foundational techniques such as PERT, MCS, ID, and FST. Key examples include the application of ID (Al-Bahar and Crandall [44]; Diekmann [45]; Huseby and Skogen [46]), MCS (Al-Bahar and Crandall [44]; Diekmann [45]; Hull [41]; Huseby and Skogen [46]; Dawood [47]), PERT (Hull [41]; Yeo [48]; Dawood [47]; Mulholland and Christian [49]), FST (Diekmann [45]; Paek et al. [50]; Wirba et al. [51]), AHP (Dey et al. [52]; Zhi [53]), and LR (Williams [54]; Ward [55]).

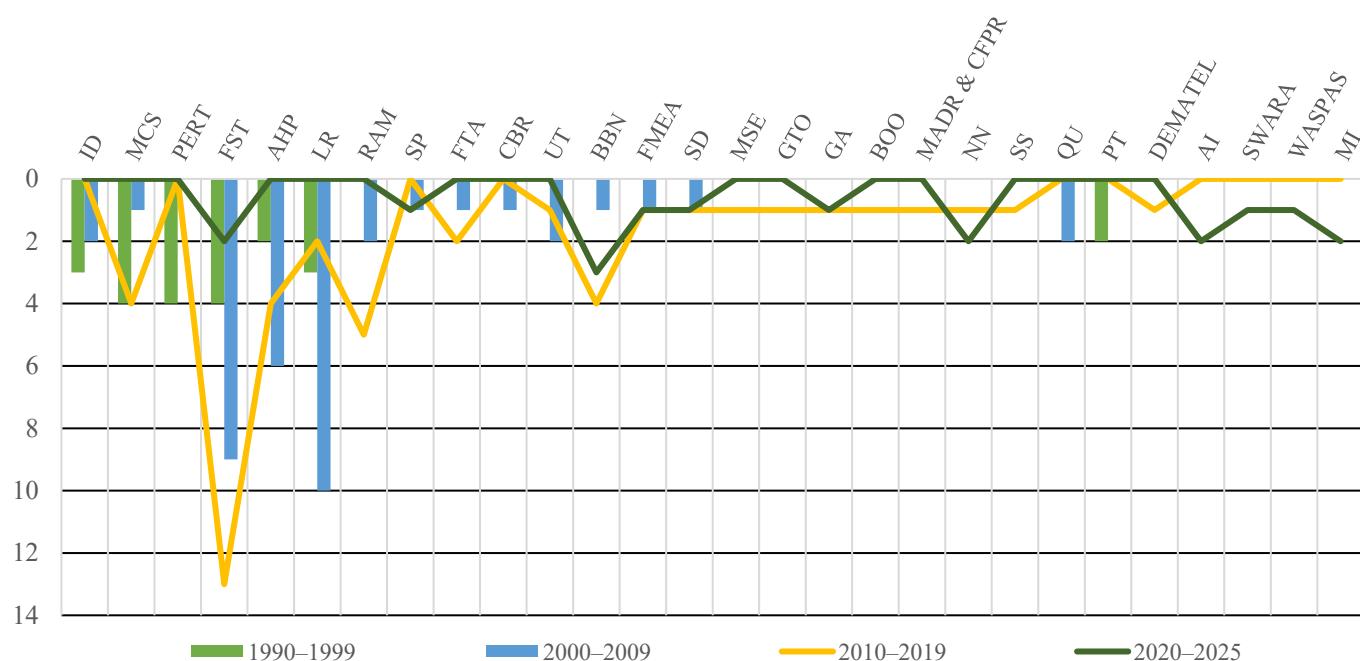


Figure 5. Combo chart illustrating the evolution and relative frequency of risk assessment methods in construction projects over time (1990–2025).

During the period 2000–2005, LR remained prevalent (Chapman and Ward [56]; Bacarini and Archer [57]; Patterson and Neailey [58]; Baloi and Price [59]; Chapman and Ward [60]; Jannadi and Almishari [61]), alongside continued use of FST (Tah and Carr [62]; Tah and Carr [63]; Choi et al. [64]; Shang et al. [65]). With the notable exceptions of Shen et al. [66] and Santoso et al. [67], few innovative methods were introduced during this interval.

To examine temporal trends, the period 1990–2025 was divided into five intervals (with the final period extending to mid-2025). Figure 5 presents a combination chart depicting both the overall frequency and the evolution of the primary risk assessment methods across these periods. This visualisation clearly shows the shift from predominantly basic probabilistic methods (e.g., PERT, MCS, and ID) in the 1990s to increasingly sophisticated hybrid, fuzzy logic-based, and AI-enhanced approaches after 2010. Research in the 1990s was relatively fragmented. From 2005 onwards, the methodological landscape became significantly more diverse and sophisticated, particularly after 2007. Twelve distinct methods were employed between 2005 and 2010, increasing further in subsequent periods. Between 2010 and 2015, 17 studies were recorded, representing 61% of the methodological applications identified in the review. While established techniques such as FST and AHP continued to feature prominently, they were often enhanced through integration with newer tools. For example, Hashemi et al. [68] applied a bootstrap approach with interval numbers for bridge construction risk analysis. There was also growing emphasis on evaluating risks against multiple project objectives, including cost, time, and quality. Overall, a wide range of innovative techniques has been adopted since the early 2000s to address the increasing complexity of construction risk assessment.

6. Discussion

6.1. The 1990s—Reliance on Basic Methods

The 1990s witnessed a marked increase in research interest in construction risk modelling and assessment. During this period, researchers primarily relied on Probability Theory (PT) and FST, although other techniques such as the AHP also emerged.

Hull [41] developed models based on MCS and PERT to evaluate risks related to project cost and duration. In the same year, Yeo [48] introduced the ‘contingency engineering’ methodology, which combined range estimating with PERT to assess project cost risk and determine appropriate contingency allowances. This represented one of the earliest structured attempts to evaluate risk contingencies. Al-Bahar and Crandall [44] applied ID and MCS techniques, implementing the P-I model to provide a systematic framework for risk identification, evaluation, and management.

ID was further utilised by Diekmann [45] to represent risky events, with MCS and FST employed for quantitative assessment. Diekmann critically examined the suitability and limitations of PT-based methods from both theoretical and practical perspectives, noting that existing techniques were often either overly simplistic or excessively complex for practical use by analysts. Similarly, Huseby and Skogen [46] used ID and MCS, supported by the DynRisk software, to analyse interrelationships and overlaps among risks.

Paek et al. [50] presented one of the early applications of FST to support contractors in determining appropriate bid prices by pricing construction risks. Dey et al. [52] reintroduced AHP into risk assessment, combining subjective and objective evaluations within a P-I framework. Zhi [53] applied AHP to assess risks in overseas construction projects, modifying the P-I model and scaling impact evaluations from 0 to 1 rather than the conventional 1–9 Saaty scale.

Williams [54] provided a seminal critique of the P-I risk model, highlighting that multiplying probability and impact produces an expected value that can be misleading for risk prioritisation. He advocated considering probability and impact separately and endorsed the three-dimensional model (probability-impact-predictability) proposed by Charette [69] as a superior alternative. In contrast, Wirba et al. [51] promoted an FST-based risk management approach that incorporated linguistic variables to identify risks, assess their likelihood, and examine interdependencies. While influential, this work faced criticism regarding the use of fuzzy weighted mean methods for calculating interdependence coefficients, which essentially reduced to simple averaging. The study also defined risk impact in terms of the cost of response strategies.

Dawood [47] applied MCS to evaluate activity durations, treating risk primarily as estimation variance to improve the accuracy of project duration forecasts. Mulholland and Christian [49] utilised PERT to analyse schedule risk, where greater variability in the project duration distribution indicated higher schedule risk.

Ward [55] echoed Williams’ concerns about the P-I model, calling for improvements in risk assessment. He emphasised the need to account for the multiple impacts of risks across all project objectives when calculating total risk exposure. Ward further criticised the use of probability-impact grids and the aggregation of numerical scores into a single composite risk rating.

The P-I model became entrenched due to its simplicity, ease of communication to diverse stakeholders, and alignment with contractual and regulatory requirements that favour straightforward risk registers. Institutionally, its dominance is reinforced by widespread adoption in project management standards (e.g., PMBOK [4]), client expectations, and the industry’s preference for tools that facilitate rapid decision-making under time and resource constraints. These practical advantages explain why the P-I model has persisted for over 35 years, even as its theoretical limitations—such as the assumption of risk independence and limited handling of uncertainty—have been repeatedly highlighted.

While these foundational techniques provided essential building blocks, their applicability was largely limited to relatively stable project environments with well-defined risks. They struggled with the increasing complexity and uncertainty of modern construction projects, particularly regarding interdependencies and dynamic conditions.

6.2. *The New Millennium (2000s)—Shift Toward Qualitative and Hybrid Methods*

The early 2000s marked a substantial growth in research on construction risk modelling and assessment, facilitated by advances in computing power and the development of more sophisticated decision support systems (DSSs). Although these systems offered improved accessibility, they were not without limitations. During this period, the AHP and FST gained prominence as effective approaches for addressing vagueness, complexity, and subjective bias in risk evaluation. Compared to traditional PT-based methods, AHP and FST were increasingly regarded as more suitable for construction contexts. While PT-based techniques continued to appear, their dominance declined markedly.

A notable conceptual shift also occurred, with risk increasingly viewed as an intrinsic project characteristic rather than merely an estimate of variance. This perspective facilitated the greater integration of risk analysis into project decision-making processes.

Chapman and Ward [56] critiqued the P-I grid for introducing unnecessary ambiguity through oversimplification. They advocated a ‘minimalist’ approach that evaluates risk using ranges rather than single-point estimates. Hastak and Shaked [70] applied AHP to assess risks in overseas construction projects within a P-I framework; however, the method was criticised for its oversimplification, relying on subjective 0–100 scales and aggregating individual evaluations into an overall project risk score.

Tah and Carr [62] developed an FST-based approach to evaluate risk probability, impact, and interdependencies, introducing a new aggregation formula to address limitations of conventional fuzzy averaging. This work required further validation. Baccarini and Archer [57] adopted a P-I-based methodology used by the Western Australian Department of Contract and Management Services to rank projects according to risks across cost, time, and quality objectives. While comprehensive in considering multiple objectives, the approach was limited by its simplistic aggregation method, which could produce misleading overall risk scores.

Shen et al. [66] introduced a risk significance index for joint venture infrastructure projects, though it remained grounded in the conventional P-I model. Xu and Tiong [71] employed stochastic programming to refine cost estimation by treating risk as estimation variance. Tah and Carr [63] further advanced FST applications for project risk rating but did not propose a method for integrating individual ratings across multiple objectives (cost, time, safety, and quality).

Patterson and Neailey [58] emphasised the value of risk registers as a core risk management tool and developed an interactive DSS. Baloi and Price [59] provided a significant review of risk analysis techniques, highlighting FST as particularly promising for the construction industry. Ward and Chapman [60] proposed replacing ‘project risk management’ with ‘project uncertainty management’ to better encompass both threats and opportunities. Jannadi and Almishari [61] introduced a 3-D risk model (probability, impact gravity, and exposure) focused primarily on health and safety, alongside supporting RAM software, although it lacked mechanisms for overall project risk aggregation.

Santoso et al. [67] continued to apply the P-I model for contingency estimation. Choi et al. [64] proposed a fuzzy-based uncertainty model capable of handling objective probabilities and subjective judgements. From 2005 onwards, publications surged, accompanied by numerous proposals for enhanced modelling techniques and DSSs.

Molenaar [72] presented the Washington State Department of Transportation’s MCS methodology for programmatic cost risk analysis, still based on the P-I model. Shang et al. [65] developed an internet-accessible DSS utilising FST and linguistic variables for risk assessment during design and conceptual phases. Poh and Tah [73] addressed risk interdependencies through influence networks focused on cost and duration, though the approach lacked simultaneous multi-objective integration. Thomas et al. [74] combined fault tree analysis with linguistic variables and the fuzzy Delphi method to evaluate specific risk scenarios.

Hsueh et al. [75] integrated AHP with utility theory (UT) for multi-criteria risk assessment in joint ventures. Dikmen et al. [76] introduced a novel fuzzy risk assessment methodology for international projects that incorporated organisational risk manageability (e.g., company experience) as a distinct factor. Zeng et al. [77] extended the P-I model by adding a factor index (FI) representing environmental influence ($R = L \times S \times FI$), combining it with FST and AHP. Zhang and Zou [78] developed a fuzzy AHP approach, while Zhang [79] emphasised project vulnerability, comprising exposure and coping capacity, as a critical but underexplored dimension.

Additional contributions included Dikmen et al. [80] on case-based reasoning for bid markup and contingency estimation, Zou et al. [81] on key risks in Chinese construction, Han et al. [82] on a significance-probability-impact model, Choi and Mahadevan [83] on data integration using fuzzy methods, El-Sayegh [84] on P-I-based contingency estimation, Nasirzadeh et al. [85] on fuzzy system dynamics (SD) for risk simulation, Zayed et al. [86] on a macro-micro risk indexing approach, and Luu et al. [87] on BBN for schedule delay probability.

Although fuzzy logic and hybrid approaches improved handling of linguistic uncertainty, their applicability remained constrained by subjectivity in membership function definition and limited validation in large-scale, multi-stakeholder infrastructure projects. Many studies relied on hypothetical or small-sample cases, reducing generalisability to real-world mega-projects.

6.3. 2010–2020—Focus on Quantitative and Integrated Methods

A defining characteristic of this period was the growing emphasis on quantitative risk assessment methods that combine the probability of risk occurrence with its potential impact, offering a more structured basis for risk prioritisation and evaluation [88]. These approaches frequently integrated multiple techniques, including multi-criteria decision-making (MCDM) tools and fuzzy systems [89,90]. Critical risk factors (CRFs) also received increased attention as key drivers of project outcomes.

Fung et al. [91] developed an Excel-based tool for safety-focused project risk assessment, defining risk as the product of accident frequency and severity. Severity was calculated as the aggregate of additional cost, time, and injury, with each component normalised to a 0–1 scale. Mojtahedi et al. [92] broadened risk evaluation by incorporating safety and environmental dimensions through the Group Technique for Order of Preference by Similarity to Ideal Solution (GTOPSIS), enabling the aggregation of expert opinions and the assessment of risk impacts across cost, time, and health, safety, and environmental categories.

Several studies addressed the influence of risk context and surrounding environment. Ökmen and Öztas [93], Jun and El-Rayes [94], and Choudhry et al. [95] applied MCS to quantify risk impacts. Chan et al. [96], along with Wambeke et al. [97], Hanna et al. [98], and Al-Sabah et al. [99], employed the RAM and the P-I model for overseas projects and contingency estimation. However, these approaches were often limited by simplistic aggregation methods that failed to fully quantify overall project risk.

Nieto-Morote and Ruz-Vila [100] combined AHP and FST to mitigate subjectivity and complexity in risk evaluation. Hashemi et al. [68] introduced a bootstrap technique with interval numbers to address data scarcity in probability and impact assessment. Fuzzy AHP was widely adopted for risk structuring by Xu et al. [101], Li and Zou [102], Cho et al. [103], and Subramanyan et al. [104].

Beyond hierarchical structures, researchers increasingly explored methods to model risk interdependencies, including BBN, ID, and fault trees [105–108]. Gurcanli et al. [109] applied the Fine-Kinney and L-matrix methods for safety risk assessment, assigning risk scores as resources to construction activities, although the approach was primarily limited to cost and schedule impacts.

Hyari et al. [110] proposed a risk-based model for detecting unbalanced bids, addressing the stochastic nature of quantities. Qazi et al. [111] introduced a project complexity and risk management framework grounded in Expected UT and BBNs to capture causal relationships and interdependencies. Tavakolan and Etemadinia [112] developed fuzzy weighted interpretive structural modelling (FWISM) to identify risk interactions, although it analysed risks largely in isolation.

Li et al. [113] addressed dynamic risk simulation in prefabricated construction through SD modelling, enabling scenario analysis for schedule risk mitigation. Xia et al. [114] combined BBN with a modified Human Factors Analysis and Classification System (HFACS) to predict safety performance and identify critical causal factors. Yuan et al. [115] applied Social Network Analysis (SNA) to examine social risks and stakeholder relationships in high-density urban projects in China, while acknowledging limitations in capturing uncertainty and dynamic propagation.

Sarvari et al. [116] presented a conceptual model for evaluating drought-related risks on sustainable urban development. Hatefi and Tamošaitienė [117] utilised an integrated fuzzy DEMATEL/fuzzy ANP approach to analyse interdependencies among risk factors, concluding that time, cost, and safety were the most critical in construction projects.

Bayesian and simulation-based methods demonstrated strong potential for modelling interdependencies; however, their practical applicability was often hindered by high data and expertise requirements, computational intensity, and challenges in integration with existing project management systems. Most applications were tested in controlled or single-project settings rather than across diverse procurement models or international contexts.

6.4. Post-2020—Integration of Advanced and Hybrid Approaches

Post-2020 research has shown a clear acceleration in the adoption of advanced digital and hybrid approaches. AI and machine learning (ML) techniques have emerged as particularly promising, with studies applying neural networks (NN), random forests, and deep learning models for predictive risk forecasting. For example, several works utilised historical project data combined with BIM and IoT inputs to predict cost overruns and schedule delays with higher accuracy than traditional methods [118,119]. These approaches excel in pattern recognition and handling large datasets, offering the potential for real-time risk monitoring.

However, the evaluation of these methods reveals significant limitations. Many applications remain proof-of-concept studies with limited generalisability due to small sample sizes or reliance on simulated rather than real project data. The black-box nature of complex models reduces interpretability, making it difficult for practitioners to understand and trust the underlying reasoning, a critical barrier in contractual and high-stakes environments. Furthermore, issues of data scarcity, high computational requirements, and integration challenges with legacy project management systems persist. Hybrid models that combine AI and ML with established methods (e.g., Fuzzy-AHP or BBN) show better potential but still require more robust validation through longitudinal case studies in live construction settings.

The period from 2020 to 2025 has been characterised by significant advancements in risk modelling and assessment methodologies, with a clear shift toward hybrid, data-driven, and technology-enhanced approaches aimed at improving project outcomes in increasingly complex environments. Alongside traditional and quantitative methods, ML and artificial intelligence (AI) techniques have gained traction for predicting risk factors and managing uncertainties [120,121].

Guan et al. [122] proposed a fuzzy Bayesian Belief Network (FBBN) model for systematic risk assessment in international construction projects. The model incorporates both occurrence probability and magnitude of impact, providing decision-makers with

structured guidelines for identifying and mitigating critical risk factors through expert-informed causal relationships and conditional probability tables.

Yaseen et al. [123] developed a hybrid Random Forest-Genetic Algorithm (RF-GA) model for predicting construction project delays. The approach demonstrated superior performance compared to classical Random Forest models in forecasting time and cost outcomes, utilising inputs related to stakeholders, project characteristics, resources, and external factors.

Etemadinia and Tavakolan [124] introduced a hybrid SD and interpretive structural modelling (SD-ISM) framework for risk analysis during the design phase, enabling dynamic evaluation of interrelated risks and their effects on project objectives. Alvand et al. [125] presented an integrated fuzzy FMEA-SWARA-WASPAS model for identifying and prioritising critical risks in Iranian construction projects, further highlighting the growing application of fuzzy multi-criteria methods in complex environments.

Erol et al. [126] developed an Analytic Network Process (ANP)-based risk quantification model tailored for mega construction projects, integrating risk, complexity, and uncertainty management strategies. Pham et al. [32] conducted a systematic review of supply chain risk management in construction, confirming the dominance of fuzzy approaches in the literature.

Recent innovations have further leveraged AI and ML technologies. Nabawy and Gouda Mohamed [118] developed a neural network-based expert system for risk analysis in infrastructure projects. Jia et al. [127] explored Graph NN to model complex interdependencies among risk factors, while Sirin et al. [119] applied the Adaptive Neuro-Fuzzy Inference System (ANFIS) for project performance evaluation. Additional ML applications have been reported by Kazemi et al. [128] and Mohammed Abdelkader et al. [129]. Digital twin technology has also emerged as a promising tool, enabling real-time simulation and proactive risk identification [130].

The integration of these advanced techniques with established qualitative and quantitative methods represents a substantial evolution in construction risk management, offering greater predictive accuracy, improved handling of interdependencies, and enhanced support for decision-making.

The literature reviewed in this study is synthesised in Table 3, with papers arranged chronologically. For each study, the primary tools and techniques, key findings, and critical observations are presented. This tabular synthesis has proven instrumental in identifying persistent gaps and historical trends in risk modelling and assessment, thereby laying the foundation for meaningful contributions to the field.

Table 3. Risk assessment papers from notable construction journals from 1990 to 2025.

Phases	Year	Author(s)	Journal	Main Tools
The 1990s (13)	1990	Al-Bahar and Crandall [44]	JCEM	ID
	1990	Hull [41]	IJPM	MCS, PERT
	1990	Yeo [48]	JME	PERT
	1992	Huseby and Skogen [46]	IJPM	ID, MCS
	1992	Diekmann [45]	IJPM	MCS, FST, ID
	1993	Paek et al. [50]	JCEM	FST
	1994	Dey et al. [52]	IJPM	AHP, PT
	1995	Zhi [53]	IJPM	AHP
	1996	Williams [54]	IJPM	LR
	1996	Wirba et al. [51]	ECAM	FST
	1998	Dawood [47]	CME	MCS, PERT
	1999	Mulholland and Christian [49]	JCEM	PT, PERT

The new millennium (2000s) (32)	1999	Ward [55]	IJPM	LR
	2000	Chapman and Ward [56]	IJPM	LR
	2000	Hastak and Shaked [70]	JME	AHP
	2000	Tah and Carr [62]	CME	FST
	2001	Baccarini and Archer [57]	IJPM	LR
	2001	Shen et al. [66]	JCEM	RAM
	2001	Tah and Carr [63]	JCCE	FST
	2001	Xu and Tiong [71]	CME	SP
	2002	Patterson and Neailey [58]	IJPM	LR
	2003	Baloi and Price [59]	IJPM	LR
	2003	Ward and Chapman [60]	IJPM	LR
	2003	Jannadi and Almishari [61]	JCEM	LR
	2003	Santoso [67]	ECAM	QU
	2004	Choi et al. [64]	JCEM	FST
	2005	Molenaar [72]	JCEM	MCS
	2005	Shang et al. [65]	ECAM	FST
	2006	Poh and Tah [73]	CME	ID
	2006	Thomas et al. [74]	CME	FST, FTA
	2007	Aven et al. [131]	RESS	LR
	2007	Dikmen et al. [76]	AIC	CBR, UT
	2007	Dikmen et al. [80]	IJPM	FST, ID
	2007	Hsueh et al. [75]	AIC	AHP, UT
	2007	Zeng et al. [77]	IJPM	AHP, FST
	2007	Zhang and Zou [78]	JCEM	AHP, FST
	2007	Zhang [79]	IJPM	LR
	2007	Zou et al. [81]	IJPM	LR
	2008	Choi and Mahadevan [83]	JCEM	FST
	2008	El-Sayegh [84]	IJPM	RAM
	2008	Han et al. [82]	AIC	LR, AHP
	2008	Zayed et al. [86]	IJPM	AHP, QU
	2008	Nasirzadeh et al. [85]	CME	SD
	2009	Imbeah and Guikema [132]	JCEM	FMEA
	2009	Luu et al. [87]	IJPM	BBN
2010–2020 (34)	2010	Fung et al. [91]	IJPM	MSE
	2010	Mojtahedi [92]	SS	GTO
	2010	Ökmen and Öztas [93]	CME	MCS
	2010	Tang et al. [133]	JCCE	FST, GA
	2010	Xu et al. [101]	AIC	FST
	2011	Abdelgawad and Fayek [105]	JCEM	FST, FTA
	2011	Chan et al. [96]	JME	RAM
	2011	Cho et al. [103]	KSCE	AHP
	2011	Hashemi et al. [68]	JCEM	BOO
	2011	Jun and El-Rayes [94]	JCCE	MCS
	2011	Li and Zou [102]	JCEM	FST, AHP
	2011	Nieto-Morote and Ruz-Vila [100]	IJPM	FST, AHP
	2011	Zhou and Zhang [107]	JCEM	FST, BBN
	2012	Abdelgawad and Fayek [106]	JCEM	FST, FTA
	2012	Subramanyan et al. [104]	JCEM	FST, AHP
	2012	Wambeke et al. [97]	JCEM	RAM
	2013	Hanna et al. [98]	JCEM	RAM
	2013	Kuo and Lu [134]	IJPM	MADR & CFPR

Post 2020 (13)	2014	Al-Sabah et al. [99]	CME	RAM
	2014	Choudhry et al. [95]	JCEM	MCS
	2014	Ebrat and Ghodsi [135]	KSCE	FST, NN
	2014	Taroun [23]	IJPM	LR
	2014	Zhang et al. [108]	SS	FST, SS
	2014	Zhang et al. [136]	RESS	FST, BBN
	2015	Cheng and Lu [121]	AIC	FST, FMEA
	2015	El-Sayegh and Mansour [137]	JME	RAM
	2016	Hyari et al. [110]	JCEM	MCS
	2016	Qazi et al. [111]	IJPM	UT, BBN
	2017	Tavakolan and Etemadinia [112]	JCEM	FST
	2017	Li et al. [113]	JCP	SD
	2018	Xia et al. [114]	SS	BBN
	2018	Yuan et al.	JCP	LR
	2019	Hatefi and Tamošaitienė [117]	JCEM	FANP, DEMATEL
	2019	Sarvari et al. [116]	SU	FANP
	2020	Guan et al. [122]	JCEM	BBN
	2020	Yaseen et al. [123]	SUST	AI, GA
	2021	Etemadinia and Tavakolan [124]	IJCM	SD
	2021	Alvand et al. [125]	IJCM	FMEA, SWARA, WASPAS
	2022	Erol et al. [126]	ESWA	ANP
	2022	Pham et al. [32]	IJCM	FST
	2023	Jia et al. [127]	AIC	NN
	2023	Tao et al. [138]	JCEM	BBN
	2024	Sirin et al. [119]	SU	AI
	2024	Nabawy and Gouda Mohamed [118]	IJCM	NN
	2024	Kazemi et al. [128]	ESWA	ML
	2025	Deng et al. [139]	ECAM	FST
	2025	Mohammed Abdelkader et al. [129]	IJCM	ML, BBN

Post-2020 research has increasingly focused on the integration of advanced digital technologies and hybrid approaches. Contemporary toolkits typically combine traditional methods with data-driven solutions. Prominent software products include @Risk and Crystal Ball (for MSC and probabilistic modelling), Primavera Risk Analysis and Acumen Risk (for schedule risk analysis and P-I integration), and BIM-enabled platforms such as Autodesk BIM 360 and Synchro Pro that support real-time risk visualisation. More recent AI-enhanced tools, such as IBM Watson, MATLAB-based predictive analytics modules, and specialised solutions like Riskturn and Safran Risk, incorporate ML algorithms (e.g., NN, random forests, and deep learning) for predictive risk forecasting, often integrated with IoT sensor data and digital twins. Hybrid systems frequently combine FST with BBN or GA within platforms like SuperDecisions (for AHP/Fuzzy-AHP) or custom Python/R-based frameworks.

While these tools demonstrate promising predictive capabilities, their applicability remains limited by data scarcity, the black-box problem affecting interpretability and trust among practitioners, high implementation costs, and insufficient longitudinal validation in live construction environments. Hybrid models, while conceptually robust, still face integration barriers with legacy systems and varying levels of digital maturity across the industry.

6.5. Analysis of the Risk Modelling and Assessment Literature

The reviewed literature reveals a clear evolution in the conceptualisation of risk in construction projects. Initially, risk was predominantly treated as an estimation variance amenable to probabilistic analysis. Over time, it has come to be understood as an intrinsic project attribute, most commonly expressed as the product of the probability of occurrence and its potential impact. Despite its widespread application, the P-I model has faced consistent criticism [61,69,131]. Critics argue that it fails to adequately capture interdependencies among risks and their cascading effects on multiple project objectives, thereby limiting its capacity to provide a comprehensive representation of construction risk.

Methodological developments reflect this conceptual progression. Early studies relied heavily on PT-based statistical methods, which faced significant challenges due to the scarcity of objective historical data in construction. This limitation prompted the incorporation of subjective elements, such as expert judgement and intuition, leading to the adoption of FST as a practical means of addressing uncertainty and bias. Although FST gained initial prominence in the 1990s, its application expanded considerably after 2000 in response to growing project complexity. More recently, the AHP has been extensively employed, particularly in Public–Private Partnership (PPP) projects, due to its structured approach to organising and prioritising multifaceted risks. While both FST and AHP offer valuable decision-support capabilities, their limitations in fully modelling risk interdependencies have been widely acknowledged, underscoring the need for more advanced methodologies.

A persistent and critical gap in the literature concerns the narrow focus of most risk assessments. The majority of studies have concentrated on cost and schedule risks, while the impacts on project quality and overall performance remain significantly underexplored. This imbalance, coupled with the absence of a unified measurement scale for evaluating risk effects across diverse objectives [140], impedes the development of a holistic project risk profile. The lack of integrated frameworks capable of simultaneously addressing cost, time, quality, and performance dimensions represents a major theoretical and practical shortfall.

Systematic literature reviews, such as the present study, can play a vital role in advancing risk management by synthesising existing knowledge and proposing structured pathways forward [141]. A robust risk management framework typically comprises four core elements: risk identification, classification, analysis, and response [88]. Complementary selection frameworks assist practitioners in choosing appropriate techniques, qualitative, semi-quantitative, quantitative, or simulation-based, according to specific project contexts [142]. The integration of advanced analytical approaches, including ML models [143], probabilistic analysis, and information entropy techniques for contractual risks [120], further enhances predictive capability and supports more adaptive, evidence-based risk management strategies.

This synthesis highlights both the progress achieved and the substantial opportunities that remain for developing more comprehensive, dynamic, and multi-objective risk assessment frameworks in construction.

6.6. Critical Evaluation of Dominant Risk Assessment Approaches

While the preceding analysis has documented the evolution and distribution of risk assessment methods, a deeper critical evaluation is necessary to understand their respective strengths, weaknesses, and suitability for contemporary construction projects.

The P-I model continues to dominate practice owing to its simplicity, intuitive visualisation, and ease of communication among diverse stakeholders [44]. Its primary advantage is the ability to facilitate rapid prioritisation under time and resource constraints. However, its core limitations, including the assumption of risk independence, failure to capture interdependencies and cascading effects, and heavy reliance on subjective scoring,

frequently result in underestimation of systemic risks and poor alignment with multi-objective project realities. These shortcomings explain why, despite decades of criticism, the model persists: it aligns with the industry's preference for straightforward, experience-based tools amid tight project schedules and contractual pressures.

FST, often integrated with AHP, effectively addresses linguistic uncertainty and imprecise data prevalent in construction environments [62,77]. Its strength lies in modelling vagueness and supporting multi-criteria decision-making in early project stages or data-scarce contexts. Nevertheless, challenges include subjectivity in defining membership functions, potential loss of transparency in complex hybrid models, and limited scalability for very large networks of risks.

BBN represents a more sophisticated probabilistic approach capable of modelling causal relationships and updating beliefs with new evidence [87,144]. Their key advantage is the explicit handling of uncertainty propagation and interdependencies. However, constructing accurate network structures and conditional probability tables demands substantial domain expertise and data, which can limit practical adoption in fast-paced construction settings.

Recent AI and ML techniques (including NN, GA, and hybrid deep learning models) offer powerful predictive capabilities, particularly when leveraging BIM, IoT, and historical project data [118,119]. Strengths include superior pattern recognition and the potential for real-time, adaptive risk forecasting. Significant weaknesses, however, persist: heavy dependence on large, high-quality datasets (often scarce in construction), reduced interpretability (black-box problem), high computational demands, and insufficient validation across multi-objective (cost, time, quality, performance) scenarios. These barriers explain why AI and ML applications, while growing rapidly after 2010, have not yet displaced more traditional methods in mainstream practice.

In summary, each approach offers distinct advantages but also exhibits critical shortcomings that hinder holistic risk management. The field would benefit from hybrid frameworks that combine the practicality of P-I models with the uncertainty-handling strengths of FST and Bayesian methods and the predictive power of AI and ML, while explicitly addressing interdependencies and multi-objective impacts. Such integration represents a key direction for bridging the persistent theory-practice gap identified in this review.

6.7. Future Research Directions

This review highlights several promising avenues for advancing risk modelling and assessment in construction projects. The following systematically structured directions are prioritised to address identified gaps and respond to evolving industry needs:

1. **Dynamic and Real-Time Risk Assessment Frameworks:** The development of integrated systems leveraging IoT sensors, BIM data, and digital twins should be prioritised. Such frameworks would enable continuous updating of risk probabilities and impacts throughout the project lifecycle. Hybrid architectures combining BBN for causal reasoning with ML algorithms for predictive analytics offer particular promise for adapting to emerging site-specific conditions [135,139,144,145].
2. **Multi-Objective and Interdependency-Focused Models:** Greater emphasis is required on models capable of simultaneously optimising risks across cost, time, quality, safety, and sustainability objectives. Promising approaches include extending FST and AHP with SD or DEMATEL to better capture cascading effects and feedback loops. Empirical case studies involving mega-projects and international collaborations would provide valuable validation and reveal context-specific implementation barriers [132, 137,146,147].
3. **Explainable AI and Practical Implementation:** AI and ML applications warrant deeper investigation, with particular focus on addressing data scarcity, model interpretability, and generalisability. Research could explore transfer learning techniques

and explainable AI methods to enhance practitioner trust and adoption. Practical implementation issues, including integration with existing project management software, training requirements for non-technical users, ethical considerations around data privacy, and varying levels of digital maturity, should be systematically examined through action research and industry-academia partnerships [134,148,149].

4. Contextual, Comparative, and Longitudinal Studies: Comparative studies across different project types (e.g., infrastructure vs. building), geographical contexts, and procurement models are needed to identify boundary conditions for method effectiveness. Longitudinal studies tracking the actual performance of advanced risk models in live projects are particularly important to bridge the persistent theory-practice gap [150–152].

By pursuing these directions, future research can contribute to the development of more holistic, adaptive, and practitioner-friendly risk management systems that better align with the complexities of modern construction under conditions of high socio-economic uncertainty.

7. Conclusions

Despite notable methodological advances over the past 35 years, the construction industry continues to face substantial challenges in effective risk reduction. The rapid growth in published research has made it increasingly difficult to maintain a clear and concise overview of the field. In response, this study conducted a systematic taxonomic review of 91 articles from 15 leading journals in construction management, project management, and risk analysis, covering the period 1990–2025. Through a structured four-stage process, the review examined publication trends, geographical distribution, and methodological developments.

The findings reveal several important insights. The P-I model remains the most widely adopted approach, despite its well-documented limitations—most notably its inability to adequately capture interdependencies among risks and their cumulative effects across multiple project objectives. While FST, AHP, and MCS have been extensively applied, and hybrid, fuzzy, and AI-enhanced methods have gained momentum since 2010, significant gaps persist. There is a notable lack of integrated frameworks capable of simultaneously assessing risks across cost, time, quality, and overall project performance.

This review synthesises the evolution of construction risk modelling and assessment, identifies persistent theoretical and practical shortcomings, and provides a comprehensive roadmap for future research. To advance the field, scholars and practitioners should prioritise the development of holistic, multi-objective risk assessment frameworks that incorporate dynamic modelling, ML techniques, and improved handling of risk interdependencies. While AI and ML techniques represent a promising frontier for more predictive and adaptive risk management, their application in construction faces significant obstacles, including data scarcity, the interpretability problem, integration challenges with legacy systems, and limited real-world validation. These issues warrant focused attention in future research on risk assessment modelling. Such advancements will be essential for better aligning risk management theory with the complex realities of modern construction projects, ultimately contributing to more successful project outcomes and enhanced industry performance.

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