Probabilistic Risk Assessment and Monte Carlo Simulation for Enhancing Resilience in Construction Projects: A Review

Arnab Nandi
Final-Year Student, M.Tech. (Civil) Construction Engineering & Management Birla Vishvakarma Mahavidyalaya (Engineering College), Anand, Gujarat nandiarnab747@gmail.com

Prof. (Dr.) J. R. Pitroda
Professor, PG Coordinator, Construction Engineering and Management, Civil Engineering Department, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar
jayesh.pitroda@bvmengineering.ac.in

Prof. (Dr.) Reshma L. Patel
Head of Civil Engineering Department, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar rlpatel@bvmengineering.ac.in

Er. Yatinbhai D. Desai
Engineer, Proprietor, Jay Maharaj Construction, Karamsad, Vidyanagar Road, Vallabh Vidyanagar
jparth308@gmail.com

Abstract: Assembly arrangements communicate ongoing uncertainty on the cost, agenda and safety outcomes, and deterministic planning instruments misapply that uncertainty. The present study summarizes twenty surveys that concern probabilistic liability appraisal (PRA) and Monte Carlo simulation (MCS) in building and related technologies, which shows how the field has evolved from a normal risk management approach model to a simulation-based portfolio-type risk quantification. The major aim here is to establish the core within the six theme areas: cost and schedule liability functions, safety risk objectives, resilience and fragility model, PRA/dynamic-PRA methodological taxonomy, deterministic versus probabilistic AI approach, and the reappraisal and foundation of risk management. Monte Carlo simulation with built-in threat register, Time-at-Risk quantiles, and risk-matrix-informed allocation choice, together and sequentially exceed Single-Point deterministic estimations, especially where comparatively large sample sizes diminish traditional statistical evaluation. The synthesis matrix and figures from this page describe the scope of the research, the implementation method, and possible dissemination of the results, indicating that Program Evaluation and Review Technique (Beta-PERT) and triangular distribution dominate the agenda objectives, while risk matrix-derived distributions generate data for cost purposes. The objective of this study is to summarize the end point by recognizing the shortcomings, limited integration of probabilistic cost, agenda, and adaptability models into one system, minimal real-time knowledge utilization, and uneven treatment of the beneficial side of risk, and to guide the next analysis.

Keywords: Construction Risk Management, Deterministic and Probabilistic methods, Monte Carlo Simulation, Probabilistic Risk Assessment, Resilience, Time-at-Risk.

1. Introduction

Construction doesn't work on a set agenda. Cost estimates are shifted by delays, scheduling slips, and safety incidents among some of the highest-risk activities, problems that have elicited high correlations with risk management practice, with many using single-point deterministic estimates of unintended uncertainties [1], [2]. Iqbal et al. inquired about financial issues, site incidents, and faulty design, and in these cases, experts said that financial issues, site incidents, and poorly designed architecture made up the most serious risks in the practice [3]. Contractors and consumers were spread across the spectrum [4]. Azevedo et al. from the literature, there is another study in which we would follow a systematic approach to investigate twenty-three construction risk-management models with the risk-management methods; as: the three years prior analyses

of the Risk Management Model were similar and the risks Management Models, in which we studied the project at a comparable stage are characterized by its similar response: usually they have a small project context, but have effected at a bad level with similar circumstances, and almost none consider the risk to have a strong positive/negative outcome with a high probability of this situation, and that too [5].

This project was initially developed for construction and is currently applied to nuclear, aerospace, and structural-health monitoring, where dynamic fault trees, dynamic Bayesian networks, or hybrid discrete-event simulation frameworks like Simulation-based Probabilistic Risk Assessment (SimPRA) and Reactor Analysis and Virtual Control Environment (RAVEN) are used to evaluate changes in risk [6], [7], [8]. In construction, Monte Carlo simulation has also been used to help reflect cost estimation and scheduling risk [9], [10], [11], [12], [13].

The text also includes twenty papers on construction-related fields, with guidance on how Monte Carlo simulation could be used for any building type in large, expensive, high-risk projects. So how do the risk matrices, Time-at-Risk framing, and distribution-selection decisions serve as the cornerstone of such applications that fit with such large risks? Are rigorous; and what obstacles of knowledge still penetrate the gap, fanned between the literature of that domain and the subject matter and what architecture is needed. Next, we jump forward: Risk, Probabilistic Risk Assessment (PRA), Monte Carlo simulation, and resilience modeling are connected. In the next step, the corpus of data is presented in a thematically focused way. There is a synthesis matrix and field and method type data. Afterwards, the methodological choices are presented, particularly the distribution and risk matrix integration of the solution. Later, the use case is discussed, following a gap finding. Finally, presents future research directions in the end of the paper.

2. Background and Fundamental Concepts

In order to build up a broad overall picture of the research area, the background and basic concepts are divided into different clusters. These clusters consist of separate sets of theoretical concepts in the area of risk-based analysis in construction projects, which are interconnected and contribute to the background. These clusters are listed below.

2.1 Risk in Construction Projects

In the classic construction management manner, risk is the variation, which is either positive or negative, between an object's value and any expected resulting variable from that object's expected value; successful management is based on noting, analysis of the potential or impact of such variable, and controlling its risk to the optimum [1], [2]. Schieg's early approach takes it in the first four phases that divide the information up through identification and response to policy to be a very powerful way of making comparisons among the more detailed models [2]. Iqbal et al. The analysis based on the survey data illustrates this taxonomy in practice: financial issues, site accidents, and defective design were identified as the risks practitioners counted most, and the study additionally distinguishes the use of preventive risks, like not before, rather than before, risks, developed to remedial means, a feature repressed at the beginning in the Monte Carlo studies of pre- and post-mitigation approaches [10], [3]. De Azevedo et al.'s review of the bibliometric literature further suggests that this perspective comes with a warning: construction projects may be one context without being homogeneous, unique, and a construct from many non-aligned people is rarely moving to another; this observation is consistent with the notion that a risk model that is produced in one context invariably goes out into space without finding the line with the rest which indicates a position for probabilistic, data-adaptive methods versus fixed deterministic checklists [5].

2.2 Probabilistic Risk Assessment

Risk is defined as the sum of an event's probability and its consequence, using PRA, which draws on the methods used in structured systems such as nuclear and aerospace engineering based on model-element analysis [8]. Hughes et al. utilize the six-step PRA sequence to develop a Bayesian-network-based decision framework for structural health monitoring by using influence diagrams to determine which action maximizes expected utility under uncertain circumstances [8]. The dynamic-PRA landscape is categorized into three broad families by Parhizkar's tutorial review: dynamic probabilistic logic methods such as Dynamic

Logical Methodology (DYLAM), Dynamic Flowgraph Methodology, and dynamic Bayesian networks; Monte Carlo simulation; and hybrid discrete-event/system-simulation framework Accident Dynamics Simulator paired with the information, Decision, and Action in a Crew Context Cognitive (ADS-IDAC) and Reactor Analysis and Virtual Control Environment (RAVEN) [6]. Nejad et al.'s Simulation-based Probabilistic Risk Assessment (SIMPRA) framework, which employs a Simulator-Scheduler-Planner architecture and focuses on scenario exploration through specialized Planner modules, is the weak link between these families [7]. Such an approach would seem better to have been made when it comes to the larger scenario that could be served in a biased Monte Carlo simulation. Canesi et al.' s PRIMoS framework utilizes PRA, which assigns a probability class and an impact interval to each cost item in the double-entry risk matrix, leading to its implementation in construction as supplementary to expert judgmental distribution selection through Monte Carlo simulation [11].

2.3 Monte Carlo Simulation and Related Techniques

Monte Carlo simulation repeatedly samples input variables from their assigned probability distributions to build up a distribution of possible project outcomes, rather than relying on a single deterministic estimate [9], [14]. Using the Time-at-Risk measure from finance's Value-at-Risk, Sobieraj and Metelski partner Monte Carlo Simulation (MCS) with a Time-at-Risk (TaR) measure using financial's Value-at-Risk: TaR focuses on the schedule delay that will not be exceeded at a confidence level rather than simply listing the expected completion date; at the same time, they treat project phases like a portfolio of assets whose risks can be leveraged over concurrent scheduling [13]. Hassi et al. perform a more comparative approach that runs the same 21-activity schedule through Triangular, Beta-PERT, and Uniform distributions to look at the shift in distribution choice of tasks placed on the critical path [10]. Hartono et al. apply MCS precisely to compensate for the small response pool (predictable uncertainty of risk factors based on performance of only nine employees) for large structures, to bring probability-and-severity assessment for just nine of the respondents to a robust 10,000-iteration simulation of risk index values [12]. There have also been recent review papers, including those by Kuru and Halicioglu and Patil and Patil. They summarize this general mass of MCS applications with reference to cost estimation, scheduling, and contingency planning – both of them reporting a considerably more robust performance in MCS predictions than deterministic approaches, and that they consider these improved numbers as summaries of the original literature rather than the benchmarks independently cited [15], [16].

2.4 Resilience and Fragility Modeling

Resilience shifts the framing from preventing failure to sustaining and recovering function under stress, and probabilistic methods have been used to quantify it in construction-adjacent domains before making their way into construction proper. De Angelis et al. expand the seismic fragility curve, a concept originally applied to measure a building's conditional probability of reaching a damaged state at a certain level of ground motion, into the energy domain, as follows a graphing analogy for the probability of a building's heating energy consumption falling short of an equivalent threshold during current climatic scenarios, merging and joining the two with the intent of promoting retrofit intervention [17]. Outside construction, Poudyal et al. quantify power-grid resilience by combining multiple resilience-driven parameters through a Conditional Value-at-Risk measure evaluated via Monte Carlo simulation of wind events [18], while Gerkis and Wang push back on Monte Carlo's role in this exact setting, arguing that it is computationally inefficient for resilience assessment and proposing Polynomial Chaos Expansion as a faster, more repeatable alternative [19]. Multiple studies have also demonstrated the convergence of resilience quantification to the common probability-sense of the existing data between domains, indicating that this computational method, simulation, versus expansion-based approximation, remains very competitive.

3. Literature Review and Thematic Synthesis

The literature review is grouped into thematic clusters to analyze the major findings, research methods, and contributions of the previous research. This synthesis synthesizes the common tendencies, research shortcomings, and fills the research gap that the present study intends to cover.

3.1 Cost and Schedule Risk Applications

The largest cluster of construction-specific studies in this review applies Monte Carlo simulation to cost and schedule risk on real or realistic projects. Armijos De La Cruz et al. developed a pre- and post-mitigation risk register for a telecom software project, running 10,000 iterations in @RISK's Schedule Risk Analysis add-in and finding that post-mitigation strategies reduced the 95%-confidence project cost from $787,892 (pre-mitigation) to $758,377, even though the corresponding reduction in project duration was comparatively modest [9]. Canesi et al.'s PRIMoS framework, applied to a €59.6 million Italian road project, went further by separating aleatory and epistemic uncertainty through a two-dimensional Monte Carlo simulation, reducing the ex-ante cost-estimation error to under 5% against an actual cost overrun of 8.06% under the conventional budgeting approach used on the same project [11]. On the scheduling side, Sobieraj and Metelski's Time-at-Risk analysis of the Fort Bema housing complex in Warsaw - a 128-month, 120,000-square-meter development - reported a 95% TaR of 4.48 quarters and a 99% TaR of 6.36 quarters of schedule risk, and showed that shifting two project stages by three quarters moved the 99% TaR by only 0.42 of a quarter, illustrating that schedule buffering has diminishing returns past a point [13]. Hassi et al. (2002:3) simulated three distribution types in Morocco [10]. This verified that the Uniform distribution of a potentially critical task, which was injected directly into a critical path, is the only distribution type that is Transferrable, and had an Average 1% criticality (which has the following ratio vs. Triangular, Beta-PERT) when compared to 1,000-scale trials, and the importance of distribution change is not only to decide which risks a project team takes this is indicative of a project team's choice to reduce risk in practice, such as where it is located [10]. Shinde's hypothetical-project study is not as relevant for experience, but they are similar: The strongest correlation between delay and timing was found by sensitivity analysis for 10,000 iterations, which was the strongest in relation to material shortages (0.72), while iteration uncertainty (0.65) and productivity (0.58) were also strong [14].

3.2 Safety Risk Applications

Hartono et al.'s research on bridges is an exciting new field to research [12]. Through the use of Monte Carlo simulation, a study was conducted on nine contractor workers to address an important obstacle in Indonesian construction sites. The results showed that the low probability and decay risk associated with 24 identified hazards were combined into a ' stable' risk index over 10,000 simulation attempts, which allowed for ten attempts of less than one level of risk and reflected the variance on standardized risk-and-severity scales. In a high-risk group, girder falls were not reported on the site (higher than 12.60) in this procedure [12]. This approach achieves an Monte Carlo Simulations (MCS) perspective in a way like in a cost and schedule case, above, which we describe above, but we present above with different cost and schedule cases.

3.3 Deterministic versus Probabilistic Methods

Khodabakhshian et al. conducted a systematic review to analyze cost-schedule-safety literature from a point of view; the systematic review deconstructs the cost-schedule-safety literature in a manner different from that of the data, and groups the methods (AI) and machine-learning methodologies applied to construction risk management from their substantive arithmetic (the reason for the method, in other words, is its application domain [20]. Deterministic techniques such as neural networks, decision trees and support vector machines can yield reliable results without that factor. The training of Bayesian networks, structural equation modelling and fuzzy logic, among other probabilistic methods, is often based on expert judgment, but may

also involve training inference from data input and updating probability estimates with new evidence. Professional judgement allows for corrections to be made to probability estimates [15]. This contrast is what makes Monte Carlo simulation more repeatable, given that it works on multiple small samples or data-sparse constructions: its probabilistic foundation allows it to take expert-elicited distributions where deterministic ML methods would simply have no size for the data volume to work.

3.4 Methodological Reviews and Foundational Studies

Several papers in the corpus function as literature reviews or conceptual foundations rather than original empirical applications, and are best read as the scaffolding the empirical studies sit on. Szymański's taxonomy of risk such as assurance, uncertainty, and risk proper, each tied to a different investor risk posture, and Schieg's six-step risk-management process both predate the Monte Carlo-specific literature but continue to frame how later studies define and sequence risk management [1], [2]. de Azevedo et al.'s ProKnow-C bibliometric review, which comes from an initial pool of 12,032 articles down to 23 fully evaluated risk-management models, provides the most methodologically robust of the review-type sources and is one of the most striking findings of a review type where risk models tend to not generalize across contexts, and frequently revert the context to opportunity and threat in contrast and provides a practical test for how far in any particular Monte Carlo study conclusions ought to travel [5]. Kuru and Halicioglu's and Patil and Patil's more recent narrative reviews cover similar ground with a tighter Monte Carlo focus, both concluding that the method is well established for cost and schedule risk but still faces adoption barriers tied to data quality, computational cost, and the specialized software it typically requires [15], [16].

4. Synthesis Matrix

The categories of all twenty reports on one topic identified under a significant domain of research, methodologies, distribution, and relevant quantitative results are noted below, and the categories are labeled as well as numerically determined in the following Table 1 as presented in Figure 1 and on the second tab, respectively. For instance, one study was classified as the sixth-largest study as claustrophobic. The clustering follows a cluster process in which construction risk-management reviews and foundations are classified by dimensions as the first group, with six studies, and further categorized in the following way (need to repeat this method in different areas based on how such a dimensional classification process is used and when, to what extent; it starts with cost-and-schedule Monte Carlo applications with five studies), PRA/dynamic-PRA methodological models with four studies. There are three studies focused on resilience and fragility modeling, but two are focused on power systems instead of construction; these are here, methodological analogs and not tangible evidence for construction. Safety risk application and probability assessment are two common shortcomings of the present literature. Even though safety-related Monte Carlo studies have been infrequent in much of the current literature, an empirical analysis of risk-reasoning processes (e.g., AI-based risk-reasoning methods) has been rarely followed, so it has probably been infrequent if any sort of convergence has been perceived as a blip; in all of the Monte Carlo literature, it probably feels like there is a convergence of such type in fact, especially for the Monte Carlo literature.

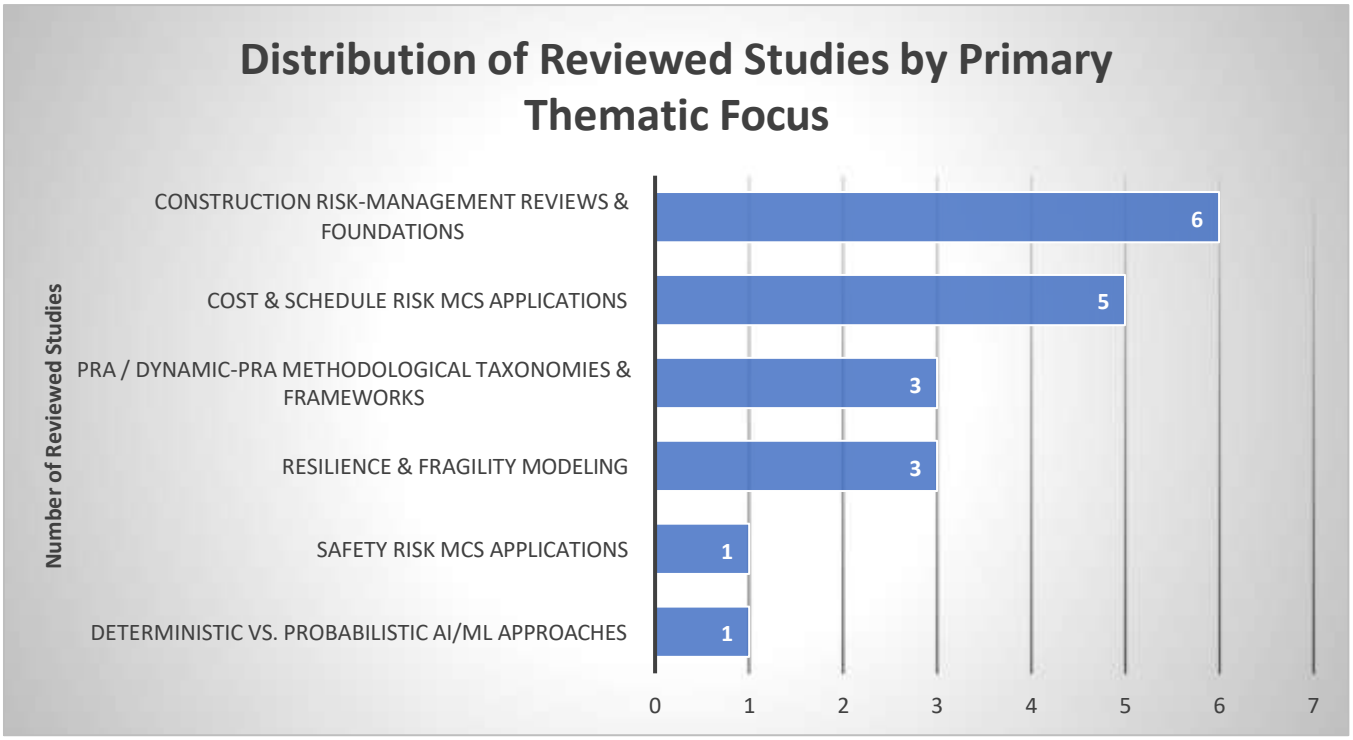


Figure 1. Distribution of reviewed studies by primary thematic focus.

The corpus also mirrors the growing region of the field and geographical region in a manner that is similar to what is observed in the existing field. Year of publication for the 20 reviews in a study (Table 1); in 16 volumes there are 17 volumes at all; 16 of these volumes were published before 2020, and a total of 7 four of them were in 2020 that further proof the rate of evolution that Kuru and Halicioglu and Patil and Patil had recorded in their own review [15], [16]. Below, we provide an unambiguous articulation of the number of studies that conducted theoretical research in that area; for the twenty studies re-indexed, the cite (6 document data) from that country as Italy twice is mentioned, De Angelis et al. national building stock [17] and Canesi et al. s Treviso Road project [11] and Morocco, Indonesia, Pakistan and Poland present only once. These supplementary 14 studies are in short of any literature reviews, conceptual frameworks, simulated benchmark systems e.g., the Institute of Electrical and Electronics Engineers (IEEE) test networks referred to by Poudyal et al. [18] or like Gerkis and Wang [19], which indicates the project of “conflict” project in Shinde’s case and, in fact, that the geographic model in Figure 3 would prefer the empirical subset over mass of the material.

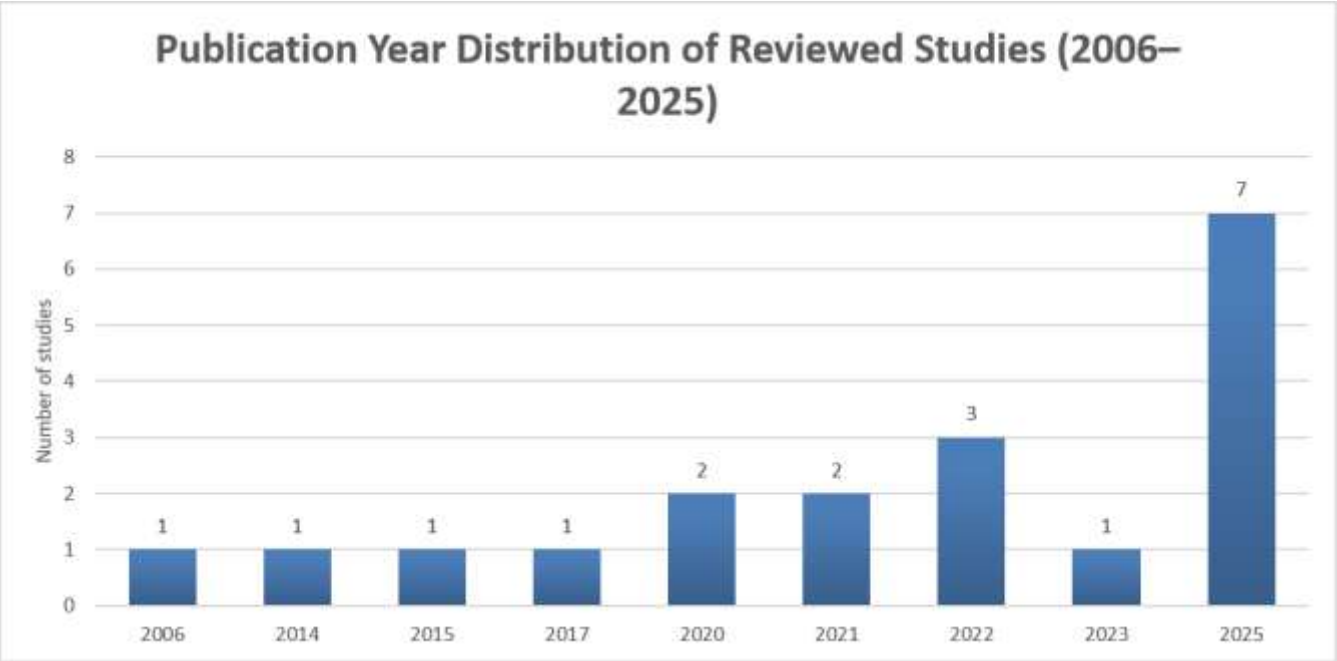


Figure 2. Article publication year distribution of the reviewed studies (2006–2025).

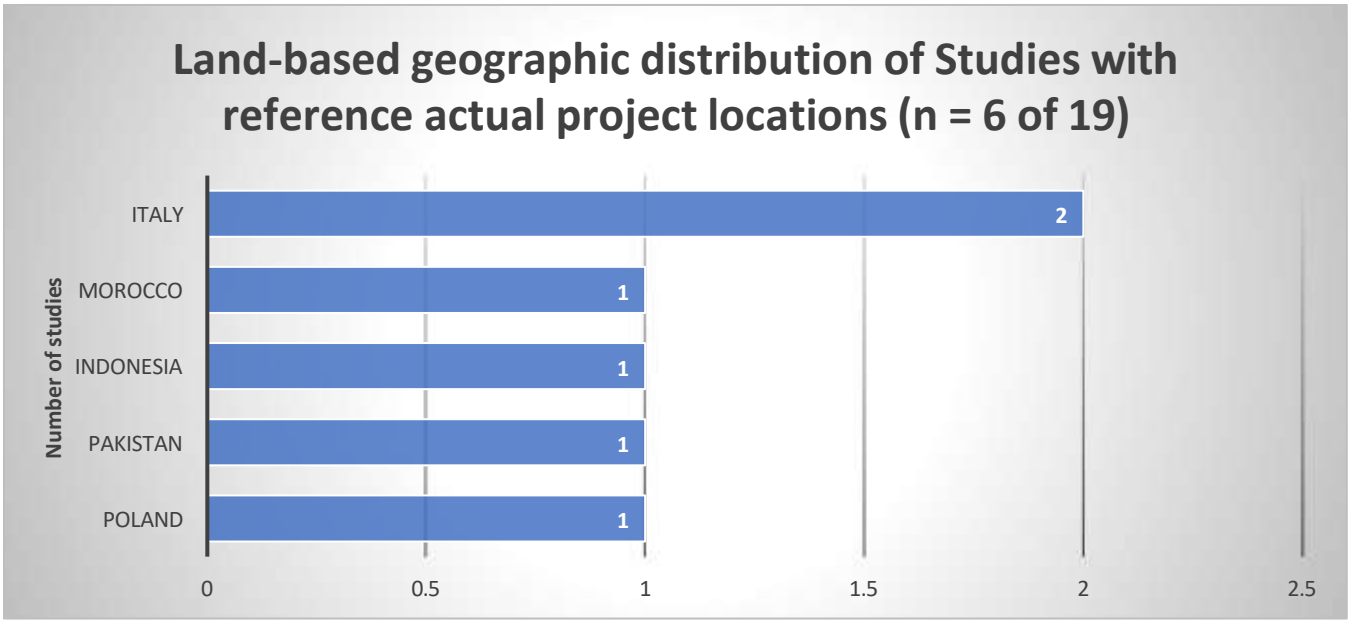


Figure 3. Land-based geographic distribution of Studies with reference to actual project locations (n = 6 of 19).

Table 1. Review matrix for approved articles (n = 19).

Study (Author, Year)	Domain / Focus	Method / Technique	Distribution(s) Used	Key Result / Contribution
Armijos De La Cruz et al. (2025)	Cost & schedule risk (risk registers)	@RISK Schedule Risk Analysis; pre- and post-mitigation MCS	Beta-PERT (duration); Bernoulli/Binomial (occurrence)	10,000-iteration MCS on a telecom software project; post-mitigation cut projected cost from $787,892 to $758,377 (95% level) versus pre-mitigation
De Angelis et al. (2020)	Resilience & fragility (seismic + energy)	Semi-probabilistic energy fragility curves paired with seismic fragility curves	Cumulative log-normal distribution over heating degree-days	Introduces energy fragility curves analogous to seismic ones; combined index flags Avellino and Benevento as priority retrofit cases in the Campania case study
Kuru & Halicioglu (2025)	General MCS review	Narrative literature review, summary table of ~25 studies (1997-2025)	Not applicable (review)	Synthesizes MCS applications across cost estimation, scheduling, and contingency planning; flags data quality and software cost as adoption barriers
Hassi et al. (2025)	Schedule risk; distribution comparison	MCS in Excel (1,000 iterations); Triangular, Betapert, Uniform compared	Triangular; Betapert; Uniform	On a 21-activity Moroccan project, Uniform distribution was the only one to shift a near-critical task (technical rooms) into the critical path (1% criticality)
Patil & Patil (2025)	General MCS review	Narrative review comparing MCS to deterministic methods	Not applicable (review)	Reports 60-70% better cost-prediction accuracy and 25-35% better schedule-forecasting accuracy for MCS versus deterministic methods, based on a 150-project sample
Shinde (2020)	Schedule risk (delay prediction)	MCS (10,000 iterations) with	Not specified in detail	On a fictitious project, mean completion time was 215 days (185-250
		sensitivity/tornado analysis		day range); material shortages showed the strongest delay correlation (0.72)

Parhizkar (2022)	PRA / DPRA methodological taxonomy	Tutorial review of dynamic PRA methods	Not applicable (review)	Classifies dynamic PRA into probabilistic-logic methods (DYLAM, DFM, Markov, DBN), Monte Carlo simulation, and hybrid discrete-event/simulation models (ADS-IDAC, RAVEN)
Khodabakhshian et al. (2023)	Deterministic vs. probabilistic AI/ML	PRISMA systematic review (533→48 papers); bibliometric + thematic analysis	Not applicable (review)	Classifies AI-based risk-reasoning methods as Bayesian/probabilistic (BN, SEM, fuzzy logic, MCS) or frequentist/deterministic (ANN, SVM, DT); builds a comparative table of strengths and data needs
Canesi et al. (2025)	Cost overrun risk	PRIMoS: double-entry risk matrix + Bayesian Monte Carlo (2D-MC separating aleatory/epistemic uncertainty)	Gaussian (low risk); Triangular (moderate risk); Uniform (high risk), matrix-selected	On a €59.6M Italian road project, 2D-MC reduced cost-estimation error to under 5%, versus an 8.06% actual overrun under conventional budgeting
Hartono et al. (2025)	Safety risk (bridge construction)	MCS (10,000 iterations) on likelihood × severity risk index, small sample (n=9)	Distribution fit to survey-frequency data across 5-point scales	Identified girder collapse during installation (risk index 16.19) and worker falls (12.60) as the highest-priority safety risks among 24 identified hazards
Nejad et al. (2021)	PRA / DPRA methodology (SIMPRA)	Simulator-Scheduler-Planner framework; continuous event tree guided by engineering knowledge	Not applicable (framework)	Proposes SIMPRA as more efficient than biased Monte Carlo simulation for exploring large scenario spaces, via a knowledge-guided Planner module; demonstrated on an earth observation satellite
Hughes et al. (2021)	PRA methodological	Bayesian networks, fault trees, and	Not applicable (framework)	Formalizes a risk-based decision framework for SHM by adapting event-
	foundations (SHM)	influence diagrams mapped onto structural health monitoring		tree/fault-tree PRA steps; demonstrated on a truss structure with experimental data

Poudyal et al. (2022)	Resilience modeling (power grid, adjacent domain)	Conditional Value-at-Risk per resilience parameter, combined via Choquet Integral; MCS for wind-event impact	Wind-speed probability density function; Bernoulli line-failure model	Demonstrated on an IEEE 123-bus system; combines attribute-based and performance-based resilience measures into a single risk-driven metric
Gerkis & Wang (2025)	Resilience modeling (power grid, adjacent domain)	Polynomial Chaos Expansion (PCE) proposed as a faster alternative to MCS	Fragility-curve-based failure-time PDFs	Explicitly frames standard MCS as computationally inefficient for resilience assessment; demonstrates improved repeatability on an IEEE 39-bus system
de Azevedo et al. (2014)	Construction RM models (bibliometric review)	ProKnow-C systematic selection (12,032→23 papers) + content analysis	Not applicable (review)	Finds risk-management models are highly context-specific and that only 2 of 23 reviewed models address risk's positive side (opportunities) rather than only threats
Szymański (2017)	RM taxonomy (general)	Conceptual / descriptive	Not applicable (conceptual)	Establishes the classical risk taxonomy (assurance, uncertainty, risk) and the qualitative/quantitative distinction (WV = probability × consequence) used across later MCS studies
Iqbal et al. (2015)	RM practice (survey, Pakistan)	Questionnaire survey of construction practitioners	Not applicable (survey)	Finds financial issues, site accidents, and defective design are the most significant risks; contractors are held responsible for most execution-phase risks, clients for financial/design/scope risks
Sobieraj & Metelski (2022)	Schedule risk (Time-at-Risk)	Combined MCS (10,000 runs) + Time-at-Risk (TaR) quantiles; covariance matrix across project stages	PERT (baseline); Triangular/Weibull discussed as alternatives	On the Fort Bema housing project (Warsaw, 128 months, 120,000 m²), 95% TaR = 4.48 quarters and 99% TaR = 6.36 quarters of schedule risk

Schieg (2006)	RM process foundations	Conceptual: 6-step RM process, risk portfolio, risk-team analysis	Not applicable (conceptual)	Establishes an early structured RM process model (identification → analysis → assessment → policy) that later probabilistic and simulation-based methods build upon

5. Methodological Approaches

A summary list for the methodological pipeline for these studies: Look at the corpus instead of one study at a time; the reviewed literature is consistent in suggesting a common process for the systematic development. In Figure 4, these common structures are grouped: Risks are first identified and assessed through a qualitative probability-impact risk matrix, facilitating the choice of probability distribution for each uncertain input that is passed to the next stage through a Monte Carlo simulation for probabilistic outputs–time–at–risk quantile, risk index, cost or schedule distribution – that correspond to project decision-making and, in turn, contribute to project planning such as contingency allocation or schedule shift [9], [11], [12], [13], [21]. The three subsections are more in-depth in looking into the middle connections of this pipeline: what studies choose a distribution, how they tie the qualitative risk matrix to the simulation, and how they describe the output that is presented for decision-makers.

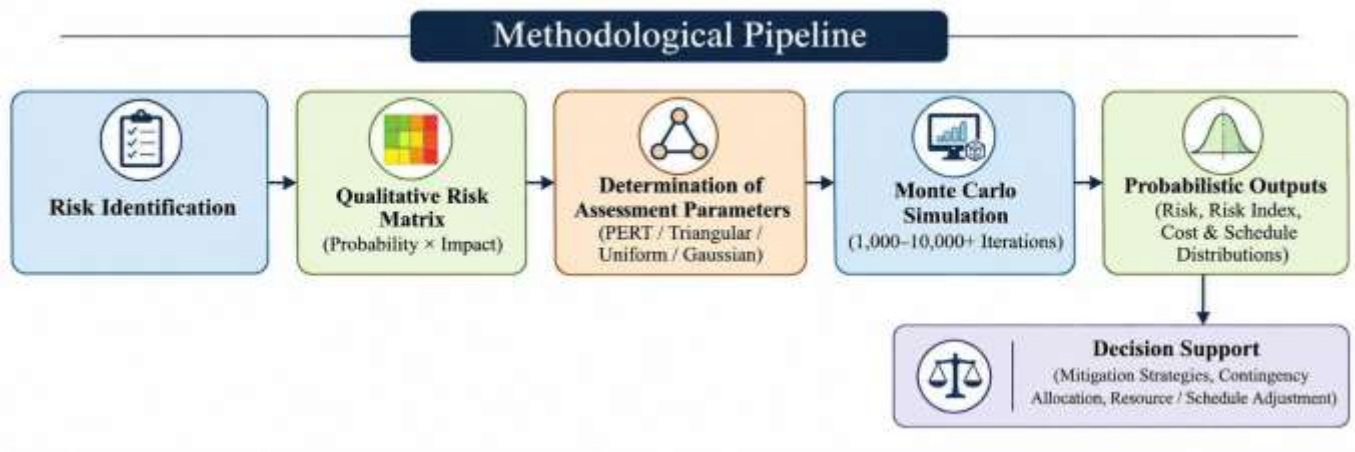


Figure 4. The conventional methodological pipeline is used in the Monte Carlo simulation work.

5.1 Probability Distribution Selection

This variation is neither as specific as that we find at the onset of many controversies and while it was considered by most of the studies to do it to the point where the classification of types is paired but I would be interested in trying out whether one or the other might yield as much as the best probability distribution was not included in this article. The distributions employed in Figure 5 are used to quantify the size of the paper. Beta-PERT distributions dominate duration modeling wherever optimistic, most-likely, and pessimistic estimates are available, on the reasoning that they weight the most-likely value more heavily than a Triangular distribution while still respecting the same three-point structure [9], [10], [13], [22]. Triangular distributions serve a similar role with a simpler, more linear probability assumption, and Hassi et al.'s side-by-side comparison shows this simplicity comes at a cost: Triangular and Beta-PERT produced nearly identical criticality outcomes in their case study, while the Uniform distribution - which assumes every value in a range is equally likely - was the only one of the three to shift a near-critical task into the critical path [10]. Canesi et al. finally use these deductions for Gaussian, Triangular, or Uniform to match their probability class applied to weight the cost item in their risk matrix, so he can use Fleiss' kappa test to find a 0.36-point difference between the agreement between the cost item in their risk matrix as an example [11]. While Weibull distributions are more exhaustive than normal representations of longer project stages, because of the fat right tails that have arisen, PERT allocations could also be complemented in their case study; De Angelis et al. and Armijos De La Cruz et al. carry out the case using lognormal fragility curve distribution and discrete Bernoulli/Binomial occurrence model, [9], [17], [13], [23], [4].

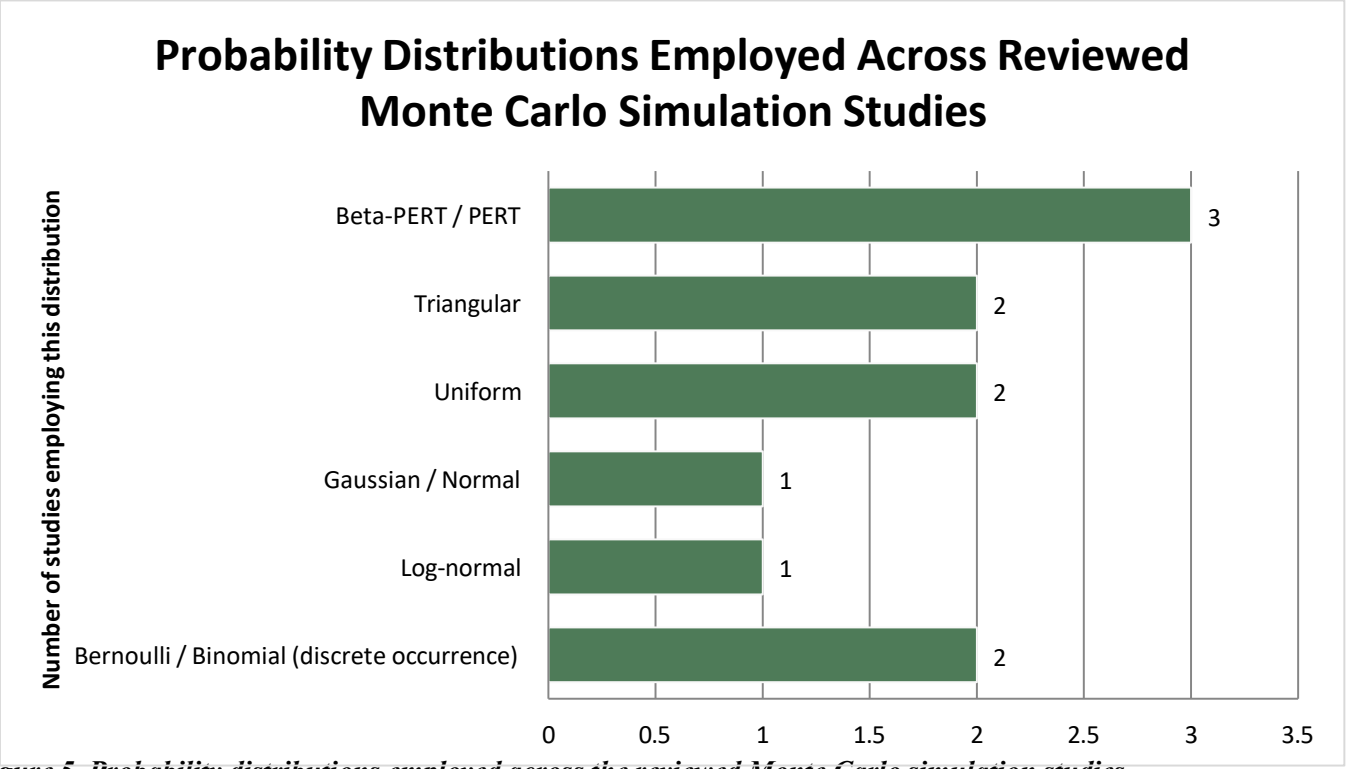


Figure 5. Probability distributions employed across the reviewed Monte Carlo simulation studies.

5.2 Integration of Risk Matrices with Simulation

There is a second methodological thread, of which the qualitative risk assessment, namely the proven probability impact matrix, is incorporated into quantitative simulation rather than as a separate, disconnected action. Canesi et al.'s PRIMoS framework is the most obvious one, where a double-entry matrix measures how each cost item is expected to affect and contribute to its odds, and the probability or damage level is entered into a Risk Magnitude level, causing that matrix to define the shape or range of distribution

employed in Monte Carlo and, at last, to determine the distribution that will later be used in this Monte Carlo simulation [11]. There were no previous studies where selection of distributions was modeled from unstructured expert judgment. Armijos De la Cruz et al. The pre- and post-mitigation risk register works according to the same but much different logic; there is a risk register with which 2 parallel simulations--one before the mitigation and one after mitigation can be executed, which allows it to calculate the cost and schedule benefit of the mitigation directly and calculate the difference between the two simulated distributions directly [9]. Hartono et al. is the same approach sped up because the risk index is calculated according to simulated probability and severity values: It switches a qualitative 5-point rating scale from an ordinal ranking, to a quantitative index by simulation resulting in not an ordinal ranking [12].

5.3 Time-at-Risk and Portfolio-Based Risk Framing

Time-at-Risk approaches by Sobieraj and Metelski have gained interest because they reframe timing risk evaluation within a centralized premise from financial risk management [13]. Value-at-Risk in finance quantifies the minimum expected loss in a portfolio to a given confidence level at a given time frame; TaR employs the same logic for project duration, treating a project's stages as a portfolio of interdependent activities whose overall schedule risk depends on a covariance matrix between stages rather than on any single stage in isolation [13]. The framing serves a practical utility - explicitly, it points out that running stages concurrently when feasible functions as such, as diversifying a financial portfolio and decreasing the overall schedule risk of the project regardless of any risks at the individual stages. Such a framing seems to restrict its impact and entails varying levels of generalization, both of which should be addressed in the reviews that largely focus on cases and include those that are widely represented in the literature [13]. In their comments about how they can go further based on data, for example, and other types of cases, the authors tended to use a wider sample of cases to make a more accurate case-study review approach, a tendency shared across many of the e-book reviews in the paper review.

6. Applications in Construction Projects

There are multiple architectural models primarily used in Monte Carlo simulation, such as schedule risk analysis. Sobieraj and Metelski, Hassi et al., and Armijos De La Cruz et al., for instance for calculating probability distributions to the activity duration and simulations for thousands of possible completion dates, in each model project schedule it can be concluded that every model can be classified into probability distributions on project duration that do differ significantly from deterministic critical path estimate; this pattern, is derived from Time at Risk, shift on task status, position in critical path, and the time it will take for one particular job to finish under pre- and post-mitigation assumptions [9], [10], [13], [24], [25]. The aspect that is most important to estimate the cost, and Canesi et al.'s PRIMoS model differs a great deal between simulation outcomes as well as the actual cost of the construction in one case and an exact comparison of it, which (non-quantitative) in situ estimation as observed [11]. The safety risk reviews lack much scope for applications to safety use. But Hartono et al.'s example in the case of the bridge construction stands out, since, when given the standard number of respondents, it is not always practical to test any of the probabilities that Monte Carlo could in order to generate a stable and ranked risk index [12]. For example, applications devoted to resilience are demonstrated by De Angelis et al. 's energy- and seismic fragility curves are inadequate in the theory of probability to design structural systems in particular, even in a certain scenario of probability the theory of probabilistic reasoning already had a good track record in the power-system literature and construction studies might consider it less easily [17], [18], [19], [23].

7. Research Gaps

By examining the limitations of prior research, this review of documents shows there are many aspects within probabilistic risk assessment and construction project resilience that need to be further studied. These research gaps can be summarized as follows:

1. The aspects of risk analysis continue to primarily represent costs, schedules, safety, and resilience. There has been a gap where the total sum of all four of these topics was made separate in any given study in this corpus into a single probabilistic framework for the same project.

2. There are still risk-management models that continue to be highly context-relevant, and the literature has little reassurance of what can be done to transform a risk-management model that had been validated for particular projects or regions into another one.

3. Safety risk assessment is markedly underrepresented in the Monte Carlo literature relative to cost and schedule risk, despite construction's persistently high accident rates.

4. Most studies do not assign allocation to any experts, so only Canesi et al. offers an organized, testable alternative and has been evaluated notwithstanding the single case studies.

5. Many of the reviewed risk-management models focus exclusively on risk's positive side - opportunity - with greater accuracy than the negative side, leading to large quantities of the probability upside of a project being overlooked.

6. Static Monte Carlo simulation relies on very high computational speeds and increases uncertainties, and there is a significant concern that this is addressed within the power-systems literature. This phenomenon is very clearly connected with large, multi-risk construction models that would affect large simulations of real computational limits.

7. There is virtually no overlap in terms of deterministic AI/ML methodologies and probabilistic simulation methods in the literature; systematic comparison between the two families is hardly possible due to the rareness of comparisons to the same construction dataset.

8. A single, low-cost, methodologically robust case study is most prevalent in this review; however, as they are relying on only one project, it cannot broaden its quantitative results, as it must be elaborated on.

8. Future Research Directions

This review has uncovered many directions for future research into probabilistic risk assessment and construction project resilience. The following trajectories center around what can be done to overcome current limitations, as well as to better simulate and quantify, and develop more practical methods of dealing with, uncertainty and resilience.

1. Develop collaborative models incorporating probability-matrix-based decision-making models within one simulation-based sphere, not attempting to analyze in the same frameworks.

2. Expand risk-matrix-informed distribution selection to scheduling and safety practices, as demonstrated by Researcher, and validate the design across various types and regions.

3. More systematically leverage Monte Carlo simulation in construction safety risk — particularly in small-scale constructions similar to the projects of individuals in a community.

4. Study alternative computational solutions to standard Monte Carlo simulation, e.g., the Polynomial Chaos Expansion method provided in the literature of power systems or SIMPRA knowledge-guided scenario planning, for large, multivariable construction risk models.

5. Establish risk management systems that account for opportunity as an equal part of threat, not the perception of risk as simply a downside.

6. Combine bigger, multi-project datasets to validate Time-at-Risk and other similar quantile-based metrics over the single-case-study evidence currently available.

7. Explore deeper integration of deterministic AI/ML techniques with probabilistic simulation, to put

it differently: combining machine learning to direct distribution parameter distribution, with a Monte Carlo model then propelled.

9. CONCLUSIONS

In view of the previous literature review, it could be concluded that probabilistic risk assessment, simulations, and resilience are the critical elements in construction project management. As a result-

1. Construction risk is not limited to the likelihood of any of the other integrated risk types of labour, materials, equipment, design, financial, and external shocks that will cause an impact on performance, schedule, and cost of work.

2. The literature review provides an argument for why a probabilistic approach is essential: Limits to Deterministic Planning. There are several likelihoods of probability, with a Monte Carlo simulation or another model-based simulation representing risk as an aggregated projection of the expected work at one point.

3. The synergy of the integration**:** CPM/PERT network schedule in conjunction with Monte Carlo simulation gives a systematic way to measure activity-level uncertainties, evaluate the potential of schedule delays and cost overruns, and also to highlight the key risk drivers.

4. Some risks do not qualify for calculation, and information regarding them cannot be collected for all risks. Project resilience refers to identifying, anticipating, and responding to disruption and restoring after disruption has occurred, which involves developing well-planned, resource-adaptable, and resourced contingency plans.

5. Future studies, in this review, should generate more integrated and adaptive approaches that construct data-driven models, bringing together probability-based risk outputs and concrete resilience indicators. These are evidenced through the use of case studies, project data, and more validation.

Acknowledgement

The authors sincerely acknowledge Prof. (Dr.) Vinay Patel, Principal, Birla Vishvakarma Mahavidyalaya Engineering College (BVM), and Prof. (Dr.) Reshma L. Patel, Head of Civil Engineering Department, BVM, Vallabh Vidyanagar, Gujarat, India, for their encouragement and valuable infrastructural support in facilitating this research. Sincere thanks are also extended to **Er. Yatinbhai D. Desai,** Engineer, Proprietor, Jay Maharaj Construction, for his valuable support and cooperation.

References

[1] P. Szymański, “Risk management in construction projects,” in Procedia Engineering, Elsevier Ltd, 2017, pp. 174–182. doi: 10.1016/j.proeng.2017.11.036.

[2] M. Schieg, “Risk management in construction project management,” Journal of Business Economics and Management, vol. 7, no. 2, pp. 77–83, 2006, doi: 10.1080/16111699.2006.9636126.

[3] S. Iqbal, R. M. Choudhry, K. Holschemacher, A. Ali, and J. Tamošaitienė, “Risk management in construction projects,” Technological and Economic Development of Economy, vol. 21, no. 1, pp. 65–78, 2015, doi: 10.3846/20294913.2014.994582.

[4] R. Vachheta, M. J. Shah, and J. R. Pitroda, “Ranking the Risks based on its Impact for Redevelopment Projects: A Review,” Studies in Indian Place Names, vol. 40, Issue 60, Mar 2020, ISSN: 2394- 3114.

[5] R. C. de Azevedo, L. Ensslin, and A. E. Jungles, “A Review of Risk Management in Construction: Opportunities for Improvement,” Modern Economy, vol. 05, no. 04, pp. 367–383, 2014, doi: 10.4236/me.2014.54036.

[6] T. Parhizkar and B. John, “Simulation-based Probabilistic Risk Assessment,” ResearchGate, July 2022, doi: 10.48550/arXiv.2207.12575.

[7] H. S. Nejad, T. Parhizkar, B. John, and A. Mosleh, “Simulation-Based Probabilistic Risk

Assessment (SIMPRA): Risk-Based Design," ResearchGate, Sep 2021, doi: 10.48550/arXiv.2110.06806.

[8] A. J. Hughes, R. J. Barthorpe, N. Dervilis, C. R. Farrar, and K. Worden, "A probabilistic risk-based decision framework for structural health monitoring," Mech. Syst. Signal Process., vol. 150, Mar. 2021, doi: 10.1016/j.ymssp.2020.107339.

[9] B. A. Armijos De La Cruz, J. R. Castro Esparza, J. F. Leoro Benitez, and W. Y. Armijos De La Cruz, "Leveraging Monte Carlo Simulation for Project Risk Management: A Study on Pre-Mitigation and Post-Mitigation Techniques in Risk Registers," Ciencia Latina Revista Científica Multidisciplinar, vol. 9, no. 5, pp. 6975–6992, Oct. 2025, doi: 10.37811/cl_rcm. v9i5.20089.

[10] H. Hassi, M. El Mkhalet, and N. Lamdouar, "Scheduling Optimization and Risk Analysis Using Monte Carlo Simulation for a Construction Project in Morocco," International Journal of Engineering Trends and Technology, vol. 73, no. 6, pp. 336–349, Jun. 2025, doi: 10.14445/22315381/IJETT-V73I6P128.

[11] R. Canesi, L. Gabrielli, G. Marella, and A. G. Ruggeri, "Probabilistic risk assessment framework for cost overruns predictions in infrastructure projects using randomized simulations," Computer- Aided Civil and Infrastructure Engineering, vol. 40, no. 27, pp. 4774–4796, Nov. 2025, doi: 10.1111/mice.70100.

[12] W. Hartono, S. A. Kristiawan, D. Handayani, and W. Sutopo, "Risk Assessment with Monte Carlo Simulation to Improve Bridge Construction Safety," Engineering Proceedings, vol. 84, no. 1, Feb. 2025, doi: 10.3390/engproc2025084056.

[13] J. Sobieraj and D. Metelski, "Project Risk in the Context of Construction Schedules-Combined Monte Carlo Simulation and Time at Risk (TaR) Approach: Insights from the Fort Bema Housing Estate Complex," Applied Sciences (Switzerland), vol. 12, no. 3, Feb. 2022, doi: 10.3390/app12031044.

[14] R. Shinde, "Monte Carlo Simulations in Construction Project Risk Management: A Practical Approach to Predicting and Mitigating Delays", Journal of Basic Science and Engineering, Vol. 17, Issue 1 (2020), doi: 10.5281/zenodo.18151820.

[15] O. N. Kuru and F. H. Halicioglu, "A review of applications of Monte Carlo Simulation in construction risk management," Golden Light Publishing, Jul. 2025. doi: 10.31462/icearc2025_a_aen_634.

[16] Aditya Ajit Patil, Dr. Prof. D. M. Patil, "Monte Carlo Simulation in Construction Risk Management: A Comprehensive Review," Journal of Emerging Technologies and Innovative Research, vol. 12, Issue. 8, Aug. 2025.

[17] A. De Angelis, F. Ascione, R. F. De Masi, M. R. Pecce, and G. P. Vanoli, "A novel contribution for resilient buildings. Theoretical fragility curves: Interaction between energy and structural behavior for reinforced concrete buildings," Buildings, vol. 10, no. 11, pp. 1–28, Nov. 2020, doi: 10.3390/buildings10110194.

[18] A. Poudyal, A. Dubey, and S. Poudel, "A Risk-Driven Probabilistic Approach to Quantify Resilience in Power Distribution Systems," ResearchGate, Mar. 2022, doi: 10.1109/PMAPS53380.2022.9810633.

[19] A. Gerkis and X. Wang, "Efficient Probabilistic Assessment of Power System Resilience Using the Polynomial Chaos Expansion Method with Enhanced Stability," ResearchGate, Mar. 2025, doi: 10.48550/arXiv.2501.09857

[20] A. Khodabakhshian, T. Puolitaival, and L. Kestle, "Deterministic and Probabilistic Risk Management Approaches in Construction Projects: A Systematic Literature Review and Comparative Analysis," Buildings, vol. 13, no. 5, May 2023, doi: 10.3390/buildings13051312.

[21] E. C. Shivamkumar Gavit, Prof. Ashish H Makwana, Dr. Jayeshkumar R Pitroda, "Risk Management: High Rise Construction," International Journal of Technical Innovation in Modern Engineering and Science, vol. 5, Issue. 5, May 2019.

[22] H. D. Senghani, Prof. A. N. Bhavsar, Dr. J. R. Pitroda, and Ar. D. H. Patel, "Project's Success Factor in the Building Construction: A State of Art Review," International Journal of Scientific Research in Engineering and Management, vol. 07, no. 03, Mar. 2023, doi: 10.55041/ijsrem18138.

[23] A. H. Makwana and J. Pitroda, “Factors Affecting Risk Management for Construction by Analytic Hierarchy Process (Ahp),” Journal of Structural Technology, vol. 2, Issue. 1, 2017.

[24] C. S. Chauhan, A. N. Bhavsar, and J. R. Pitroda, “Challenges in High-Rise Building Projects for Parameters of Project Management: A Review,” International Research Journal of Engineering and Technology, vol. 09, Issue 03, Mar 2022.

[25] G. S. Chandubhai, D. Jayeshkumar, R. Pitroda, P. Ashish, and H. Makwana, “Risk Management in High Rise Construction Projects in Surat City,” International Journal of Technical Innovation in Modern Engineering and Science, vol. 05, Issue 05, May 2019.