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A Review of Advanced Investment Appraisal Techniques for Public Infrastructure Decision-Making in the United States

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Abstract: Cost-benefit analysis (CBA) has long been used in the public infrastructure investment appraisal to make resource allocation decisions and policy choices. Nonetheless, due to the growing insecurity that climate change poses to U.S infrastructure systems, the technological disruption, and the social equity issues, deterministic evaluation models are not proving to be effective. It has been the shortcomings of the traditional economic systems that have led to increased progression towards complex and dynamic approaches that can take multidimensional performance and long-term dynamics of the systems into consideration. The research paper is a synthesis of the current methodological developments in the appraisal models, with emphasis on the real options analysis, Monte Carlo simulation, and multicriteria decision analysis (MCDA), and new hybrid models that combine these techniques. Taken together, these methods improve the ability of the public decision systems to meet the goals of uncertainty, diversity of the stakeholders, and resiliency. According to comparative analysis, the application of methodological pluralism based on quantitative rigor and participatory and data-driven information dramatically enhances the strength and autonomy of infrastructure investment judgments. In the case of U.S. public projects, such a pluralistic model is a major move towards adaptive, transparent, and future-responsive governing in the management of complex infrastructure systems.

Keywords: Infrastructure Investment Appraisal, Cost–Benefit Analysis (CBA), Multicriteria Decision Analysis, Real Options Analysis, Monte Carlo Simulation.

INTRODUCTION

The United States still relies on public infrastructure investment as a key to economic development and welfare of society. Recent federal policies such as the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) have made massive government investments in refurbishing deteriorating infrastructure, building out transit networks, and advancing renewable energy. These huge investments, however come with an increased complexity due to fiscal restraint, demographic shifts, and climatic uncertainty. This has made the validity and usefulness of investment appraisal systems critical in making sure that the public funds are employed effectively and fairly. According to Campbell & Brown (2022), and Nyikos & Ermasova (2022), the credible appraisal techniques are needed to maintain the trust and interveneability of the population in the governance of infrastructure.

The continued problems of cost management, realization of benefits and prioritization of projects have brought out the constraints in the current appraisal practices. The studies have identified the presence of consistent optimism bias and underperformance in the delivered benefits of projects which resulted in inefficiencies and lack of confidence by the people in the largescale U.S. public works. It is expected that rigorous and transparent economic evaluation will be used accordingly as a form of enhancing financial management and reestablishing democratic legitimacy of decision-making (Islam & Rehman, 2022; Marcelo *et al*., 2016). Incorporating the principles of sound appraisal in capital budgeting, governments can achieve a more effective balance between fiscal disciplines and social results, thus, according to Nyikos & Ermasova (2022), infrastructure investments should create mutual and long-term value across different communities.

Historically, infrastructure appraisal in the United States has particularly been dominated by a cost-benefit analysis (CBA) under structures such as the Office of Management and Budget Circular A-94. The introduction of welfare-based evaluation as a norm was predetermined by the works of Jenkins & Harberger (2018) and Campbell & Brown (2022). Recently, scholarship (Joseph *et al*., 2020; Venezia, 2023) however, criticizes deterministic CBAs as poorly representing uncertainty, distributional implications, and non-market resilience outcomes like environmental and social resilience. The conventional CBA approaches have a tendency of simplifying intergenerational equity and climate risk because of the discounting factor that may not readily reveal the overall social benefits of long-term infrastructure development (Jiang & Marggraf, 2021).

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In order to fill these gaps, scientists have improved complementary methods of filling traditional appraisal models. Real Options Analysis (ROA) offers flexibility through the appreciation of managerial flexibility in an uncertain situation (Di Maddaloni *et al*., 2022; Marques *et al*., 2021). Monte Carlo simulations are probabilistic, which means that variability is included in outcome projections (Hriday, 2022; Zavala *et al*., 2025). Multi-Criteria Decision Analysis (MCDA) extends the assessment to the stakeholder-driven and qualitative aspects (Ward *et al*., 2019; Juričic *et al*., 2020), whereas system dynamics modeling presents the effects of time and feedback (Du *et al*., 2023; Wang *et al*., 2025). All these changed approaches broaden the scope of analysis of infrastructure appraisal and allow it to consider uncertainty, sustainability, and equity more carefully.

The U.S. literature is still a piecemeal despite international developments with a tendency of dealing with methodologies one by one. The limited body of research effectively evaluates the role of advanced appraisal methods in incorporating into the U.S. federal and state decision-making structures and the application of the international best practices in the agencies (Awodire *et al*., 2023). Over forty articles published in 2016-2025 are synthesized in this review, cutting across theoretical, methodological, and applied research in sectors. The review will emphasize the intersection of economic, environmental and social appraisal approaches by explaining how the emerging tools, including digital twins, probabilistic models, and multi-criteria frameworks, can support the changing U.S. policy priorities. Finally, it aims to chart a course of adaptive, transparent and inclusive infrastructure governance, which captures the complexity of twenty-first-century social investment in the public.

CONCEPTUAL AND THEORETICAL BACKGROUND

The public infrastructure in investment appraisal is based on the field of welfare economics -the one that analyzes the impact of economic choices on the general welfare. In this tradition cost benefit analysis (CBA) became the main paradigm of the assessment of the public projects based on their evaluation of their overall social costs and benefits. Economists like Jenkins & Harberger (2018) perfected this method upon the concept of Pareto efficiency, or that a project is desirable when it can make a person better without rendering the other person worse off. This reasoning, which focuses on the allocative efficiency, became ingrained in U.S. policy by such mechanisms as Circular A-94 by the Office of Management and Budget which institutionalized the evaluation of the projects financed by the federal government economically. Consequently, CBA has been historically used to establish the principle of maximizing the aggregate welfare of any investment people make.

Nonetheless, welfare economics have grown to appreciate that efficiency is not a sure way of achieving fairness and social justice. The contemporary theorists, including Liscow & Sunstein (2024), point out that the allocation of benefits and burdens is equally significant as their total. The conventional CBA approach in thinking that a dollar is a dollar, whether it goes to a rich person or a poor person, does not reflect the equity and environmental justice aspects which are currently defining the socio-economic policies (Fenichel *et al*., 2025). The appraisal models of today are thus becoming more and more related to efficiency and equity such that infrastructure decisions invariably facilitate social inclusion and intergenerational justice. The move is indicative of the increasing agreement that welfare should not be gauged only by the overall gains, but the distribution of and the distribution of gains both within the communities and over time.

The main theoretical characteristic of CBA is the concept of discounting, or, to put it differently, the transformation of future costs and benefits into present-day values with the help of a social discount rate. The time preference and the opportunity cost of capital are reflected in this technique that is preferred by society (Campbell & Brown, 2022). Although it is handy in comparing long-term projects, discounting has been a source of serious controversy especially in the area of sustainability. The high discount rates are likely to undermine the long-term benefits, thus discouraging the investments that safeguard the future generation or environment. In order to overcome this tension, researchers suggest declining or dual discount rates that can be more consistent with the goals of sustainability (Fenichel *et al*., 2025; Liscow & Sunstein, 2024). These changes can be seen as a dynamic attempt to balance short term economic rationality and long-term societal wellbeing.

In addition to discounting, there is another theory problem of valuing non-market goods. A lot of the national infrastructure projects produce benefits such as better accessibility, cleaner air, or social cohesion, which are not directly marketed. Economists use the shadow pricing techniques to estimate their social value, contingent valuation and hedonic models (Jenkins & Harberger, 2018). Yet, these methods frequently fail to reflect complicated social and environmental aspects in a proper way. The need to monetize the equity or ecosystem services can cause oversimplification or distortion, as Venezia (2023) and Fenichel *et al*. (2025) remark. Therefore, although welfare-based appraisal offers a stringent basis, it has epistemic constraints to multidimensional objectives like climate resilience, equity, and sustainability.

Responding, there has been an increase in the conceptual repertoire of public investment appraisal through new theoretical paradigms, including the Real Options Theory (ROT), Multi-Criteria Decision-Making (MCDM) and systems-based sustainability systems. ROT views investment as a dynamic process and makes flexibility and adaptability in uncertainty conditions valuable (Di Maddaloni *et al*., 2022; Kottayi *et al*., 2019). MCDM is based on the utility theory and recognizes various and frequently contradictory goals that are not always monetizable by focusing on participatory and pluralistic decision-making (Ward *et al*., 2019; Juričić *et al*., 2020). Lastly, the system thinking and sustainability incorporate the environmental feedback loops and principles of resilience into the appraisal as a change in perspective to a dynamic optimization (Wang *et al*., 2025; Du *et al*., 2023). All these trends together recontribute the meaning of value in the context of public infrastructure, this time around not to do with efficiency, but with resilience, inclusion, and sustainability of the entire system.

EVOLUTION OF INVESTMENT APPRAISAL TECHNIQUES

The appraisal methods of public infrastructure have been varied throughout the last 50 years, as the complexity and uncertainty of the infrastructure designs, along with the socio-environmental aspects of the projects has intensified. The conventional use of deterministic cost-benefit analysis has over time been extended to encompass superior quantitative and qualitative techniques of probabilistic simulation, real options analysis, multi-criteria decision analysis, and system dynamics. Collectively, these approaches can be described as a forward-looking change of some of the more certainty-incorporated efficiency models to adaptive, risk-aware, and more stakeholder-focused models. This section follows the development of theoretical and methodological background of these techniques, including review of major studies and how they apply to the decision-making process of the infrastructure of people in the United States and similar situations in other countries.

Traditional Cost–Benefit Analysis (CBA) in Public Infrastructure

The cost benefit analysis model has continued to be the pillar of government investment evaluation in the US where it has been a longtime method of appraising infrastructure projects. CBA is based on welfare economics and evaluates the social benefits of a project relative to the social costs to ensure efficient allocation of resources. Developed by the early 20th-century public works analysis in the United States, especially in the Army Corps of Engineers, it was developed over the course of the work of economists like Harberger & Jenkins who formalized the attempt to quantify social opportunity costs (Jenkins & Harberger, 2018). CBA was institutionalized within federal policy mechanisms like the Circular A-94 of the Office of Management and Budget as one of the compulsory appraisal mechanisms in major investments by the government.

Jiang & Marggraf (2021) have indicated that the intellectual development of CBA was influenced by the post-war attempts to accomplish efficiency in terms of the expenditure of the government. Their comparison of practices between France and the U.S. reveals that administrative traditions shaped the philosophy of appraisal: whereas France focused on welfare planning, social inclusion, the U.S. practice was prone to market-based valuation and fiscal rationality. This has persisted with the American models focusing on analytical accuracy and comparability and European models incorporating social welfare and sustainability. However, the advantage of the U.S. framework is that the competing projects are ranked objectively based on a common monetary metric, and the framework is rather transparent. Modern uses of CBA go on in the transport industry, energy industry, and urban planning what Islam & Rehman (2022) demonstrate in pre-construction analyses, and Joseph *et al*. (2020) depict in environmental analyses of megaprojects, which concludes that whereas CBA is still a powerful tool in measuring efficiency, it tends to underestimate ecological and social values.

The introduction of environmental and social aspects to CBA is an indication of a progressive transition towards the sustainability-based appraisal. Fenichel *et al*. (2025) provide arguments to include the ecosystem services and natural capital accounting in the benefit-cost assessment and Venezia (2023) shows how distributional weighting and social discounting can bring the equity to the process of assessing transport projects. The innovations are manifestations of efforts to orient CBA to the contemporary policy objectives of inclusivity, resilience, and justice. Nevertheless, there are still methodological shortcomings. First of all, there is uncertainty uncertainty CBA usually uses deterministic point estimates when estimating the costs and the benefits, underestimating risks and overconfidence in net benefits (Marcelo *et al*., 2016; Venezia, 2023). Even though sensitivity analysis is a usual method, it often does not consider the systemic or correlated risks especially when the climate is uncertain.

The other significant criticism is the commercialization of non-market and intangible outcomes. Fenichel *et al*. (2025) and Joseph *et al*. (2020) warn of the distortion of the priorities of the population and the blurring of the ethical aspects of policy-making in terms of the dollar assessment of ecological or cultural assets. Contingent valuation and hedonic pricing techniques have drawbacks in bias and data constraints despite their convenient methodology. Moreover, results can be biased by political and procedural factors. Jenkins & Harberger (2018) indicate that assumptions regarding discount rates, shadow prices, and time horizons can be altered to deliver positive results, and Nyikos & Ermasova (2022) emphasize the discrepancies between states in the United States, where CBA is applied differently depending on politics and provides a degree of uncertainty in its application.

In response to such shortcomings, researchers have extended CBA by probabilistic methods and hybrid methods. Campbell & Brown (2022) support the idea of using spreadsheet-based probabilistic modeling to better reflect the risk, whereas Alsultan *et al*. (2020) support the risk-cost-benefit framework with the clear inclusion of uncertainty in infrastructure assessment. Marcelo *et al*. (2016) present the Infrastructure Prioritization Framework, in which non-economic factors like institutional readiness and social inclusion are combined. Such innovations show a trend to hybrid evaluation, which is economically rigorous and participatory legitimacy. Likewise, Joseph *et al*. (2020) suggest that environmental and public-interest assessments ought to be used in addition to CBA, which is an emerging pattern in methodological pluralism that includes enhanced analytical and democratic accountability.

The policy in the U.S. puts a heavy emphasis on institutional reforms that would form a step-by-step modernization of appraisal standards. CBA remains richly utilized by agencies like the Department of Transportation, Environmental Protection Agency, and Department of Energy, although it is becoming more and more intertwined with sustainability and equity aspects. In Executive order 14094 of the Biden Administration, agencies are instructed to update their benefit-cost guidance with climate and environmental justice effects, which is an indicator of a transition to a more holistic assessment. Recent research, such as Lei (2023) and Orabi & Shatila (2024), emphasizes increasing the use of life-cycle and sustainability-enhanced CBA models as an institutional response to the requirements of 21st century governance.

Finally, the development of CBA within the context of appraisal of the public infrastructure is a manifestation of the conflict between technicity and social responsibility. The economic grounds of the framework are reasonable, although its applicability in the long term is contingent upon its ability to include the social, environmental, and ethical aspects of value. Traditional CBA still offers the analytical framework to new techniques, including the real-options analysis, Monte Carlo simulation, and multi-criteria assessment, but its strength lies in flexibility. The future of infrastructure appraisal in the United States of America does not lie in abandoning CBA but in converting this framework into an age-adaptable, transparent, and responsive (socially) decision-support mechanism in accordance with the challenges of contemporary governance.

Real Options Analysis: Flexibility under Uncertainty

One of the most impactful advances to the contemporary investment appraisal introduced by the Real Options Analysis framework has overcome the major shortcomings of the traditional cost-benefit analysis frameworks in high uncertainty situations. Based on the financial options pricing theory introduced by Black and

Scholes, ROA propagates the concept of flexibility to non-financial assets, which are real and not monetary, like infrastructure. It does not view investment as an irreversible and one-time action but as a series of contingent actions that could be adjusted to changes in information. ROA explicitly appreciates managerial flexibility to have a systematic way of estimating the value of waiting, expanding, or abandoning projects in the face of uncertainty (Marques *et al*. 2021; Li *et al*., 2020). This flexibility especially applies to long-lived infrastructure investments that are prone to volatility in technology, regulatory, and demand.

Contrary to the conventional discounted cash flow and CBA models that assume some form of fixed stasis, ROA recognizes that postponement is valuable in spite of uncertainty and irreversibility. It allows decision-makers to postpone investment until they receive more information and eliminates downside risk at the cost of the upside potential (Di Maddaloni *et al*., 2022). ROA has practical relevance in terms of application in transportation schemes and in public-private partnership projects. Di Maddaloni *et al*. (2022) have used scenario analysis, combined with real options, to work out the best moment to invest in significant transport projects, whereas Marques *et al*. (2021) applied a Brownian Bridge model to evaluate infrastructure capacity expansion. In both studies, it was discovered that the appreciation of the importance of strategic flexibility provides better results than deterministic appraisal models.

Li *et al*. (2020) take the framework further to PPPs by modelling government subsidies and privately guaranteed options that vary with the results of performance. The method facilitates flexible risk sharing and enhances financial resilience, which is in line with the current PPP programs that place an emphasis on value-for-money. In addition to transport and PPPs, the dynamism of ROA has been applied in urban and environmental infrastructure. GUAJE Guerra & Restrepo Vélez (2022) measured the worth of flexible design in resilient buildings, and Deng *et al*. (2023) incorporated ROA and the MIVES sustainability index to measure the underground utility tunnels. Combined, these studies show that ROA has the ability to match the infrastructure investment with certain policy objectives, including adaptability, resilience, and sustainability.

Despite being promising, ROA has hindrances to mainstream adoption in the decision-making of the public sector. The intensity of the data in the method and the complexity of the analysis needed, including probabilistic modeling, the study of volatilities, and stochastic simulation, present technical and institutional difficulties (Di Maddaloni *et al*., 2022). Most of the agencies do not have the skills to execute ROA strictly, and the regulatory frameworks are still bound to deterministic budgeting and procurement procedures (Zhao *et al*., 2023). The political and procedural inertia also impedes the uptake because the institutions of the state usually prefer to focus on the short-term fiscal predictability rather than long-term adaptive planning. Therefore, although there is solid academic support for ROA, its practical application is lower than the potential it has in theory.

Policy-wise, the introduction of ROA would transform the U.S. public investment appraisal to a great extent. Phased, climate-sensitive investment planning would be possible by incorporating flexibility valuation into models such as the Climate-Informed Public Investment Management model (Glenday, 2020). The inclusion of ROA in PPP assessments, as suggested by Li *et al*. (2020) and Marques *et al*. (2021), may improve the transparency in the federal and state infrastructure programs and intertemporal efficiency. Finally, ROA is an economic theory/adaptive governance practice that proposes to redefine uncertainty as an asset more than a constraint. The potential of it can be achieved only through institutional reforms supporting the data transparency, analytical training and methodological standardization. The policymakers are faced with a cultural problem, not a technical one; they need to move away from the inflexible, ex-ante evaluation towards a learning-based and iterative investment appraisal that aligns with the uncertainties of the 21st century.

Table 1. Comparative Summary of Real Options Applications in Infrastructure Appraisal

Study	**Option Type**	**Infrastructure Type**	**Decision Focus**	**Main Contribution**
Di Maddaloni, Favato & Vecchiato (2022)	Timing (deferral)	Transportation	When to invest under uncertainty	Combines scenario analysis and ROA for timing flexibility
Marques,	Expansion	Capacity	Adjustment to	Introduces the Brownian

Bastian-Pinto & Brandão (2021)		expansion (transport)	demand growth	Bridge model for dynamic expansion valuation
Li *et al*. (2020)	Policy / Incentive option	PPP infrastructure	Risk-sharing, subsidy allocation	Uses ROA to optimize government–private financial incentives
Deng *et al*. (2023)	Abandonment / Expansion	Underground utility tunnel	Sustainability and flexibility	Integrates MIVES and ROA for sustainable infrastructure
GUAJE Guerra & Restrepo Vélez (2022)	Flexibility in use	Commercial / building	Future-proof design	Quantifies adaptability value in building investments
Glenday (2020)	Phased / Sequential	Climate-resilient infrastructure	Climate adaptation	Embeds ROA in the Climate-Informed PIM framework for staged investment
Zhao *et al*. (2023)	Procurement / Contract option	PPP transport	Value-for-money and risk allocation	Applies ROA to evaluate global PPP procurement flexibility

Probabilistic and Simulation-Based Appraisal (Monte Carlo and Stochastic Analysis)

The uncertainty is a characteristic attribute of the public infrastructure investment on the one hand, because the decisions have to be made with the lack of information related to the future costs, benefits, and performance. Conventional deterministic techniques like cost-benefit analysis assume these variables to be fixed to make analysis easier, but mask the magnitude of the possible risk and foster overconfidence about the success of projects. Probabilistic and simulation-based appraisal methods have, in turn, risen as an extension or addition to traditional models, providing systematic methods to measure levels of uncertainty and analyse the probability of outcomes. Monte Carlo simulation is now the most popular of them, allowing an analyst to model the most important variables: costs, demand, or interest rates as a probability distribution instead of a single-point estimate (Hriday, 2022; Zavala *et al*., 2025). Such a change promotes transparency and the stochastic nature of infrastructure systems.

The Monte Carlo simulation makes a set of thousands of random samples of the probability distributions of the input variables to obtain a set of possible outcomes. Rather than only one net present value or benefit-cost ratio, the technique produces a probabilistic profile, which shows not only the most likely results but also the likelihood of success. According to Vagdatli & Petroutsatou (2021), it will enable policymakers to determine the probability of project viability and focus on the risk drivers that might be critical. Its use in transport and energy sectors has proven useful in risk-based planning. The Monte Carlo and fuzzy logic rail infrastructure appraisal by Hriday (2022) demonstrated that the variability in cost escalation and delay significantly changes the risk exposure, and correlated risk modeling by Zavala *et al*. (2025) demonstrated that the systematic underestimation of total project risk is caused by the neglect of the interdependence of inflation, materials, and interest rates.

Infrastructure risk changes with time, and it is also being incorporated in recent studies through the inclusion of probabilistic simulation in the frameworks of life-cycle evaluation as well. The Vagdatli & Petroutsatou (2023) review of life-cycle cost benefit models emphasized that probabilistic simulation is more effective at representing uncertainty in degradation, maintenance, and the external cost determinants than the deterministic averages. On the same note, Lv *et al*. (2025) assessed the China cross-border bridge with Russia by applying Monte Carlo analysis to consider the exchange rate and demand variability; the simulation showed that there is 45 percent likelihood of a positive NPV with marginal feasibility in the deterministic models. Similar conclusions were made by Gomez-Fuster and Jimenez (2020) in the case of the evaluation of port infrastructure, where they proved that the probabilistic methods are more appropriate in terms of achieving investment in accordance with the real-world volatility and risk tolerance.

Probabilistic simulation, as opposed to deterministic CBA, has several methodological advantages. It introduces uncertainty, converts assumptions in the background into variables that can be analyzed, and allows sensitivity analysis of the parameters that have the most significant impact. Decision-makers can rank projects based on risk-adjusted as well as expected value by computing the full probability distributions of performance indicators. Furthermore, Monte Carlo may be used together with real options and multicriteria decision analysis as hybrid frameworks that blend quantitative rigor and qualitative judgment (Henke *et al*., 2020; Vagdatli & Petroutsatou, 2021). These hybrid solutions transform the practice of appraisal beyond stalemate evaluation to adaptive and iterative governance.

The use of a probabilistic approach is spreading out slowly but surely in the U.S. context, specifically in transportation and environmental infrastructure planning. Monte Carlo-based cost estimation is starting to be integrated into risk-informed decision making by the Federal Highway Administration and the U.S. Army Corps of Engineers, but institutional inertia, lack of technical capacity, and policy standards of the past continue to limit its use (Islam & Rehman, 2022). With the worsening fiscal uncertainty and climate risk, probabilistic appraisal provides a way to more evidence-based and transparent governance. Artificial appreciation of uncertainty enhances responsibility and trust in investment choices through simulation-supported structures. These approaches, as Lv *et al*. (2025) and Zavala *et al*. (2025) show, change risk into a limitation and make it instead a measurable and viable aspect of strategic planning of infrastructure, which is a critical development of 21st-century government investment.

Table 2. Probabilistic and Simulation-Based Methods in Infrastructure Appraisal

Technique	**Example Study**	**Uncertainty Variable**	**Infrastructure Type**	**Observed Benefit**
Monte Carlo + Fuzzy Logic	Hriday (2022)	Cost escalation, construction delay	Rail infrastructure	Quantifies project risk and improves contingency estimation
Monte Carlo with Correlated Variables	Zavala *et al*. (2025)	Material prices, inflation, interest rate	Transportation	Accounts for correlation among risks; refines cost estimation accuracy
Probabilistic Life-Cycle CBA	Vagdatli & Petroutsatou (2023)	Maintenance, degradation, operating cost	Road infrastructure	Improves long-term budget forecasting and asset management
Stochastic Economic Evaluation	Lv *et al*. (2025)	Exchange rate, demand, capital cost	Cross-border bridge	Identifies risk-adjusted feasibility; enhances investor confidence
Probabilistic Risk Modelling	Gómez-Fuster & Jiménez (2020)	Port throughput, market volatility	Port infrastructure	Supports risk-based prioritization and funding allocation
Meta-Analytic Simulation	Uddin & Rabbi (2025)	Benefit–cost ratios across studies	Transport and utilities	Reduces estimation bias; harmonizes multi-project comparisons
Stochastic Socio-Economic Modelling	Kantianis (2020)	GDP growth, social cost variables	Road transport	Integrates economic and social risks into ex-ante evaluation

Multi-Criteria Decision Analysis (MCDA)

Public infrastructure investment appraisal involves navigating multiple and often conflicting objectives, including economic efficiency, social equity, environmental sustainability, and political feasibility. The conventional cost-benefit analysis provides a rigorous quantitative basis but fails to provide the non-monetary and qualitative nature that determines the value of the people. Multi-Criteria Decision Analysis has been introduced to address these shortcomings: as a supplementary method, the structured assessment of various criteria is provided, where weighting is done by stakeholders, and qualitative judgments are made (Ward *et al*., 2019; Baumli & Jamasb, 2020). MCDA is therefore a compromise approach between value pluralism and analytical rigor and is particularly applicable in complex and politically sensitive infrastructure decisions.

MCDA basically offers a framework that incorporates technical, social and environmental aspects into one assessment framework. MCDA does not translate all the impacts into financial terms to evaluate projects, but rather evaluates them according to a series of performance metrics that reflect the views of the stakeholders (Mecca, 2023). The process consists of finding pertinent criteria, weighting of projects alternatives, scoring, and combining the outcome using systematic approaches which include weighted sums, outranking or the Analytic Hierarchy Process. This methodology is flexible to both professional and participatory feedback and brings transparency in the trade-offs of such decisions, which is essential in the public-sector setting when only economic efficiency is not enough and legitimacy and trust hold equal importance.

MCDA has been of great value in infrastructure appraisal, as it provides an opportunity to incorporate economic, environmental and social goals in the process of making decisions. The empirical research conducted by Ward *et al*. (2019) and Baumli and Jamasb (2020) demonstrates the empirical benefits of MCDA in the assessment of complex investment in the infrastructure. Ward *et al*. (2019) in the U.K. prioritised urban regeneration projects with the aid of MCDA by weighting objectives in terms of community preferences, which enhances the comprehension of trade-offs and encourages the society to trust the results of preceding decisions. On the same note, Baumli & Jamasb (2020) developed an EU-wide smart grid investment framework based on multi-criteria and focusing on the reliability of the technology, carbon reduction, and energy security. Using these applications, MCDA can reconcile the principles of infrastructure appraisal with the principles of sustainability and governance by ensuring that a wide portfolio of policy objectives is incorporated in the process of evaluation.

MCDA is applicable to transport and digital infrastructure because of its flexibility. In their study, Rasit Ozdas *et al*. (2025) have used advance MCDA methods like Analytic Network Process and TOPSIS to evaluate ICT projects in Turkey including innovation, inclusivity, and connectivity. Similarly, Kahraman & Haktanir (2024) also applied fuzzy AHP to assess transport projects to convert qualitative under uncertainty judgments into decision weights. These papers indicate that MCDA can operate within highly dynamic and unpredictable environments and facilitate participatory decision-making. Nevertheless, critics state that depending on subjectivity in weighting and scoring can result in bias or inequitable results. To overcome these issues, Zarei *et al*. (2021) suggest hybrid models that would introduce MCDA with probabilistic methods or the fuzzy set theory to improve resilience and replicability. MCDA is becoming popular in the U.S. to fulfill a new policy need in equity, sustainability, and resilience of government-level investments. Islam & Rehman (2022) report on the use of MCDA-based transportation prioritization and climate adaptation tools by federal and municipal agencies, whereas Liscow & Sunstein (2024) note the relevance of the pluralistic and participatory models which comply with the MCDA principles. Although challenge of methodological subjectivity persists, transparency, inclusion of stakeholders, and flexibility of MCDA can never be ignored in the 21st century infrastructure governance, even though its use continues to be matched with traditional economic-related tools and inequalities in results due to its more holistic and deliberative decision-making.

Table 3. Key Criteria and Weighting Approaches in MCDA for Infrastructure Appraisal

Study	**Criteria Used**	**Weighting Method**	**Case Type**	**Outcome**
Ward *et al*. (2019)	Economic growth, environmental quality, and social inclusion	Weighted Linear Combination	Urban regeneration (UK)	Promoted transparency and stakeholder trust
Baumli & Jamasb (2020)	Energy security, carbon reduction, reliability, and social acceptance	Analytic Hierarchy Process (AHP)	Smart grid (EU)	Balanced monetary and non-monetary objectives
Rasit Ozdas *et al*. (2025)	Connectivity, inclusiveness, and innovation capacity	ANP–TOPSIS hybrid	ICT infrastructure (Turkey)	Enhanced decision precision and adaptability
Kahraman & Haktanır	Safety, accessibility, economic efficiency	Fuzzy AHP	Transport (Turkey)	Integrated expert judgment under

(2024)				uncertainty
Mardani *et al*. (2022)	Economic, environmental, and social indicators	Mixed stakeholder weighting	Energy projects (global)	Increased legitimacy and participation
Zarei *et al*. (2021)	Sustainability, resilience, carbon intensity	Fuzzy ANP	Green construction (U.S.)	Improved uncertainty representation

System Dynamics and Scenario Planning

System Dynamics (SD) and Scenario Planning are increasingly vital tools for public infrastructure investment appraisal, as they capture complex feedbacks, nonlinear interactions, and long-term dynamics that conventional models such as cost–benefit analysis and Monte Carlo simulations often overlook. Unlike static approaches, these dynamic frameworks simulate how socio-economic and environmental systems respond over time to policy actions and investment decisions (Wang *et al*., 2025; Mashamba, 2024). By allowing policymakers to explore how alternative strategies perform under varied future conditions, SD and Scenario Planning provide valuable insights for building resilient and sustainable infrastructure systems operating within uncertain technological, fiscal, and ecological environments.

Originating from Jay Forrester's work in the 1950s, SD has evolved into a robust framework for analyzing urban and infrastructural systems, linking stocks (e.g., assets, environmental quality) with flows (e.g., investments, depreciation) through differential equations. In practice, SD exposes the delayed and nonlinear impacts of policy choices can lead to long-term maintenance deficits or how early environmental mitigation can reduce future costs (Du *et al*., 2023). Empirical studies have reinforced its value: Wang *et al*. (2025) found that productivity and human capital gains from U.S. railway investments manifest only after long time horizons, while Mashamba (2024) identified policy leverage points for reforming South Africa's power sector through diagnostic SD models.

SD's strength lies in integrating quantitative data with qualitative factors within a single simulation framework (Di Maddaloni *et al*., 2022). When combined with Real Options Analysis, SD enhances flexibility by explicitly valuing the timing and sequencing of investments under uncertainty, as shown in Di Maddaloni *et al*. (2022), who linked scenario analysis and ROA to guide transport investments under shifting climate conditions. Scenario Planning extends this adaptability by testing strategies across divergent futures—high-growth, low-carbon, or budget-constrained trajectories (Du *et al*., 2023; Lee *et al*., 2022). However, despite their analytical power, SD and Scenario Planning face institutional and data barriers that limit adoption. Glenday (2020) suggests open causal mapping, stakeholder co-modeling, and iterative validation to enhance credibility and alignment with democratic governance. Ultimately, these methods enrich U.S. infrastructure appraisal by embedding feedback learning, uncertainty adaptation, and long-term resilience. A capability essential in an era of climatic, fiscal, and technological disruption.

Hybrid and Integrated Approaches

System Dynamics and Scenario Planning have become very relevant instruments in public infrastructure investment appraisal because they elicit more complex feedbacks, nonlinear interactions, and long-term dynamics, which are usually ignored in traditional models, including costbenefit analysis and Monte Carlo simulations. In contrast to the rigid models, these dynamic models can model the behavior of socio-economic and environmental systems to actions of policy and investment choices as time passes (Wang *et al*., 2025; Mashamba, 2024). SD and Scenario Planning would be useful in constructing resilient and sustainable infrastructure systems that will operate in uncertain technological, fiscal and ecological settings by enabling policy formulation by giving the policymakers an opportunity to experiment with alternative strategies under different future conditions.

SD, developed out of the work of Jay Forrester in the 1950s, has since become a powerful methodology of studying urban and infrastructural systems that connects stocks (e.g., assets, environmental quality) and flows (e.g., investments, depreciation) with differential equations. Practically, SD reveals the latent and sluggish effects of policy options, such as the potential to cause a maintenance deficit in the future when taking short-term cost reductions or mitigate future costs by taking early environmental actions (Du *et al*., 2023). Its value has been strengthened by the findings of empirical studies:

Wang *et al*. (2025) revealed that the positive productivity effect and human capital effects of U.S. railway investments become evident after long time periods and Mashamba (2024) established the points of leverage in the policy in order to reform the power sector in South Africa with diagnostic SD models.

The advantage of SD is the ability to combine quantitative data and qualitative variables (stakeholder engagement and institutional learning) into a unified simulation model (Di Maddaloni *et al*., 2022; Ahuja, H. 2025). SD together with Real Options Analysis increases flexibility by directly accounting flexibility of investments in a manner of time and sequence when uncertainty exists as illustrated in Di Maddaloni *et al*. (2022) who connected scenario analysis and ROA to inform transport investments in changing climate conditions. Scenario Planning builds upon this flexibility by trying out plans under divergent futures - high-growth, low-carbon, or low-budget paths (Du *et al*., 2023; Lee *et al*., 2022). Nevertheless, SD and Scenario Planning have institutional and data barriers that restrict their adoption, regardless of their analytical power. According to Glenday (2020), open causal mapping, stakeholder co-modeling, and iterative validation may be used to boost credibility and conformity to democratic governance. In the end, these approaches add value to U.S. infrastructure appraisal by instilling feedback learning, uncertainty adaptation, and long-term resilience, which are needed during the period of climatic, fiscal, and technological turmoil.

POLICY AND PRACTICE IN THE UNITED STATES

The policy and institutional structure in the infrastructure appraisal in the United States is the product of a complicated relationship between the federal requirements, the state spheres of autonomy, and the increasing requirements of transparency and social accountability. Principles like circular A-94 of the Office of Management and Budget (OMB) define the federal foundation of cost-benefit analysis (CBA), which implies systematization of costs and benefits of the public investments. These standards are further refined in the complementary documents such as the U.S. Department of Transportation Benefit-Cost Analysis Guidance to be applied in the sector, especially in transportation, with a specification of discount rates and a treatment of uncertainty. Additional institutionalization of data-driven, resiliency-focused, and equitable appraisal practice was further institutionalized by the Infrastructure Investment and Jobs Act (IIJA, 2021) focusing on sustainability and modernization of digital infrastructure (Lee *et al*., 2022; Chhibber, R. 2021).

In spite of these improvements, there is still an unequal spread of the high-tech appraisal between federal agencies besides the traditional CBA. Environmental externalities and resilience metrics are inherent in the Environmental Protection Agency and U.S Army Corps of Engineers, and others use deterministic models. Fenichel *et al*. (2025) point out that the paradigm of including ecosystem services in federal benefit-cost analysis has changed national wealth into a new definition of the value of natural capital. In the meantime, Liscow and Sunstein (2024) note that there is a debate between efficiency-oriented and welfare-oriented appraisal frameworks, which reflects a more general conflict between market efficiency and distributive justice. Case studies like Lei (2023) Lei (2023) on the Frederick Douglass Memorial Bridge and Gant (2021) on the USACE P3 Pilot Program feature the combination of real options, probabilistic tools, and community impact measures and hybrid methods based on CBA, risk simulation, and a life-cycle analysis approach are presented by Wu (2024) and Orabi and Shatila (2024).

The ongoing issues are chaotic governance between federal, state, and local levels, inadequate technical expertise to support high-order modeling, and the lack of data on climate and equity indicators (Nyikos and Ermasova, 2022). However, resilience-based efforts including FEMA Building resilient infrastructure and communities and Value-for-Money models are creating new opportunities that incorporate stochastic and real options approaches (Zhao *et al*., 2023). The implementation of predictive analytics and artificial intelligence would provide opportunities to have ongoing, dynamic appraisal. The future U.S. systems of appraisal ought to further institutionalize environmental appraisal and equity analysis, in keeping with the requirements of the Biden agenda of inclusive, sustainable, and long-term investment by the populace, as Liscow and Sunstein (2024) and Fenichel *et al*. (2025) observe.

Table 4. Adoption of Advanced Appraisal Methods across U.S. Agencies

Agency	Method Used	Policy Area	Challenge	Example Outcome
U.S. Department of Transportation (DOT)	Cost–Benefit Analysis (with probabilistic risk modeling)	Transportation infrastructure	Data uncertainty; limited integration of non-monetary values	Updated BCA guidance under IIJA (2021)
U.S. Army Corps of Engineers (USACE)	Real Options & Monte Carlo Simulation	Water resources and climate adaptation	Institutional resistance to model complexity	P3 Pilot Program emphasizing flexibility and equity (Gant, 2021)
Environmental Protection Agency (EPA)	Ecosystem Service Valuation integrated into CBA	Environmental and ecosystem management	Limited standardized valuation methods	Incorporation of natural capital valuation (Fenichel *et al*., 2025)
Federal Highway Administration (FHWA)	Hybrid (CBA + MCDA + LCA)	Transportation resilience	Inconsistent weighting and discount rates	Implementation in bridge and highway sustainability assessments (Lei, 2023)
Department of Energy (DOE)	Probabilistic and Life Cycle Costing	Energy infrastructure	Data availability; uncertainty in long-term projections	Adoption of stochastic models for nuclear infrastructure (Wu, 2024)

Critical Synthesis and Future Directions

The relative assessment of the current appraisal and decision-support systems depicts that there is a definite shift towards more integrative and adaptive and data-driven systems. Classic methods like cost-benefit analysis and multicriteria decision analysis are still the focus and provide systematic frameworks of decreasing the economic, environmental, and social goals. Nevertheless, CBA can be very useful as it gives a solid quantitative basis, but it tends to overlook a question of social equity and resilience in the long-term view. Being flexible and incorporating the element of stakeholder input, as well as the qualitative aspects, MCDA is not as predictive and systemic as proper long-term planning needs to be.

These approaches will complement one another when applied simultaneously. Decision frameworks based on both social responsiveness and data would be enabled by the combination of the economic rigor of CBA and the participatory inclusiveness of MCDA. Inclusion of such tools as life-cycle assessment and system dynamics models complement these frameworks with the feedback of the environment and time dynamics. Such hybrid solutions are becoming necessary when addressing the difficult questions of sustainability and infrastructural planning, in which the economic performance should coincide with environmental safety and social welfare.

New technological developments have sped up this trend to data-driven appraisal. Nowadays, real-time evaluations of the performance of the systems and their impact on society are possible due to the work of big data analytics, remote sensing, and machine learning. Simulation, monitoring, and adaptive optimization can also be performed with the use of digital twins, the virtual models of real-world systems. Incorporation of AI into these digital ecosystems alters the traditional evaluation into learning-based governance systems, which are able to react to emerging risks and uncertainty with greater speed and accuracy as well.

Even though, improvements have been made, there are still major gaps. Social equity has not yet been well internalized so fairness and vulnerability are usually put on the backburner. Resilience modelling is often marginalised out of the mainstream appraisal and uncertainty is also represented poorly in most evaluations. The future direction is in creating unified systems that connect the qualitative and quantitative measures within scales, implementing uncertainty into MCDA, interlinking equity indices with spatial information, and integrating digital twin modeling with participatory governance. The desired destination is convergence: to bring together economic rigor, participatory design, environmental wisdom, and computational intelligence to produce resilient, adaptable, and fair policy systems of an uncertain future.

CONCLUSION

Infrastructure development and policy evaluation have changed to adaptable, data-driven, and participatory systems as opposed to the deterministic, inflexible models. Old methodologies, including cost-benefit analysis and multicriteria decision analysis, have been broadened with the addition of the life-cycle assessment, system dynamics modeling, and AI-based tools. This represents one of the significant methodological changes, not only between the permanency of efficiency and economic maximization but also between the incorporation of environmental, social, and resilience aspects into the systems. Although these developments may be of particular importance to U.S. infrastructure planning, they put extra pressure on agencies to make investments not only financially viable but also sustainable and fair. Through the incorporation of resilience measurements, spatial equity measurements, as well as probabilistic models, transparency, accountability, and flexibility in the policy and infrastructural governance can be attained.

The future of appraisal and governance is in integrating in an adaptive way and not refining one mode of operation. With the emergence of iterative learning-based systems, which replace traditional but static models driven by stakeholder interaction and computational intelligence, the institutional structures will need to adapt to facilitate fairness, inclusiveness, and ethical algorithm-driven decision-making. The combination of economic rigor, environmental concern, and social justice into data-enrichment, multi-criteria appraisal tools provides a way to successful and inclusive infrastructure systems. With this convergence, policymakers are able to manage uncertainty better and have future-ready, adaptive, and responsive governance structures that are capable of handling the complexities of the twenty-first century.

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