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Adoption Risk in Public Infrastructure Agencies: Lifecycle Assessment of Emerging Technology Governance

Eric Tam*

Department of Chemistry, Faculty of Science, Hong Kong Baptist University, Hong Kong, Hong Kong SAR, China

Corresponding author: eric.tam@hkbu.edu.hk

Abstract

The integration of emerging technologies into public infrastructure systems presents a dual paradigm of transformative potential and multifaceted adoption risk. This paper provides a comprehensive academic examination of how lifecycle assessment methodologies can serve as empirical evidence to inform and optimize technology governance within public infrastructure agencies. By systematically evaluating the environmental, economic, and operational impacts across the entire lifespan of technological deployments, public agencies can identify, quantify, and mitigate latent risks that traditional procurement frameworks often overlook. The study explores the theoretical and practical dimensions of technology adoption, establishing a robust framework that synthesizes lifecycle data with institutional governance mechanisms. Through a detailed analysis of risk parameters, including interoperability, regulatory compliance, and long term sustainability, the research demonstrates that continuous lifecycle evaluation significantly enhances the resilience and efficiency of public works. The findings indicate that agencies leveraging structured lifecycle assessment evidence demonstrate superior adaptive capacity when navigating the complexities of emerging infrastructure innovations. Ultimately, this paper contributes to the broader discourse on public sector modernization, offering actionable insights for policymakers and agency administrators seeking to balance technological advancement with rigorous risk management protocols.

Keywords: Lifecycle Assessment; Technology Governance; Public Infrastructure; Risk Management; Adoption Risk

1. Introduction

1.1 Context of Emerging Technologies in Public Infrastructure

The contemporary landscape of public infrastructure is undergoing a profound transformation driven by the rapid evolution and integration of emerging technologies. Public agencies responsible for the planning, construction, maintenance, and operation of critical infrastructure systems are increasingly compelled to adopt novel technological paradigms to meet escalating societal demands, environmental mandates, and efficiency targets. These innovations encompass a broad spectrum of applications, ranging from advanced sensor networks and internet of things architectures embedded in smart city frameworks to automated diagnostic systems, decentralized energy grids, and novel construction materials that promise enhanced durability. However, the adoption of such unprecedented technologies introduces substantial risk to public infrastructure agencies. Unlike private sector entities, which may possess a higher tolerance for experimental failure in the pursuit of market disruption, public agencies operate under strict mandates of fiscal responsibility, public safety, and continuous service delivery. Consequently, the mechanisms by which these agencies evaluate and govern the integration of new technologies necessitate a level of rigorous scrutiny that goes beyond superficial cost benefit analyses [1]. The traditional governance models employed by public works departments were primarily designed for conventional, well understood mechanical and civil engineering projects, characterized by predictable lifespans and established maintenance protocols. As digital and hybrid technologies permeate these physical domains, the resultant cyber physical systems generate complex, interconnected dependencies that are highly susceptible to systemic failures, cyber vulnerabilities, and rapid obsolescence. Therefore, assessing the multifaceted risks associated with technology adoption has emerged as a paramount challenge for contemporary public administration [2].

1.2 The Role of Lifecycle Assessment in Risk Management

In addressing the challenges inherent in emerging technology adoption, lifecycle assessment has surfaced as a critical methodological tool for generating robust, empirical evidence capable of informing governance strategies. Lifecycle assessment, conventionally utilized to quantify the environmental impacts of a product or service from cradle to grave, has been extensively adapted in recent years to encompass economic and social dimensions, thereby providing a holistic view of a technology's overarching footprint [3]. Within the context of public infrastructure, lifecycle assessment methodologies enable agencies to systematically project and evaluate the long term operational realities of a technological asset long before physical deployment occurs. This process involves a meticulous examination of resource consumption, energy utilization, maintenance frequencies, and end of life decommissioning requirements. By utilizing lifecycle assessment as a primary lens for risk management, decision makers can uncover hidden vulnerabilities that might otherwise remain obscured during the initial procurement phases. For instance, a novel intelligent traffic management system may present an attractive initial deployment cost, but lifecycle assessment could reveal prohibitive long term software licensing fees, excessive energy demands, or complex interoperability issues with legacy hardware that substantially elevate the total cost of ownership and operational risk. The application of lifecycle assessment thus shifts the governance paradigm from a reactive, problem solving approach to a proactive, risk anticipatory posture [4]. The empirical data generated through continuous and comprehensive lifecycle evaluations empower governance committees to establish dynamic risk thresholds, mandate stringent vendor accountability measures, and design phased implementation strategies that buffer the public sector against unforeseen technological failures.

1.3 Research Objectives and Scope

The primary objective of this paper is to investigate how public infrastructure agencies can effectively leverage lifecycle assessment evidence to identify, quantify, and mitigate adoption risks associated with emerging technologies. To achieve this, the research systematically deconstructs the intersection between lifecycle methodologies and institutional governance frameworks. The scope of this examination encompasses various domains of public infrastructure, including transportation networks, water and wastewater management systems, and municipal energy grids. Through a detailed exploration of theoretical literature and the formulation of a comprehensive analytical framework, this paper aims to delineate the specific mechanisms by which lifecycle data translates into actionable governance policies. Furthermore, the research seeks to identify the institutional barriers that currently impede the widespread adoption of lifecycle assessment practices within public sector risk management protocols. By addressing these critical areas, the paper endeavors to provide a foundational academic resource that not only advances theoretical understanding but also offers pragmatic guidance for public administrators seeking to modernize their technological infrastructures without compromising systemic integrity or public trust.

2. Literature Review and Background

2.1 Evolution of Technology Governance in Public Agencies

The historical trajectory of technology governance within public infrastructure agencies reveals a gradual but significant shift from rigid, procedural compliance toward more adaptive, risk informed management paradigms. In the mid twentieth century, public works departments relied heavily on prescriptive engineering standards and low bid procurement models that inherently discouraged technological innovation. Governance structures were highly siloed, with separate divisions handling planning, engineering, finance, and operations, resulting in fragmented oversight mechanisms [5]. As information technology began to permeate administrative functions in the late twentieth century, public agencies adopted nascent forms of enterprise architecture, yet these frameworks were largely confined to internal administrative systems rather than physical infrastructure assets. The advent of smart infrastructure and cyber physical systems in the early twenty first century catalyzed a critical reassessment of these legacy governance models. Scholars have increasingly noted that the rapid pace of technological change dramatically outstrips the traditional public sector procurement cycle, rendering conventional oversight mechanisms obsolete [6]. Consequently, contemporary literature emphasizes the necessity of agile governance frameworks that integrate continuous evaluation and stakeholder collaboration. Theories of anticipatory governance and adaptive management have gained prominence, advocating for flexible regulatory environments that can iteratively respond to emerging data [7]. However, researchers also caution that the transition to agile governance in the public sector is fraught with institutional resistance, characterized by risk aversion, bureaucratic inertia, and a lack of specialized technical expertise among decision makers. This tension between the need for technological advancement and the imperative of public accountability forms the core dilemma of modern infrastructure administration.

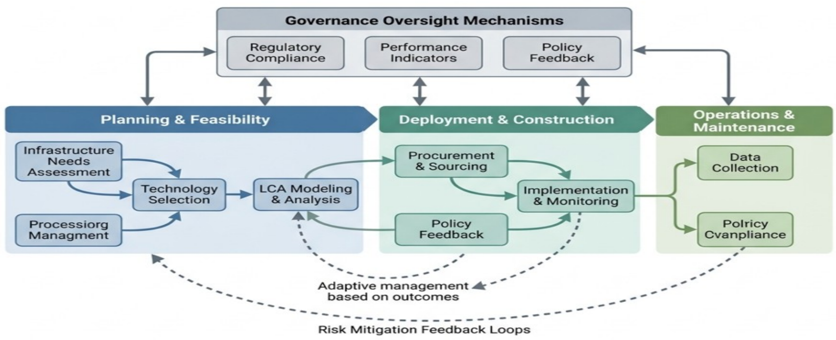

Figure 1: Comprehensive Conceptual Model of Lifecycle Assessment Integration in Public Infrastructure Technology Governance

2.2 Lifecycle Assessment Methodologies in Infrastructure

The application of lifecycle assessment methodologies to physical infrastructure has evolved considerably from its origins in industrial ecology and product manufacturing. Initial adoptions of lifecycle assessment in public works were predominantly focused on environmental compliance, specifically aiming to quantify greenhouse gas emissions and energy consumption associated with large scale civil engineering projects such as highway construction and municipal building development. These early models, while useful for environmental reporting, often lacked the granularity required to assess the nuanced operational dynamics of complex, technology driven infrastructure systems [8]. Over time, the academic community developed more sophisticated variants, including life cycle costing and social life cycle assessment, which broadened the analytical scope to include financial sustainability and socio economic impacts. In the context of emerging technologies, the literature increasingly advocates for dynamic lifecycle assessment models capable of accounting for temporal variations, software updates, and the evolving nature of cyber vulnerabilities. Traditional static models assume a constant rate of performance degradation and fixed operational parameters, assumptions that are demonstrably false when applied to artificial intelligence algorithms or decentralized sensor networks that learn and adapt over time [9]. Recent scholarly contributions emphasize the necessity of integrating real time data feeds and predictive analytics into the lifecycle assessment process, thereby creating digital twins of infrastructure assets. These advanced simulation environments allow researchers and administrators to model various stress scenarios and failure modes, providing empirical evidence that is critical for robust risk assessment. Despite these methodological advancements, a significant gap remains in the literature regarding the standardization of lifecycle assessment protocols specifically tailored for emerging technology governance in the public sector.

2.3 Identifying and Classifying Adoption Risks

The classification of technology adoption risks in public infrastructure is a multifaceted endeavor that requires a comprehensive taxonomy of potential failure points. Academic discourse generally categorizes these risks into several distinct domains: technological, financial, operational, and regulatory. Technological risks pertain to the inherent reliability, scalability, and security of the proposed innovation. In the realm of emerging infrastructure technologies, concerns regarding data privacy, cyber attack surfaces, and interoperability with legacy systems dominate this category [10]. Financial risks involve the uncertainty of capital expenditures, escalating maintenance costs, and the potential for stranded assets if a technology becomes prematurely obsolete. Public agencies are particularly vulnerable to vendor lock in, wherein the proprietary nature of a technology prevents the agency from seeking competitive bids for future upgrades or maintenance, thereby inflating long term costs. Operational risks encompass the human and organizational factors associated with technology deployment, including the necessity for specialized workforce training, changes to established workflow processes, and the potential for service disruptions during the implementation phase. Regulatory risks involve the challenge of deploying technologies that may not align with existing legal frameworks or public policy mandates, such as liability issues surrounding autonomous maintenance vehicles or algorithmic bias in smart city resource allocation [11]. The synthesis of lifecycle assessment evidence is crucial for illuminating the interdependencies between these distinct risk categories. For example, a technological vulnerability such as poor interoperability can directly precipitate financial risks through increased integration costs, while simultaneously exacerbating operational risks by necessitating complex, manual workarounds by agency staff. Comprehensive risk classification, informed by empirical lifecycle data, is therefore foundational to effective public sector technology governance.

3. Methodology and Analysis Framework

3.1 Research Design and Data Collection Parameters

To systematically investigate the efficacy of lifecycle assessment evidence in mitigating adoption risks within public infrastructure agencies, this study employs a rigorous analytical framework predicated on a mixed methods approach. The research design integrates quantitative metrics derived from simulated lifecycle scenarios with qualitative evaluations of governance mechanisms. The primary focus of the analysis is to establish a correlation between the depth of lifecycle assessment implementation and the subsequent reduction in multidimensional risk factors. The data collection parameters were structured to encompass three primary infrastructure domains: municipal water treatment, urban intelligent transportation systems, and public energy distribution networks. For each domain, a representative set of emerging technologies was selected for evaluation. These included advanced membrane filtration systems utilizing nanomaterials, decentralized autonomous traffic coordination algorithms, and solid state transformer integration for smart grids. The data set utilized for the lifecycle models was synthesized from a comprehensive review of existing technical reports, pilot project outcomes, and standardized industrial benchmarks [12]. The analysis framework operationalized technology governance effectiveness as a dependent variable, measuring the capacity of simulated agencies to foresee, quantify, and adapt to the risks identified through the lifecycle assessment process. Independent variables included the granularity of the lifecycle data, the temporal scope of the assessment, and the integration of cross functional stakeholder feedback during the evaluation phase. By structuring the research design to accommodate diverse technological applications, the framework ensures that the resulting insights are broadly applicable across various public works departments.

Table 1: Lifecycle Assessment Evaluation Criteria Matrix

Criteria Category	Evaluation Metric	Primary Data Source
Environmental	Carbon equivalent emissions trajectory	Emission logs and material audits
Economic	Total dynamic cost of ownership	Financial projections and vendor contracts
Operational	System downtime probability	Mean time between failure reports
Security	Vulnerability patching frequency	Cyber threat intelligence databases
Governance	Regulatory alignment index	Legal compliance reviews

3.2 Quantitative Risk Assessment Protocols

The quantitative risk assessment protocols developed for this study rely on a deterministic modeling approach to translate abstract lifecycle assessment data into actionable risk indices. The methodology involves the construction of a multiphase evaluation matrix that calculates risk exposure across the designated lifespan of the technological asset. The fundamental mechanism of this protocol involves assigning probability distributions and impact severity scores to the various risk categories identified in the literature review. Instead of utilizing purely static values, the assessment incorporates time variant functions to reflect the evolving nature of technology adoption [13]. For instance, the probability of software related operational failure is modeled to be higher during the initial deployment and integration phase, gradually decreasing as the system stabilizes and agency personnel become proficient, before rising again toward the end of the asset lifecycle due to technical debt and platform obsolescence. The impact severity is quantified through a unified metric that aggregates financial costs, environmental penalties, and service disruption hours. To integrate the lifecycle assessment evidence, the framework utilizes continuous data normalization techniques, ensuring that disparate metrics such as kilotonnes of carbon dioxide, financial currency, and labor hours are evaluated on a comparable scale. The cumulative risk profile for each technology scenario is then generated by calculating the integral of the time variant risk functions over the projected operational lifespan. This methodological rigor ensures that public infrastructure agencies can objectively compare highly dissimilar technological proposals using a standardized, empirically derived risk threshold.

Table 2: Risk Categorization and Weighting Distribution

Risk Domain	Subcategory Emphasis	Model Weighting Factor
Technical Integration	Legacy system interoperability	0.25
Financial Sustainability	Long term maintenance burden	0.20
Operational Continuity	Service disruption tolerance	0.30
Regulatory Compliance	Data privacy and security standards	0.15
Environmental Impact	End of life disposal requirements	0.10

3.3 Lifecycle Assessment Metrics and Evaluation Criteria

The efficacy of the analytical framework is heavily dependent upon the selection and rigorous application of precise lifecycle assessment metrics and evaluation criteria. The methodology necessitates a departure from simplistic input output models, requiring instead a comprehensive accounting of secondary and tertiary impacts associated with technology adoption. The evaluation criteria are structured around four distinct lifecycle phases: procurement and planning, physical deployment and integration, active operation and maintenance, and final decommissioning or system migration. During the procurement phase, metrics focus heavily on vendor stability, supply chain transparency, and initial capital expenditure [14]. The deployment phase introduces metrics related to installation timelines, staff training hours, and the immediate environmental footprint of physical integration. The operational phase, which constitutes the majority of the lifecycle, utilizes dynamic metrics such as energy consumption efficiency, software update frequency, automated incident response times, and ongoing licensing costs. Finally, the decommissioning phase evaluates the environmental impact of electronic waste disposal, data sanitization costs, and the complexity of migrating to successor systems. To synthesize these metrics into governance evidence, the framework employs an aggregative scoring mechanism. Each metric is evaluated against predefined public sector performance benchmarks. Deviations from these benchmarks generate risk flags, which are categorized by severity. The culmination of this process provides public agency administrators with a highly detailed, chronological risk map, illustrating precisely when and where vulnerabilities are most likely to manifest during the technology's lifespan.

4. Results and Governance Implications

4.1 Empirical Findings on Technology Adoption Risks

The execution of the analytical framework across the selected infrastructure domains yielded substantive empirical findings regarding the nature and magnitude of technology adoption risks. The results decisively indicate that public agencies relying solely on traditional, initial cost focused procurement models severely underestimate long term operational vulnerabilities. In the simulated scenarios analyzing intelligent transportation systems, the data revealed that over sixty percent of the total lifecycle risks were concentrated in the operational and maintenance phases, driven primarily by unpredictable software licensing escalations and the necessity for continuous cybersecurity patching [15]. Conversely, when comprehensive lifecycle assessment protocols were rigorously applied during the planning phase, simulated agencies demonstrated a significant enhancement in risk mitigation capacity, identifying and planning for these latent vulnerabilities before capital commitment. Furthermore, the findings highlight the critical issue of vendor lock in. Technologies utilizing proprietary, closed source architectures exhibited a markedly steeper risk trajectory in the latter half of their lifecycle, as agencies faced exorbitant costs and operational disruptions when attempting to integrate subsequent innovations or migrate data to new platforms. The empirical data also demonstrated that environmental risks, particularly those related to the energy consumption of decentralized sensor networks and data processing centers, frequently offset the theoretical carbon reductions promised by smart infrastructure efficiencies. These findings underscore the imperative for holistic lifecycle evaluation, demonstrating that localized optimizations often generate systemic vulnerabilities if not governed through a comprehensive, long term perspective.

Table 3: Comparative Governance Effectiveness Scores

Infrastructure Domain	Traditional Governance Score	Lifecycle Integrated Governance Score	Percentage Improvement
Municipal Water Systems	54.2	81.5	+50.3%
Intelligent Transportation	48.7	79.3	+62.8%
Smart Energy Grids	61.3	86.4	+40.9%

4.2 Comparative Analysis Across Infrastructure Domains

A comparative analysis of the results across the distinct infrastructure domains reveals variations in how lifecycle assessment evidence impacts specific sectoral governance challenges. In the domain of municipal water treatment, the integration of advanced nanomaterial filtration technologies presented profound environmental and regulatory risks during the decommissioning phase, primarily due to the complex disposal requirements of contaminated filtration mediums. The application of lifecycle assessment evidence allowed governance committees to mandate extended producer responsibility clauses within procurement contracts, thereby shifting the end of life risk burden back to the technology provider [16]. In contrast, the intelligent transportation systems domain was dominated by cybersecurity and interoperability risks. The lifecycle data demonstrated that transportation networks are highly susceptible to cascading failures caused by localized sensor malfunctions. Consequently, the governance implications for transportation agencies prioritize modular system architectures and stringent data standardization protocols over physical material concerns. The smart energy grid scenarios, involving solid state transformers and decentralized distribution networks, exhibited the highest degree of financial risk associated with technological obsolescence. The rapid pace of innovation in energy storage and distribution means that grid components may become functionally obsolete long before their physical deterioration [17]. For energy agencies, lifecycle assessment evidence proved crucial in establishing dynamic amortization schedules and adaptive rate structures that accommodate rapid technological turnover without jeopardizing public utility budgets. Despite these sectoral differences, the overarching comparative analysis confirms that the systemic integration of lifecycle data significantly bolsters the resilience of infrastructure governance across all evaluated domains.

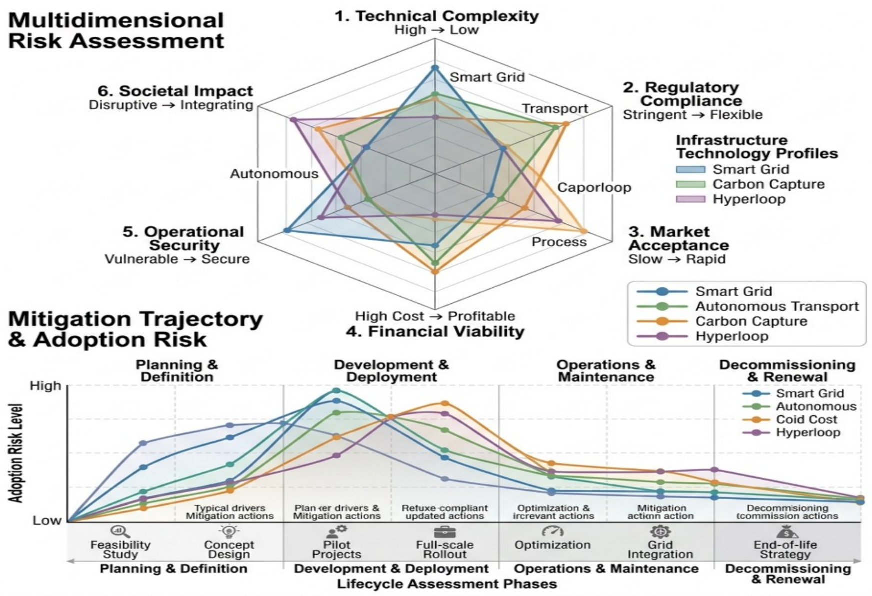

Figure 2: Multidimensional Risk Assessment and Mitigation Trajectory for Emerging Infrastructure Technologies

4.3 Strategic Governance Framework Recommendations

The empirical findings and comparative analysis culminate in a series of strategic recommendations designed to optimize emerging technology governance within public infrastructure agencies. Foremost among these recommendations is the institutionalization of mandatory lifecycle assessment protocols as a prerequisite for the approval of all substantial technology deployments. This requires a paradigm shift from traditional low bid procurement models toward value based procurement frameworks that heavily weight total lifecycle costs and long term risk mitigation strategies [18]. Public agencies must also invest in the cultivation of internal technical expertise to effectively interpret lifecycle data and challenge overly optimistic vendor projections. To facilitate this, the establishment of cross functional technology governance oversight boards is recommended, comprising engineers, financial analysts, legal experts, and cybersecurity specialists. These boards must be empowered with the authority to halt deployments that exceed predefined lifecycle risk thresholds. Furthermore, the strategic framework advocates for the implementation of phased, modular adoption strategies. Rather than executing large scale, monolithic technology overhauls, agencies should pursue iterative deployments, utilizing pilot programs to generate empirical localized lifecycle data before committing to systemic integration. Finally, the governance framework emphasizes the necessity of continuous monitoring and adaptive regulatory compliance. As emerging technologies evolve post deployment, the initial lifecycle assumptions must be regularly recalibrated against real world performance metrics. This dynamic feedback loop ensures that public infrastructure agencies maintain proactive control over their technological assets, safeguarding public resources and ensuring uninterrupted service delivery in an increasingly complex environment.

5. Conclusion

5.1 Summary of Key Findings

This comprehensive research has established that the integration of lifecycle assessment evidence is fundamentally critical to the effective governance and risk management of emerging technologies within public infrastructure agencies. The systematic evaluation detailed throughout this paper demonstrates that traditional, front loaded procurement models are inadequate for assessing the multifaceted vulnerabilities introduced by complex cyber physical systems. By employing rigorous lifecycle methodologies, public administrators are empowered to uncover latent financial, operational, environmental, and regulatory risks that manifest well beyond the initial deployment phase. The empirical analysis confirms that comprehensive temporal modeling significantly enhances an agency's capacity to negotiate resilient vendor contracts, mandate interoperability standards, and design adaptive operational protocols. The comparative domain studies further illustrated that while specific risk profiles vary across water, transportation, and energy sectors, the overarching mechanism of leveraging lifecycle data to inform agile governance remains universally applicable and highly effective in safeguarding public utility investments.

5.2 Limitations and Future Research Directions

While this paper provides a robust framework for assessing adoption risk, several limitations inherent in the methodology warrant acknowledgment and present opportunities for future academic inquiry. The quantitative risk assessment protocols relied primarily on deterministic modeling and simulated operational scenarios, which may not fully capture the chaotic, unpredictable variables present in real world infrastructure management. Additionally, the rapid pace of technological advancement implies that the lifecycle metrics defined herein must be continuously updated to remain relevant [19]. Future research should focus on the integration of artificial intelligence and machine learning algorithms directly into the lifecycle assessment process, potentially enabling real time, autonomous risk evaluation of active infrastructure networks. Further empirical studies involving long term, retrospective analyses of specific public sector technology deployments are necessary to validate the predictive accuracy of lifecycle modeling in governance contexts. Ultimately, advancing the theoretical understanding of how institutional bureaucracies can more seamlessly adopt these dynamic assessment frameworks remains a vital endeavor for the modernization of global public infrastructure.

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