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INTEGRATING CLIMATE CHANGE ADAPTATION INTO INFRASTRUCTURE PROJECT MANAGEMENT: A SYSTEMATIC REVIEW OF GLOBAL MODELS

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Abstract

Climate-driven disruptions to infrastructure systems include rising sea levels, intense precipitation, heat stress, and storm surges that are increasing in weakness to infrastructure systems across the world. The changes undermine the conservative, stagnant approaches to infrastructure project management (PM), which is founded on deterministic design principles grounded on historical climate data. The pressing need to incorporate climate change adaptation (CCA) in the infrastructure PM has led to governments, financiers and standardization organizations coming up with different models and frameworks. This paper clearly presents the world models that inform the incorporation of CCA within the infrastructure life cycle-which involves planning, design, procurement, construction, operation and decommissioning.

Through a systematic literature and policy review approach, the study identifies five major categories of adaptation integration: (1) standards-based adaptation and risk-management models (e.g., ISO 14090/14091, ISO 31000); (2) regulatory and finance-driven frameworks (e.g., EU Climate-Proofing Guidance, EU Taxonomy); (3) sectoral toolkits (e.g., PIARC, FHWA); (4) development-finance safeguards (e.g. World Bank,

The results indicate that although standards and toolkits provide process-based structures, DMDU approaches are the only methods that deal with uncertainty and variability in the long run. The regulatory and finance mechanisms also encourage the integration of the adaptation criteria in the project appraisal and procurement. Nevertheless, loopholes in equity integration, outcome measurement, compound risk treatment and operationalization of adaptive triggers remain. The paper suggests a synthesis framework to address these gaps and suggests the incorporation of ISO 14090 governance, DMDU appraisal and climate-proofing compliance in the infrastructure PM. It concludes the review with the finding that climate-resilient infrastructure must shift its paradigm to one of design to stay stable and manage to be flexible.

1. Introduction

1.1 Climate Adaptation is a Compelling Infrastructure Management Imperative.

The increasing effects of climate change in terms of increased number of floods, droughts, heat waves, and coastal inundation are systemic risks to infrastructure systems, which form the core of economies and societies (IPCC, 2022). Traditionally, infrastructure design and maintenance have been based on records of the past climatic conditions, based on the assumption that the past is the future. Non stationarity of climatic parameters however nullifies this assumption (Hallegatte et al., 2019). The construction of infrastructure that has not taken into consideration the future climate uncertainties pose the risk of approaching failure, retrofitting at high costs, or total collapse. As a result, the concept of adaptation has not only become a suitable environmental issue but has also become one of the fundamental management and risk governance questions (Ayyub, 2018).

The management (PM) of the infrastructure projects is the key point of intersection between technical, financial, and institutional decisions. Incorporating the concept of adaptation in PM means that the principles of climate-risk screening, flexible design, adaptive decision-making, and monitoring are implemented during the entire lifecycle of the project. Not only technical adjustments are necessary to achieve this alignment but also the change of government, financing, and knowledge systems (World Bank, 2021).

1.2 Reason behind a Systematic Review.

All over the world, several frameworks have been developed to operationalize adaptation, which include the ISO standards, sectoral and financial tools in infrastructure projects. However, practitioners and researchers are confronted with fragmentation: the models may focus on governance (ISO 14090), risk assessment (ISO 14091), regulatory compliance (EU Climate-Proofing) or managing uncertainty (DAPP, RDM). There is thus a need to have a systematic synthesis in order to map the ways these structures complement or diverge throughout the project lifecycle.

The study helps to add to the literature because:

1. Classification Global models of adaptation-integration: a typology of orientation and lifecycle coverage.
2. Comparing their comparative strengths, weaknesses and the maturity of their implementation.
3. Determining the similarities in processes of models; and
4. Identifying the gaps and making actionable suggestions on infrastructure PM.

1.3 Research Questions

The following four questions direct the review:

1. What are the international examples of successful mainstreaming of climate adaptation in infrastructure PM processes?
2. What effect do regulatory, and finance frameworks have on the adaptation practices at the project level?
3. Are there decision-support tools that can be used to manage deep uncertainty in long-lived assets?
4. What unanswered questions and shortcomings can be found in existing frameworks?

1.4 Conceptual Underpinnings: Infrastructure PM Adaptation.

The concept of adaptation can be applied to infrastructure PM and means changes in planning, design, implementation, or operation that moderate the damage or exploit positive opportunities in response to changing climate conditions (IPCC, 2022). Integration of adaptation includes the consideration of these factors in PM processes, including initiation, planning, risk management, quality control, procurement, and monitoring (PMI, 2021).

One sees a conceptual change towards resistance-based design (e.g., constructing higher flood walls) to resilience-based management (with its focus on flexibility, redundancy and learning) (Ahern, 2011). This paradigm requires dynamic tools and governance systems which could repeat decisions as new climatic data appear. According to Lawrence et al. (2020), adaptation of infrastructure is not a single decision, but a process that must be constantly managed with feedback and stakeholder interactions and scenario testing.

2. Methodology

2.1 Review Design

This is a systematic review that is in line with PRISMA (Preferred Reporting Items of Systematic Review and Meta-Analyses) principles (Moher et al., 2009). The research design uses the combination of the scholarly sources (peer-reviewed academic sources), institutional reports, and international standards, which covers both scholarly and policy fields comprehensively.

Scopus, Web of Science and Google Scholar databases of scholarly materials as well as institutional repositories of ISO, European Commission, World Bank, PIARC and Deltares were used as databases to review academic and grey literature, respectively.

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2.2 Search Strategy and Inclusion Criteria.

Search combinations included the following terms:

- (infrastructure AND project management AND climate adaptation AND (framework OR model OR standard OR decision making)).
- (climate-proofing or resilience assessment or adaptive management)
- (“ISO 14090” or iso 14090 or EU Taxonomy or DAPP or RDM or Decision Scaling)
- Inclusion criteria:
- Structures that only deal with adaptation (not mitigation) concerning infrastructural contexts.
- Relevance to the project management life cycle (screening to O&M);
- Global or regionally influential.
- Published between 2009–2025.
- Documented replicable process.

Disqualifying criteria: strictly local case studies that lack transferability and mitigation-only policies.

Data Extraction and Analysis The present paper will rely on secondary sources to examine the topic under investigation. <|human|>2.3 Data Extraction and Analysis The current paper will use secondary sources to discuss the issue under study.

All the identified frameworks were analyzed based on:

1. Lifecycle coverage (planning - O&M).
2. Governance and institutional congruence.
3. Risk/uncertainty treatment.
4. Financial/regulatory linkages.
5. Fairness and shareholder engagement.
6. Surveillance and adjudicated triggers.
7. Evidence of practice (case studies, policy adoption).

Thematical coding procedure was used to identify common principles and steps. The typologies were then grouped into five typologies according to their overall orientation.

3. Typology of Global Models of Incorporating Adaptation into Infrastructure PM.

In this section the five primary typologies that arise out of the review are offered, which include standards-based, regulatory/finance-created, sectoral toolkits, development-finance safeguards, and DMDU frameworks.

The standards-based model of adaptation and risk-management are two approaches that introduce risk into the domain of models that manage adaptation for disaster reduction and recovery (Kirk, 2010, p. 1).<|human|>3.1 Standards-Based Adaptation and Risk-Management Models These are two models that bring risk in the sphere of models of disaster reduction and recovery that manage adaptation (Kirk, 2010, p. 1).

ISO 14090 (2019): Principles and Requirements Adaptation to Climate Change.

ISO 14090 offers a general framework that guides the process of adapting organisations into governance, strategy, risk assessment and project design (ISO, 2019). It facilitates a circular procedure: setting the context environment and impact and vulnerability evaluating it, finding options, implementation and reviewing. The design of the standard is to facilitate the integration with other systems of ISO management, especially, with ISO 14001 (Environmental Management) and ISO 31000 (Risk Management).

In project-management applications, ISO 14090 helps to support:

- Setting up adaptation governance systems.

- Incorporation of climate risks to risk registers.
- Creation of adaptation plans including performance measures.
- Surveillance on adaptive feedback loops.

Its sibling, ISO 14091 (2021), outlines the approach to vulnerability, impact and risk assessment (VIRA) and provides step-by-step instructions to practitioners (ISO, 2021). The combination of these standards creates a well-structured, auditable route while being purposely flexible so that the sector can be customized.

Strengths: Cross-sector applicability, alignment of governance, universality.

Limitations Process-intensive, low uncertainty quantification, little guidance of equity (Röschel et al., 2022).

ISO 31000: Risk Management — Principles.

The ISO 31000 (2018) offers a general framework that can be used to identify, analyze, evaluate, and treat risks when/where the hazard is climate related. When associated with ISO 14091, infrastructure managers will be able to integrate climate risk into PM risk matrices systematically, with the processes of making decisions being traceable (Ayyub, 2018).

3.2 Frameworks that are regulated and governed by the finance department.

European Union Infrastructure Climate-Proofing (20212027).

Technical Guidance on Climate-Proofing of Infrastructure was published by the European Commission (EC, 2021) to make sure that every project that is funded by the EU considers both mitigation and adaptation. The directions are a formulation of a two-stage strategy:

1. Pre-feasibility/screening and scoping (pre-feasibility) ascertaining climate sensitivity and materiality.
2. Climate-proofing (design and implementation) in detail carrying out VIRA, option appraisal, and incorporating measures of adaptation in technical and financial documentation.

The framework is in line with the Sustainable Finance Taxonomy of the EU (2021/2139), that sets the requirements of a substantial contribution to climate change adaptation and does no significant harm (DNSH) checks. They are associated with funding eligibility and disclosure (European Commission, 2021).

Strengths: The legal binding of the EU funded projects, the combination of the adaptation with finance, the lifecycle integration and monitoring requirements.

Weaknesses: Compete with limited flexibility beyond the EU scenario (Venton and Pauw, 2022).

3.3 Sectoral Toolkits

Infrastructure-specific structures realize adaptation to specific infrastructures, in particular transportation, water, and energy.

PIARC International Climate Change Adaptation Framework of Road Infrastructure (2015).

This framework was created by the World Road Association (PIARC, 2015) and represents a four-stage process; (1) scoping and stakeholder engagement; (2) vulnerability assessment; (3) option identification and prioritization; and (4) embedding into decision-making. PIARC model clearly aligns the adaptation activities to the project stages, between planning and operation.

FHWA Climate and extreme weather vulnerability assessment framework (U.S.).

The U.S. Federal Highway Administration (FHWA, 2017) has an alternative strategy designed to suit transportation agencies. It provides the solutions to the asset's inventories, climate data acquisition, exposure analysis, and combination of the findings into investment prioritization.

Strengths: Data-driven and tested in several states in practice.

Weaknesses: Sector-specific; not easily transferable to other non-transport infrastructure.
These industry models show practical ways of integrating adaptation on asset level, which can be used as models of integrating PM more widely.

3.4 Development-Finance and Lender Safeguard Structures.

Climate-risk management and adaptation needs have become entrenched in Multilateral Development Banks (MDBs).

World Bank Climate and Disaster Risk Screening Tools.

The family of Climate and Disaster Risk Screening Tools made by the World Bank (2021) is applicable at project, sector, and policy levels. The logic of each tool is exposure → sensitivity → adaptive capacity Overall risk rating and results in outputs that are used to make project appraisal documents. The high-risk rated projects should include adaptation and budgets.

IFC Environmental and social sustainability Performance Standards.

The Performance Standards of international finance corporation (IFC, 2012) require that the clients should identify and address the environmental and climate risks as per the Performance Standard 1 (Assessment and Management of Environmental and Social Risks) and 4 (Community Health, Safety and Security). These standards adequately incorporate climate resiliency in the corporate and project risk management systems.

Strengths: Good connection between adaptation and finance; it can be enforced by covenant on loans.

Weaknesses: Not all regions are implemented equally; the results of adoptions are not often followed a loan (McGray et al., 2021).

3.5 DMDU Frameworks of Decision-Making under Deep Uncertainty.

Decisions on long-lived infrastructure climate adaptation are highly uncertain- there is a lack of knowledge of probabilities and the future. DMDU structures, thus, offer systematic ways of making sound or weak decisions.

Dynamic Adaptive Policy Pathways (DAPP).

The DAPP (Haasnoot et al., 2013; Haasnoot et al., 2024) was a program of adaptation pathways, which are time-sequenced, contingent upon the occurrence of adaptation tipping points (ATPs), developed in the Netherlands in the Delta Program. DAPP defines:

- The first set of actions (no-regret measures),
- Contingent actions (actions that occur when thresholds are crossed), and
- Pathway switching indicators monitoring.

Applications that have involved DAPP include flood management (Rotterdam), transport resilience (New Zealand) and urban planning (Singapore).

Advantages: Incorporates time plasticity and tracking; pathway graphs facilitate communication.

Weakness: Intensive resources; it needs the institutional ability of adaptive governance (Lawrence et al., 2020).

Robust Decision Making (RDM)

RDM (Lempert et al., 2003) by RAND Corporation is a stress-tests policy choices in millions of reasonable futures to find policy choices that can work reasonably well in most scenarios. RDM instead aims to achieve robustness which is minimizing regret in response to uncertainties. They can be used in water-resource planning (U.S. Bureau of Reclamation) and infrastructure investment appraisal (Groves et al., 2019).

Decision Scaling (DS)

DS (Brown et al., 2012) inverts the old-fashioned top-down climate-scenario method, beginning with vulnerabilities of the systems, then finding climatic situations that lead to unacceptable

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results. It works especially well when it comes to involving stakeholders in the determination of performance thresholds (Ray and Brown, 2015).

Real Options Analysis (ROA)

ROA uses financial-option theory to assess the leeway in the planning of investments, such as delaying or building more infrastructure based on observed weather conditions (Watkiss et al., 2020). This is conceptually strong but it is applied little in practice due to data needs and institutional unfamiliarity.

Summary of Typology

All these models demonstrate a variety of strategies to apply the concept of adaptation to infrastructure PM. The orientation, lifecycle coverage, treatment of uncertainties, and maturity of implementation of the models are summarized in table 1 (that should be included in publication).

4. Comparison of Global Models.

4.1 Cross-cutting Process Stages.

With all structures: standards, regulatory instruments, finance tools, sectoral toolkits and DMDU techniques, there is a shared pattern of stages in the process:

1. Governance and Scoping: establishing climate goals, roles, and boundaries on stakeholders (ISO 14090; EU Climate-Proofing).
2. Hazard, Vulnerability and Impact Assessment (HVIA): exposure, sensitivity and adaptability capacity (ISO 14091; World Bank screening).
3. Option Identification and Appraisal: coming up with structural, operational, policy, and nature-based options and trade-offs.
4. Inclusion into Project Lifecycle: adapting to designs, tender documentation and procurement review.
5. Financing and Disclosure: streamlining adaptation results with sustainable-finance taxonomies or lender protection.
6. Monitoring and Adaptive Management: determining triggers and indicators of needed decision revisions (DAPP; RDM).

Even though the wording may vary, the six stages offer a universal management cycle of adaptation that can be applied to infrastructure PM.

4.2 Comparative Evaluation Matrix

Framework Type	Lifecycle Coverage	Uncertainty Treatment	Finance/Policy Link	Equity Consideration	Monitoring & Triggers	Implementation Maturity
ISO 14090/14091	High	Moderate (scenario)	Medium	Low	Medium	High

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Framework Type	Lifecycle Coverage	Uncertainty Treatment	Finance/Policy Link	Equity Consideration	Monitoring & Triggers	Implementation Maturity
EU Climate-Proofing / Taxonomy	High	Low	High	Medium	High	High (EU)
Sectoral Toolkits (PIARC/FHWA)	Medium	Low	Medium	Low	Medium	High
MDB Safeguards (WB/IFC)	Medium	Low	High	Medium	Low	High
DMDU (DAPP, RDM, DS, ROA)	Medium	High	Low	Medium	High	Moderate

This comparison reveals complementarity: standards and regulatory tools institutionalize adaptation; DMDU frameworks operationalize flexibility; MDB and finance mechanism enforce compliance and funding alignment.

4.3 Institutional and Geographic Uptake.

The regional adoption patterns vary. Adaptation has been mainstreamed by the EU with legal requirements (Regulation 2021/2139), and in Australia and New Zealand, through inclusion in coastal and transport planning (Lawrence et al., 2020). Sectoral toolkits (FHWA) and risk-based asset management are important to North America (Ayyub, 2018). Multilateral lenders are used in a screening approach that is enforced inconsistently throughout the world. The ISO standards give the most transnational reference to governance, but its adoption is based on national capacity and awareness (Röschel et al., 2022).

5. Discussion: Gaps, Challenges and Emerging Directions.

5.1 Fragmentation and Lack of Integration.

One of the regularities is the piece-meal landscape of the frameworks of adaptation. The standards, finance tools and DMDU procedures tend to exist in a vacuum. As an illustration, ISO 14090 presents principles of governance, but not quantitative instruments; DAPP offers flexibility but is not created to be institutionally embedded. Not many frameworks connect the engineering design decision to the finance disclosure (Watkiss et al., 2020). The integration of these silos needs a meta-framework between adaptation planning (ISO), decision support (DMDU) and the mechanisms of finance (EU Taxonomy).

5.2 Minimal Handling of Compound and Cascading Hazards.

Most of the reviewed models evaluate the hazard separately, that is, flood, drought or heat, without modeling how failures spread across the systems that are interdependent (Hallegatte et al., 2019). The resilience of infrastructure requires the realization of cross-sectoral interdependence, e.g., the effects of power outages on water-supply failures. New systems-thinking solutions (Mostafavi et al., 2023) support network-based risk evaluation, but the complexity of these systems is unlikely to be implemented in PM practice.

5.3 Deficit Equity, Justice and Inclusion.

There is a high level of technocratization when it comes to infrastructure. Coleman et al. (2023) prove that the aspects of equity and justice are underrepresented in the field of resilience research. Present models rarely consider beneficiaries and costs of adaptation. The incorporation of procedural and distributive justice in PM by involving them in vulnerable assessment and collectively developing adaptation options would enhance effectiveness and legitimacy.

5.4 Monitoring, Evaluation and Learning Weaknesses.

DAPP and ISO 14090 focus on monitoring without offering many operating guidelines. Most of the projects do not have baseline and indicators to assess the performance of adaptation after implementation (McGray et al., 2021). Adaptation would be prone to being compliance-based and not results-based without outcome metrics, such as the amount of damages that have been avoided or service continuity. The new idea of adaptive monitoring systems (AMS) suggests incremental data gathering, which relates to decision triggers (Lawrence et al., 2020).

5.5. Institutional and Capacity Barriers.

The adaptive frameworks demand institutions that can learn through iterating, coordinating cross disciplinarily, and funding in the long term. Nonetheless, PM offices may have strict budgets, brief political lifestyles and predetermined design contracts (Ahern, 2011). The barriers to the implementation of DMDU techniques are capacity gaps in data management, stakeholder facilitation, and uncertainty communication, particularly in the developing countries.

5.6 Opportunities and Frontiers of Innovation.

Nevertheless, inventions are coming up:

- Nature-based solutions (NbS): Co-benefits and flexibility in adaptive pathways through the inclusion of ecological infrastructure (e.g., wetlands) (Raymond et al., 2021).
- Digital twins and weather analytics: Triggers of adaptive management can be operationalized through real-time monitoring.
- Sustainable finance reporting: The EU Taxonomy and Task Force on Climate-related Financial Disclosures (TCFD) requirements are encouraging the transparency of adaptation.
- Cross-scale governance: Adaptive pathways practices are institutionalizing national planning systems (Ministry of the Environment, 2022, New Zealand).

6. Suggestions on Infrastructure Project Managers.

Based on the synthesis, the recommendations to practitioners and policymakers will be as follows.

6.1 Setting up Adaptation Governance Early

Instill changing management within the project governance framework. Compliant with ISO 14090 by establishing the purpose of adaptation, roles and communication channels. Incorporate climatologists to PM teams and policy directive management buy-in.

6.2 Risk and Vulnerability Assessment as a part of PM Lifecycle.

Implement ISO 14091 or similar practices in the feasibility study to measure vulnerability and exposure. Connection to the PM risk register (ISO 31000). In the case of high-risk assets, formulate adaptation action plans and costed actions.

6.3 Implement Deep Uncertainty (DMDU) Tools.

Long-lasting, climate sensitive infrastructure should be used with DAPP or RDM. Map alternative ways of adaptation, set tipping-points and set up monitoring indicators. Where available, complement with Real Options Analysis to compute the value of flexibility.

6.4 Adaptation in line with Finance and Procurement.

Making certain project design is in line with EU Climate-Proofing Guidance or other comparable national models so as to be eligible to obtain green financing. Attract adaptation criteria into procurement e.g. scoring of tenders on resilience performance and flexibility.

6.5 Monitor, Evaluate and Learn

Establish a Monitoring, Evaluation and Learning (MEL) model that follows performance measures (e.g. service outages, number of floods overquota) and inputs findings back to future design modifications. Data visualization and communication should be done using digital tools.

Engaging stakeholders and being equitable is crucial to foster and maintain healthy relationships among the parties involved in the process. <|human|>6.6 Foster Stakeholder Engagement and Equity It is essential to engage and be equitable to the stakeholders in order to build and ensure the parties involved in a process have healthy relationships.

Involve vulnerable populations and other involved communities in vulnerability assessment and option appraisal. Adaptation pathways Co-design to represent social priorities and equitably share the benefits (Coleman et al., 2023).

6.7 Enhance Institutional Capacity.

Develop capacity in DMDU, scenario analysis and adaptive management training. Silos should be overcome by encouraging inter-agency coordination and knowledge-sharing across sectors.

6.8 Change Compliance to Performance.

Move away the emphasis on procedural compliance to performance outcomes. Apply such key measures as risk reduction, resilience dividends, and adaptation co-benefits (e.g., biodiversity, employment). Integrate them in PM dashboards and reporting.

7. Conclusion

The adaptation to climate change is changing the principles of the management of infrastructure projects. According to the systematic review various models, such as standards, regulatory frameworks, toolkits, lender safeguards and DMDU approaches are mosaics of practices, when considered together, can reshape the way projects are conceived, financed and managed.

The point worth noting is that no model is enough. Governance scaffold: The standard of ISO offers frameworks of regulation and finance; Sector toolkit: The principles are turned into practice through sectoral toolkits; DMDU methods: Deep uncertainty is managed at DMDU. These methods are synthesized and facilitate a plan act learn adapt cycle, which is needed to ensure long-term infrastructure resilience.

Nevertheless, there are considerable weaknesses in terms of compound hazards treatment, ineffective integration of equity and lack of monitoring of the consequences of the adaptation. These need systematic change - integrating adaptive governance, participatory engagement and learning through experience into the infrastructure PM DNA.

Finally, it requires a paradigm shift, and not to construct infrastructures with a set design limit but to operate under a change regime. Combining standards, finance and decision science, project managers can cease to avoid risk and move on to adaptive value creation, by delivering assets that adapt to an uncertain climate future.

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