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Chapter 10: Future Directions in Resilient and Governed Infrastructure Systems

10.1. Introduction

Resilience has become a buzzword in a broad range of disciplines and social domains, from public policy and political science to public health, urban planning, public administration, economics, ecology, produce supply chains, and infrastructure systems. Nevertheless, little is known about what resilience means in practice, how it can be effectively translated into action, and how progress can be measured. A comprehensive introduction to the concept is therefore timely for its application in transforming the resilience of infrastructure systems and the ways in which they are governed, managed, and financed.

This research characterizes resilience as the ability of a system to withstand and recover from shocks, stresses, and failures, particularly the extremes of climate and environmental conditions forecasted to become more frequent and severe. In the context of infrastructure systems, resilience is viewed as foundational for system performance and societal functioning and well-being. The theory of resilience applied here builds on ecology, Integrative Risk Governance, and the principles of Robustness, Adaptiveness, and Modular Overlaps. Governance the development and execution of economic, administrative, and regulatory decisions in complex, interdependent, and multiscale systems is closely intertwined with resilience and capacity. Together, these concepts are foundational because they provide insights into the requirements for resilient systems, identify opportunities for their advancement, and articulate ends towards which design, engineering, and operation can be directed.

10.1.1. Background and Significance

Infrastructure is critical to the functioning of society. Without functioning infrastructure, society cannot realise its potential and economic growth falters. Infrastructure is important not just for countries but for cities and communities, and the decisions taken there on investment, maintenance, management, governance, financing, trust and risk have far-reaching implications for growth and wellbeing. Society then becomes more resilient if its infrastructure functions efficiently not only under normal conditions, but also under stress, with redundancy, safety nets and institutional support mechanisms operating in a clear transparent and cost-effective manner. Conversely when an infrastructure fails, the consequences extend far and wide. Not only is it an enormous distraction from daily life with workers being pulled into service, businesses and services unable to function and logistics disrupted, but it is also costly to society and takes funds away from other long-needed investment. It is however still a costly lesson that when taken under better management frameworks, the infrastructure can be designed to support society under stress and provide for risk-free investment by the private sector.

An investment in risk management and governance can pay more dividends to society than simply throwing more investments to solve a problem after a failure. The technology for making infrastructure more resilient and risk-managed is there and is improving with developments in AI, Big Data, the Internet of Things, Analytics and Blockchain. The huge volume of remote sensing and crowdsourced data now available, together with new processing techniques, machine learning and pattern recognition allows for continuous monitoring of changes in the local and global climate. The changes in risk profiles can be better understood and anticipated, and with these advances digital twins of cities and regions are now more accessible and affordable.

10.1.2. Research design

Research design delineates the specific aims of a study, articulates hypotheses and sub-hypotheses, describes data sources and datasets, and identifies data-analytical and methodological approaches. Six overarching research objectives guide exploration of resilience and governance in infrastructure systems.

1. To determine the nature and relationships between resilience, governance, and policy measures. Resilience is increasingly highlighted in political discourse and public policy but remains poorly defined and poorly related to associated concepts and measures. A granular, policy-relevant elaboration of resilience is therefore urgently needed.

2. To map the full spectrum of climate-related threats posed to infrastructure systems those associated with natural and anthropogenic hazards as well as environmental degradation. Despite increasing attention to the climate-survival of >110 000 000 km of infrastructure (e.g., bridges, tunnels, roads, railways, buildings, ports, airports), infrastructure performance in response to a changing climate and environmental decay more broadly remains understudied.

3. To identify modularity and interoperability as high-leverage properties in infrastructure design and engineering. The resilience community has expressed growing skepticism toward the idea of redundant resilience the notion that resilience can be increased indefinitely by adding backup systems to absorb or counter shocks and stressors. The possibility of failure in allegedly redundant systems (e.g., the New Orleans levees during Hurricane Katrina) has fueled a search for other systemic properties that enable true redundancy in a more holistic sense. Among the most promising alternatives are modularity, interoperability, and the systemic design principle known as a system of systems.

4. To explore innovation in the governance, policy, and institutional arrangements underpinning infrastructure systems. Resilience rests not only on improved technology but also on better governance on strengthening the legal, institutional, and policy frameworks for risk assessment, management, funding, and sharing. What such changes might entail is becoming clearer, and preliminary analyses have begun to identify the motivations, incentives, and accountabilities that would drive effective governance of infrastructure systems.

5. To integrate emerging data-generation, modeling, and decision-support tools for climate-risk assessment and management. Data are paramount: they determine how well decision-makers understand, assess, and respond to climate risks. The need for improved data presents new, often daunting, challenges in architecture, governance, generation, quality assurance, and interoperability. Addressing these challenges is increasingly urgent, and guidance is emerging for the complex interplay of data, models, and decision-support systems in climate-risk management.

10.2. Foundations of Resilience in Infrastructure

Connectivity and dependency catalyze powerful feedback loops between natural systems and horizontal and vertical critical infrastructure for energy, communications, transport, and socioecological services. Resilience-infrastructures can be defined as a set of conditions, broadly categorized into adaptive and resistance properties, that enable these coupled systems to prevent, reduce, and respond to harm from extreme climate and environmental interactions and impacts, and to recover to desired functions and capabilities within a suitable time frame. Within a governance context, these are the preconditions for resilience in infrastructure, where failure to meet them is a source of risk, for failure can lead to unbearable costs or consequences that justify their prevention. Key metrics include critical thresholds, regional scales, and temporal performance measures.

These concepts and their interconnections are essential for analyzing technological design properties and resilience in specific areas of infrastructure, such as energy generation. These, in turn, inform how risk may be reduced or minimized within ongoing engineering and design developments adapting and increasing adaptability to stress and shock, increasing redundancy and resistance under stress, and enhancing de- and re-construction capabilities following failure. Two particularly important characteristics of resilience-infrastructures modularization and system-of-system interoperability, which, by permitting parallel quantification of such properties, facilitate the modeling, assessment, and optimization of physical connections are also informed in part by the knowledge base underpinning threats and risks.

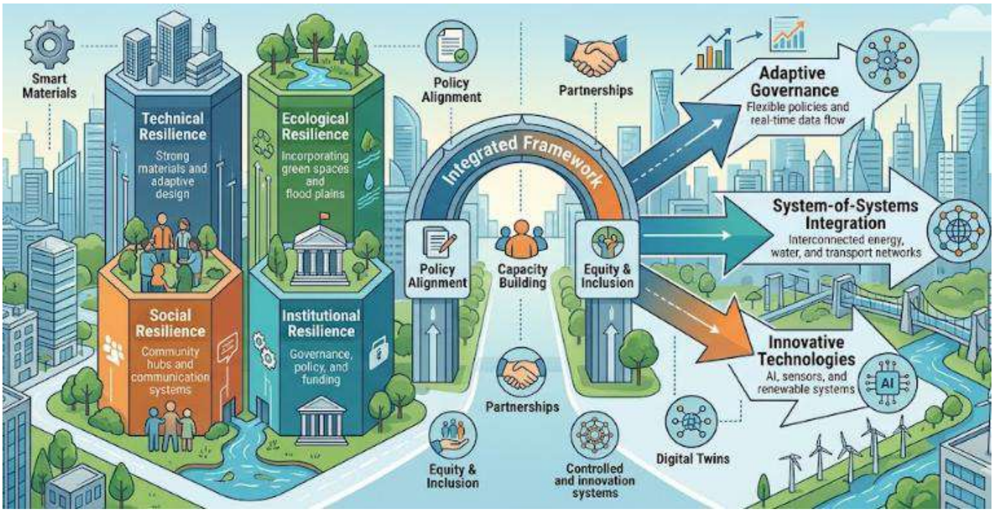

Fig 10.1: Foundations of resilient infrastructure toekomst

10.2.1. Conceptual Definitions and Metrics

Increasingly frequent and intensified climate-related hazards challenge the resilience of infrastructure and the urban environments they support. Various stresses and shocks threaten the functionality of resources and systems that underpin essential services, accessibility, and overall well-being. In response, new approaches in engineering and design, finance and economic investment, and public policy seek to strengthen and safeguard infrastructure and the core services energy, telecommunications, transport, and water they provide. Yet indeterminate risks, unknown trigger thresholds, and inexorable trade-offs complicate the design and choice of measures to support resilient and governed infrastructure.

Resilience is the capacity of a system to withstand, adapt to, and recover from weather-related hazards. Progress towards enhanced resilience is measurable across multiple dimensions social, physical, environmental, economic, functional, and, most importantly, risk governance by considering the adequacy of supportive management and institutional arrangements across respective entities. Performance monitoring spanning pre- and post-disaster conditions provides insight into resilience achievement and governance-effectiveness. Data on the frequency, intensity, and consequences of environmental hazards offer early-warning feedback about potential future conditions. Addressing these broader dimensions within hazard-specific contexts establishes the foundation for measuring progress in the design and engineering of individual infrastructure components for adaptive, robust, modular, and interoperable systems and system-of-systems.

10.2.2. Governance and Institutional Arrangements

Infrastructure systems both physical and virtual are designed, owned, operated, and maintained by a range of governments, companies, and other entities with distinct and often overlapping responsibilities. Effective governance requires far-sighted and principled coordination and collaboration among governments and societal stakeholders, and consideration of diverse factors such as accountability, alignment of regulatory and supervisory functions, complexity of risk governance, and adequacy of laws. Analysis of governance arrangements for infrastructure systems should cover the legal framework, the interplay of incentives and institutional arrangements, and the capacity for cross-jurisdictional coordination.

Governance is complex because the broad array of hazards and risks which create accountability pressures across diverse jurisdictions cannot be equally well addressed through single-purpose regulatory and supervisory structures. Instead, how a specific hazard affects a particular infrastructure asset depends upon location, the potential interactions with other hazards and particularly with other infrastructure systems, as well as a range of financial and operational considerations. These factors create diverse combinations of incentives and disincentives for investment in hazard-resistant assets or services. Effective governance thus requires coordination among multiple regulatory and supervisory bodies across jurisdictional boundaries, both within and among levels of government.

10.3. Threat Landscape and Risk Assessment

Critical infrastructure faces a broad range of threats arising from climate and environmental hazards, cyber-attack vectors, and technological accidents. These diverse potential hazards can be integrated into coherent risk-assessment frameworks that consider probability, exposure, and vulnerability. Conventional risk assessments, however, inadequately capture the full range of hazards, especially when considering the interaction of climate shifts and technological failure within cyber-physical systems. A comprehensive risk assessment must therefore clearly identify climate and environmental hazards, assess their anticipated frequency and intensity, evaluate the exposure of critical infrastructure to these hazards, and evaluate infrastructure performance under stress. Such a process must also address technological and cyber-physical risks, considering how climate change may alter the attack surface of critical infrastructure and critically undermining the robustness of safety and security margins.

Climate change and other environmental hazards are anticipated to become more numerous as systems approach safe operating limits. Quantifying the threat level for different domains of climate and environmental hazards in terms of intensity and frequency adds substance to assessments of expected hazard performance. In particular, modelling the statistical dependence between hazards using copulas enables the construction of joint hazard distributions, increases the external cross-correlation between hazards, and enhances the robustness of newly proposed hazard-generation processes. Probabilistic flood hazard assessment that incorporates non-stationarity in hazard-generating processes allows the identification of significant changes in probable flood depths, hence in flood risk, over time, while parallel analysis of hazard parameters elucidates the factors contributing to flooding.

10.3.1. Climate and Environmental Hazards

Climate and environmental hazards are critical for understanding the threat landscape facing infrastructure systems, as resilience cannot be assessed without taking the environmental context into consideration. Changes in climatic conditions and other environmental stressors impact both performance and vulnerability, affecting how infrastructure systems withstand and recover from extreme events. Infrastructure resilience is fundamentally connected to the likelihood and severity of physical failure during stress events, which can stem from climatic hazards (floods, heat waves, etc.), environmental degradation (erosion, subsidence, etc.), or a combination of both. Consequently, expanding these stressor-impact connections to include environmental stressors, beyond climate, is critical for capturing the complete risk landscape.

The dataset developed by the METRO-ADAPT project is one of the most detailed assessments of climate hazards at a city scale. It combines an extensive hazard risk analysis with an in-depth assessment of exposure and vulnerability. For all significant hazards from the Climate Hazard Taxonomy, it assesses the local likelihood of occurrence, the intensity, and throughput or exposure, as well as vulnerability mapping. In general, the methodology provides local governments with a deep understanding of the climate threat through a matrix that aggregates and compares the risk level of each climate hazard. However, when connected to infrastructure systems performance, it does not cover environmental degradation. Evidence suggests that, although less visible, processes of environmental degradation may surpass climate change as a hazard of systemic disruption by early- and mid-century, given human action on land use and ecosystem. Expanding the analysis to environmental degradation is simply a matter of looking in the right plane and level of detail for identifying the likely hazards mostly pressures of subsidence, erosion, and pollution.

10.3.2. Technological and Cyber-Physical Risks

Technological and cyber-physical risks arise from the increasing dependence on complex technology systems for critical functions and services. Major advances in communication and control technologies are creating societal systems that span the physical, cyber, and environmental domains. With the development of smart cities, smart manufacturing, and other technological integrations, a multitude of newly deployed connected devices introduce heavy dependencies across systems, sectors, and geographies. By mathematically formalizing cyber–physical dependencies as directed networks, it is possible to identify where one system is vulnerable if another fails.

The probability of catastrophic loss grows as societies deploy more complex systems. The public is challenged to make difficult judgment calls on emerging technologies and the unintended consequences that may arise through their implementation. Critical infrastructure, however, must not fall into disarray. The design of systems must move towards resilience with adaptive capabilities. An infrastructure system cannot stop operating because of an overload, but should rather carry the load within the bounds of its capabilities. Resilience reflects the imperfect nature of any infrastructure: things will fail, and there will be limits in terms of weather conditions, use loads, distance, duration of peak loads, and so on. Resilience creates options and redundancy that improves the capability of infrastructure systems to cope with stress under a range of plausible conditions.

A resilience-based strategy acknowledges that failure will happen and, when coupled with quantitative modeling, supports a desire for risk management. Resilience-by-design seeks to minimize the probability of failure while maximizing performance in or near failure. Resilient systems must be understood in terms of connectivity and response under conditions of high stress. A system-of-systems approach understands a collection of connected infrastructures against the weather conditions it is likely to meet. Systems should not be seen as a four-dimensional cube to be optimized, but as a flow chart within which key clusters can be understood at a simple level.

10.4. Advances in Infrastructure Design and Engineering

Recent years have seen important advances in the design and engineering of future infrastructure networks. Reslient design principles emphasize adaptation to future conditions, mitigation of climate change and environmental degradation, robustness under rare but extreme threats, and maintenance of critical performance levels under adverse conditions. These principles are further complemented by redundancy as a means to cope with uncertain and surprising events and propagate damage and failure in complex networks in a controlled manner. Considerable efforts are also dedicated to the development of deployment strategies that feature systems strengthened against the threats they face and incorporate redundancy.

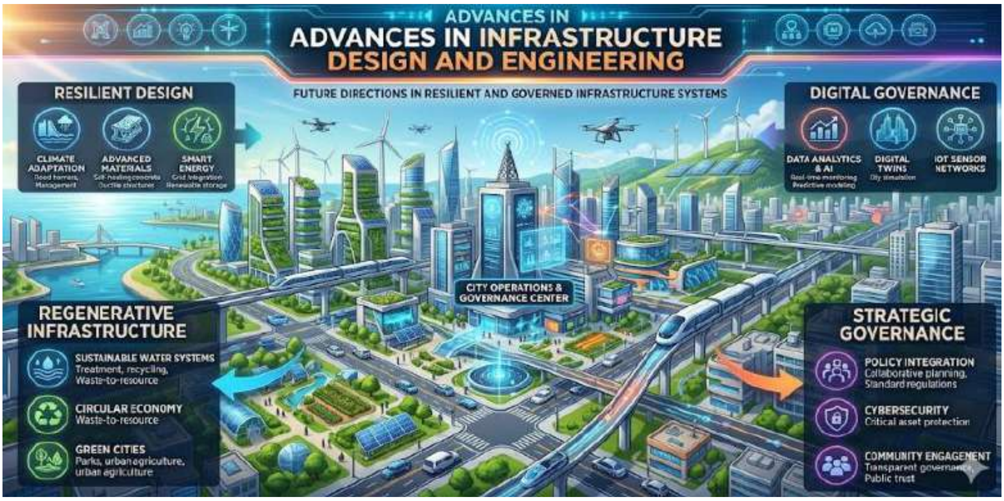

Fig 10.2: Futuristic infrastructure design and innovation

Infrastructure networks are inherently interdependent systems of systems and modularity and interoperability in their design and engineering allow adapting to new conditions or requirements by simply replacing, augmenting, or evolving one or several components. However, this design principle is not sufficient: cyber-physical systems-of-systems with flexible interfaces and well-designed interaction regardless of their temporal or spatial scales are crucial for performance and safety. System-of-systems engineering principles also need to be applied to enhance preparedness and response capabilities.

10.4.1. Adaptive and Robust System Design

Resilient infrastructure must be designed to tolerate perturbations, including intensified extreme events, even though they engage and stress a system's critical structural and functional thresholds. Correctly identifying and anticipating these structural and functional thresholds is a prerequisite for both resilient design and resilient governance.

Although infrastructure planners and engineers typically resist redundancy and underutilization, introducing spare capacity, building in resilience by design, or designing for reduced capacity under periods of stress improves resilience and reduces unexpected failures. Adaptive systems recognize that all environments change, and therefore the systems themselves must be able to rapidly adapt to evolving and uncertain conditions. Adaptive system designs are better suited to manage climate change-associated uncertainties.

Adaptive and robust design are often mutually exclusive. Making a critical infrastructure system more robust and tolerant to stressors adding material redundancy and structural or functional margins mitigates failure but also usually increases capital cost and resource utilization. However, the failure of a network of real blackouts of different types occurred when a perfectly normal thunderstorm event hit the zone. In mitigation of the heat and comfort risk to the residents using the bus-station in the metro, air-conditionings were installed. With all controlling devices functioning correctly, the station yet suffered flooding and extreme water flow. Sensing and monitoring are now accepted as being essential to risk mitigation of critical infrastructure systems. Monitoring can also assist with adaptive management by providing the information needed for making decisions under uncertainty about appropriate risk-response and decision-response patterns.

10.4.2. Modularity, Interoperability, and System-of-Systems Approaches

Modularity, Interoperability, and System-of-Systems Approaches

Modularity and interoperability increase resilience by limiting failure propagation and enabling responses to individual subsystem failures, while multidimensional networks reduce the impact of extreme events on critical functions. Modularity refers to the decomposition of systems into identifiable components, subsystems, or entities with specific functions. Modular design enhances resilience by allowing failure isolation and facilitating predictive maintenance and redundancy. Resilience-by-design recognizes that performance under stress requires special attention and that alternative designs for extreme conditions may improve standard performance. Interoperability enables disparate systems to function together, recovering critical functions by rerouting, transferring, or substituting services across systems. Systems-of-systems approaches increase resilience through additional pathways and service routes along different dimensions (e.g., transport, electricity).

Modular design simplifies system analysis, decomposing the whole into connected submodels that can be tested independently. Poor modularity impairs capacity to detect, locate, and predict failures. Conventional infrastructure systems are designed for operational efficiency and reduce redundancy, negatively affecting overall resilience.

For example, the power system of New Orleans operated at high levels of redundancy but low modularity to minimize costs. Modularity increases the number of ways in which a system can compensate for and recover from damage. Modularity and redundancy trade off reciprocal risk: oversizing one or more these dimensions can be an effective risk-control strategy against extreme events.

10.5. Governance, Policy, and Institutional Innovation

Coordinating and aligning infrastructure systems remains essential for enhancing resilience. Governance arrangements must resolve the conundrum of minimizing total risk at affordable costs while preventing moral hazard and ensuring incentives for proper operation and maintenance. Legal frameworks define regulatory, accountability, and compliance requirements; financing models create investment, operation, and maintenance incentives; and risk-sharing mechanisms help draw on public funds where needed.

Advances, gaps, and needed developments in legal frameworks, incentive structures, and funding models can be classified as drivers and barriers to effective governance. Legal frameworks govern coordination among operators of infrastructure dependencies and across political boundaries. They must establish the precise responsibilities and accountabilities of different public and private actors; ensure regulatory alignment among different infrastructures, sectors, and levels of government; provide a complete framework for the governance of risk, including prevention, detection, response, and recovery; and ensure the enforceability of legislation and regulation.

Funding models determine how the activities needed to meet incentives, and thus help achieve risk reduction, are financed. Public–private roles are defined for operation and maintenance, and for new investments; public funds are allocated to incentivize the desired activities; and public funds are made available in the event of disaster recovery or reconstruction, sharing the risk exposure and discouraging moral hazard.

10.5.1. Legal Frameworks and Accountability

Counter-terrorism law should effectively govern cyber-psychical risks and support the continuity of critical services in a resilient and governed infrastructure context. Government responses and regulations should remain proportionate and minimum compliance costs should be consistently sought in public contracts and spending. An obvious weakness of cyber-physical systems is the links and complexity of the interaction between the IT and OT systems. This enables low-cost cyber-attacks on target systems with the potential for catastrophic socio-economic effects, such as the recent attack on Ukraine. The legal framework must ensure the enforcement of laws and regulations punishing such acts with appropriate severity whilst incurring the minimum feasible cost for society as a whole. Such regulation should be part of an incremental, cost-benefit approach to the regulation of the cyber-physical domain. Regulation that anticipates all the risks of cyber threats is neither feasible nor intelligent.

Economic theory indicates that the recommended direction of regulatory change in any market is the one that improves welfare by making the market structure more like the competitive ideal. This also applies to the management of the risk of terrorism in public finance systems for the delivery of major infrastructure projects. The ideal solution for the market distortion caused by the risk of terrorist attacks on major infrastructure projects is the establishment of a private insurance market able to offer cover at affordable prices. When such a solution fails, the deployment of public funds to reduce the risk is warranted.

10.5.2. Financing Models and Incentive Structures

Recent trends point towards increasing public–private collaboration in building and managing infrastructure, especially in developing economies. However, such models cannot guarantee improved resilience by themselves. A review of the performance of publicly and privately managed infrastructure shows no obvious correlation with level of resilience (as defined through past performance) or even observed service quality. The nature of the relationship between public and private funding and the resilience of infrastructure remains an open question, as does the ability of public funds to transform the risk profile of infrastructure through insurance, investment and rebuilding incentives.

Adverse selection is a challenge in all insurance markets, and becoming more apparent in the climate insurance space. The lowest-risk assets – often also the highest-risk owners – generally pay the highest premiums. Developing countries face technological and governance challenges in making markets work. Developers of data-powered resilience models should explore different angles of using the information to close existing risk-transfer – and, therefore, infrastructure-investment gaps. An integrated framework that estimates country-conditional infrastructure risk-adjusted investment gaps across a risk-return continuum can facilitate priority investments in the infrastructure sectors with the highest potential impact on long-run growth and poverty reduction.

10.6. Data, Modeling, and Decision Support

Designing, modeling, and decision-support systems frequently employ data from many sources and types, including environmental databases (e.g., weather, climate, and Earth systems observation data) and social databases (e.g., census, hazard, demand, and consumption databases). Data quality and uncertainty are crucial to risk and systems performance assessment, design, and operational decision-making. To be useful, models must be structured in the right way, represent knowledge adequately, and be verified, validated, and tested using appropriate statistical techniques. Uncertainties in the input data, underlying model structure, model parameters, and model output must also be assessed, and the resultant measure of predictive uncertainty taken into account in decision-support systems.

A recurrent theme in recent infrastructure research is the use of big data, machine learning, and data assimilation for predictive modeling of infrastructure performance and risk, and reliable prediction intervals for the failure response and recovery processes. Recent research has also concentrated on the challenge of decision-making and resource allocation in areas facing deep uncertainty the condition wherein analysts cannot accurately describe the probability distribution of future events, nor deterministically correlate precursor signals in the present with those events. Modeling methods capable of addressing this challenge, especially exploratory modeling and analysis, robust decision-making, dynamic adaptive policy pathways, and cross-discipline scenarios, have become increasingly mature and widely applied.

10.6.1. Data Architecture and Quality Assurance

A comprehensive, integrated, and resilient architecture of big information infrastructure devices is a prerequisite for obtaining reliable data support for improving the resilience of the infrastructure system as a whole. The reliable storage, management, application, and sharing of huge amounts of temporal, spatial, and abstract data must be ensured. The data architecture must be determined according to the types of basic devices, system-level devices, and environment support devices of the system. The transmission-quality indicators of big data architecture-based levels must be of high quality, and a metadata system must be established according to use and user needs, quality construction, security processing, and potential value.

Data architecture relates to structure and transmission quality; the metadata hierarchy relates to use and user needs; quality assurance covers data quality assessment and enhancement; data governance mainly refers to data sharing, resource integration, vulnerability response, and convergence; and data-related security concerns content-based image retrieval, user privacy, and resistant security models. Quality of service not only covers the technical aspects and degree of guarantee but also shows the confidence level, which provides customers with a clearer understanding of service quality. In the context of uncertainty, a multilevel evaluation method for reliable development of public hierarchical infrastructure system based on grey clustering is established, thus ensuring that an infrastructure system is more capable of overcoming difficulties in a rapider, more efficient, less polluted, less energy-consuming, and balanced manner, thereby promoting social, economic, political, and environmental harmony and sustainable development of the whole region.

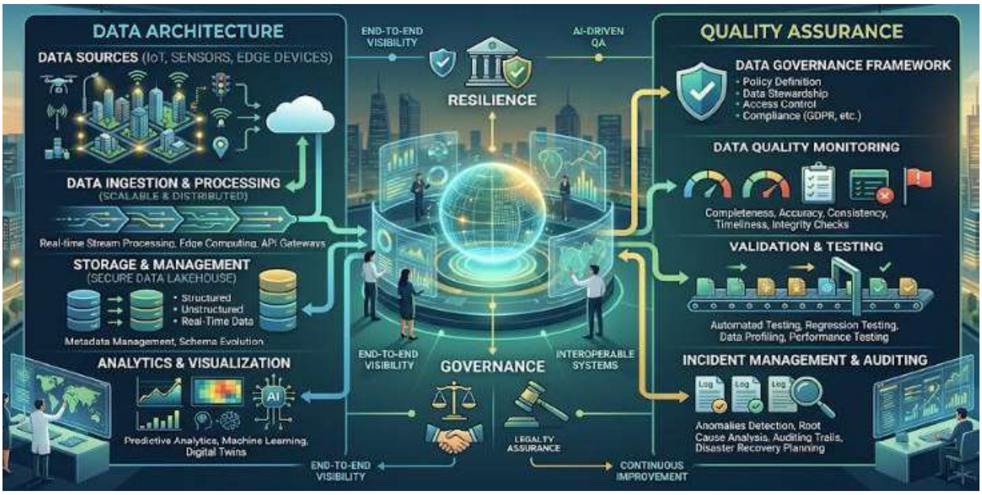

Fig 10.3: Data architecture and quality assurance overview

10.6.2. Emergent Modeling Techniques and Uncertainty Quantification

Emerging capabilities for data assimilation and coupling across hitherto disjoint models and disciplines enable optimized allocation of limited risk-reduction resources across spatiotemporal scales. For instance, methods are appearing that transform, say, multiscale urban system-of-systems models into probabilistic representations so that features of the surrounding environmental model, representing tropical or extra-tropical cyclone risk, can be assimilated directly into the system model. Methods for quantifying uncertainty within infrastructure systems models are also advancing quickly. Although verifiability is a hallmark of the scientific process, recent spectacular failures in statistical prediction of, for example, the 2008 financial crash resulted from ill-advised disregard of the core uncertainty around the patch-over of multiple nodes, each described by a complex code of extreme or deep-uncertainty. These failures have led to greater caution in analysis and prediction of complex systems such as the climate and economy.

Novel uses for history-based surrogates are now emerging in risk assessment. Traditional First Order Second Moment methods are becoming more reliable and applicable to a larger class of scenarios for highly nonlinear systems. Also maturing rapidly are screening and classification schemes identifying regions of risk for which detailed models are not yet developed or feasible, or may be presumed to be invariant over the range of environmental variations. Qualitative and semi-qualitative approaches are booming and new paradigms such as probabilistic risk assessment in a broad sense are sharpening attention to the dark side of profoundly complex systems. Exploratory analysis and deep quantitative insights have taken root, and it is with these softer but no less important evaluations that much of the future opportunity lies.

10.7. Conclusion

In recent years, climate change, technological transformation, and geopolitical competition are just a few of the prominent trends that have brought new attention to the resilience of critical infrastructures. Resilience is a central concept for understanding infrastructure performance under stress, but it is about much more than the engineering of specific systems. It encompasses governance, policy, and institutional innovation at many levels of decision-making. Seen in this way, the concept is valuable for navigating the risks of climate change and adaptation, and it is equally relevant to the exploration of risks in other domains, including environmental, technological, and cyber-physical aspects.

While resilience considerations are becoming mainstream in engineering, design principles, and modelling and decision-support systems, governing infrastructures in a manner that ensures resilience has not yet received the same level of attention or been articulated as a rigorous problem at the centre of institutional analysis and design. The relationships among climate and environmental change, technological and cyber-physical risks, underpinning infrastructure performance, and wider system performance are still being elaborated. To fill these gaps, a broad-based research agenda advances the resilience-governance nexus by integrating governance and policy dimensions into the study of climate, environmental, and technological risks. The approach draws on established definitions of resilience and governance, identifies key trends and drivers, maps assemblies of risks that have become more prominent, and brings together recent advances in infrastructure design and engineering with emerging innovations in governance, law, finance, and incentives.

10.7.1. Future Trends

The twin concepts of resilience and governance are increasingly integral to the design and operation of civilian infrastructure systems in light of a changing climate, growing environmental pressures, and more frequent and severe weather events. Advanced knowledge and capabilities in these domains contribute to lowering risks, enhancing state-of-good-repair conditions, improving system performance over the hazard spectrum, and broadening the range of extremes that a system can successfully withstand or rapidly restore following failure. Coping with the world's rising level of threat and long-range risk, however, also depends on effective policy and institutional innovation, including governance that is fit for purpose in the digital age.

By clarifying the meaning of resilience and governance in a practical context, metrics for measuring progress are identified as benchmarks are established for desirable system performance and institutional capability. Gaps in the evolving resilience and governance agenda of civilian infrastructure systems are then mapped and an associated research agenda outlined. All of these elements provide a basis for addressing the key question of future directions in resilient and governed infrastructure..

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