Sustainability Nexus Forum (2024) 32:13
https://doi.org/10.1007/s00550-024-00551-z

ORIGINAL PAPER

Sustainability nexus AID: infrastructure resilience

Tohid Erfani[1] · Mohammad Mortazavi Naeini[2] · Edoardo Borgomeo[3] · Mehrnaz Anvari[4] · Anthony Hurford[5] · Rasool Erfani[1,6] · Azin Zarei[7] · Mir A. Matin[8] · Kaveh Madani[7,8]

Received: 17 July 2024 / Revised: 23 September 2024 / Accepted: 25 September 2024 / Published online: 22 October 2024

Abstract

Infrastructure resilience advanced through nexus thinking is pivotal for societies to handle disruptions and ensure sustainable functionality. This interconnected approach understands infrastructure as an interdependent complex system and enables cooperative planning to achieve resilience. However, challenges like data inadequacy, financial limitations and governance issues impede its adoption, especially in developing regions. The United Nations University (UNU) Sustainability Nexus Analytics, Informatics and Data (AID) Programme strives to promote integrated resource management for sustainable development and fulfilling the UN 2030 Agenda. Through its Infrastructure Resilience Module, the initiative provides tools, data platforms and localised capacity building to empower professionals and communities for evidence-based, collaborative decision-making accounting for intersectoral relationships. By supporting context-specific analytical capabilities, bridging data gaps, and governance silos, the programme aims to pave the way for resilient and sustainable infrastructure development, particularly across vulnerable regions in the Global South, which face disproportionate infrastructure service disruptions.

Keywords Analytics · Informatics · Data · Infrastructure Resilience · Sustainable Development · Decision Making · Computational Modelling

1 Why infrastructure resilience matter?

Infrastructure, the complex network comprising physical, technological, social, and economic systems, is the bedrock of societal functionality and prosperity (Frischmann 2012). A study by the Organisation for Economic Co-operation and Development (OECD) highlights that by 2030, global infrastructure investment needs will reach an estimated USD 71 trillion, or roughly four times the current GDP of the U.S.A., emphasising its complexity and expansiveness (OECD 2017). These systems span an extensive range from transportation networks like roads and railways, energy supply, heat, gas and power grids that energise cities, water supply systems vital for human and industrial use, to digital communication channels that connect the world, and social institutions that uphold societal norms and governance (United Nations 2018). The efficiency and resilience of these systems transcend mere convenience; they are pivotal for economic activity, societal well-being, and the overall stability of nations.

Infrastructure resilience, an issue of paramount importance, refers to the capacity of these systems to foresee, absorb, adapt to, and rapidly recover from various

✉ Tohid Erfani
t.erfani@ucl.ac.uk

1 Department of Civil, Environmental, and Geomatic Engineering, University College London, London, UK

2 Department of Planning Industry and Environment, Parramatta, Australia

3 Department of Engineering, University of Cambridge, Cambridge, UK

4 Fraunhofer Institute for Algorithms and Scientific Computing, Sankt Augustin, Germany

5 Environment Agency, Wales, UK

6 Department of Engineering, Manchester Metropolitan University, Manchester, UK

7 United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany

8 United Nations University Institute for Water, Environment, and Health (UNU-INWEH), Richmond Hill, ON, Canada

disruptions. These disruptions can range from natural disasters like earthquakes and floods to human-induced challenges such as cyber-attacks or economic downturns (World Bank 2019). The resilience of infrastructure is not just about responding to immediate crises but also involves long-term planning and adaptability to future challenges. It encompasses proactive forward-thinking strategies and measures like incorporating redundancy in critical systems (e.g. to provide a backup in power networks in case of failure), ensuring flexibility to handle unexpected events (e.g. in transportation systems to reroute during emergencies), and developing adaptive mechanisms to respond to both immediate crises and long-term challenges (e.g. water management strategies to combat climate change impacts), thereby maintaining the continuity and reliability of these essential societal services. Such strategies are highlighted in various studies including the Cabinet Office (2011).

The socio-economic aspects of infrastructure resilience are significant. Investments in resilience lead to substantial long-term cost savings and enhanced disaster preparedness (UNDRR, 2019). It's estimated that for every USD 1 invested in resilience, about USD 4 are saved in recovery costs (World Bank 2019). Moreover, environmental benefits are equally crucial; resilient infrastructure reduces greenhouse gas emissions and minimizes environmental degradation. For instance, implementing green infrastructure solutions can lower the urban heat island (EPA 2023) and save hundreds of millions of dollars in flood losses by reducing stormwater runoff and improving water infiltration (EPA 2024). Additionally, resilient infrastructure directly supports the United Nations Sustainable Development Goals (SDGs) (World Economic Forum 2020) by promoting sustainable cities and communities (SDG 11) through the development of robust, adaptable urban systems. It plays a critical role in adapting to and building resilience against the impacts of climate change (SDG13) and contributes to ensuring access to clean water and sanitation (SDG 6) as well as robust energy systems (SDG7) by safeguarding water and energy infrastructure against disruptions. Resilience enhances industry, innovation, and infrastructure (SDG 9) by fostering sustainable industrialisation and innovation in resilient technologies. It promotes good health and well-being (SDG 3) and reduces inequalities (SDG 10) by ensuring equitable access to essential services for all, including vulnerable communities.

2 The need for a *nexus* approach

The resilience of infrastructure is particularly crucial given the interconnected nature of modern systems. Disruptions in one area, like the power grid, can have wide-reaching effects on critical sectors such as healthcare, transport, and communication. For instance, a power outage can cripple hospital operations, disrupt public transport, and sever vital communication channels (IEA 2021). This cross-sector cascading failure underscores the need for a comprehensive, integrated approach to infrastructure resilience, considering the interwoven nature of different systems and how their interdependencies can either ameliorate or exacerbate disruptions (National Infrastructure Commission 2020). This approach requires not only strengthening individual systems but also ensuring they are designed and managed to reinforce overall resilience through their interactions.

The nexus concept has matured considerably over the past decade (Brouwer et al 2023), and deeply embedded in systems thinking, emphasises the interdependence of various sectors in infrastructure resilience. It transcends traditional boundaries of engineering and natural sciences, incorporating social, political, economic, and health considerations. This holistic perspective is crucial for identifying, exploiting, and managing trade-offs and synergies across sectors. By doing so, it ensures that decisions made in one area bolster resilience in others. For example, strengthening water sector resilience is not only pivotal for achieving SDG 6 (Clean Water and Sanitation) but also reinforces SDG 3 (Good Health and Well-being), SDG 13 (Climate Action), and SDG 11 (Sustainable Cities and Communities). Such enhancements reveal the intricate and interconnected nature of these Sustainable Development Goals. The nexus approach thus serves as a comprehensive framework, enabling a deeper understanding and consideration of complex interdependencies within infrastructure systems. This leads to solutions that are not only more sustainable and resilient but also equitable, addressing the multifaceted challenges of modern societies.

Achieving resilient infrastructure is a complex, gradual journey with varying degrees of success, and this is particularly pronounced in the Global South. The path to resilience is marked by numerous challenges, each contributing to the spectrum of resilience levels that can be attained. Inadequate data collection significantly undermines the development of resilient infrastructure, as it impedes accurate need assessment and effective planning, particularly under conditions of uncertainty and changing stationarity. For example, the lack of detailed, reliable data on flood-prone areas, coupled with the uncertainties of climate change and shifting weather patterns, can result in insufficiently designed flood control infrastructure, leading to increased vulnerability to natural disasters. This scenario is not limited to flood management; it extends to various aspects of infrastructure, such as transportation, energy, and urban development, where assumptions of stationarity may no longer hold true. Furthermore, incompatible data standards across regions and sectors pose a considerable challenge. This inconsistency hinders the integration and analysis of critical information, which is vital for synchronised and efficient infrastructure planning, especially when dealing with non-stationary conditions and uncertain future scenarios. It can also slow down the uptake of artificial intelligence tools. Without standardised data formats and common frameworks for data exchange and sharing, collaboration between different regions and sectors becomes cumbersome, often leading to disjointed and ineffective infrastructure development strategies. This hinders the nexus approach to infrastructure resilience, which requires adaptive and flexible planning to accommodate evolving environmental and socio-economic landscapes.

Financial constraints are another significant barrier. Many regions struggle with limited budgets, impeding the construction of new, resilient infrastructure or the upgrading of existing facilities. Financial constraints also mean that existing infrastructure assets are often poorly maintained, reducing their ability to provide services and, in some cases, increasing the risk of failure with catastrophic consequences for populations and ecosystems. In the United States, the American Society of Civil Engineers (ASCE) suggests that slightly less than USD 6 trillion will be needed to maintain America's infrastructure to 2029, of which only USD 3.5 trillion USD are currently funded (ASCE 2021). This financial shortfall often leads to a reliance on outdated, vulnerable infrastructure, which is ill-equipped to handle modern challenges like climate change or increased urbanisation.

Political barriers and policy fragmentation add to the complexity. In some cases, political instability or changes in government can disrupt long-term infrastructure projects. The UK's HS2 project, for example, has been delayed and scaled back due to shifting political priorities across different governments. Policy fragmentation, where different agencies or levels of government operate in silos without cohesive nexus planning, further complicates the development of resilient systems. For instance, a city might develop a state-of-the-art transportation system, but if it is not integrated with regional planning, the overall effectiveness diminishes.

Social inequities play a crucial role in exacerbating infrastructure resilience challenges. Often, the process lacks a comprehensive co-design approach, involving all stakeholders, which is essential for understanding and addressing the diverse needs of different communities. Vulnerable communities, which are frequently the least served by existing infrastructure, also tend to have the least access to improved facilities and decision-making processes. This inequity in power, information, and access limits the understanding and integration of local knowledge, preventing the exploitation of potential synergies and the effective management of trade-offs. As a result, resilience measures often cater to more affluent or politically influential communities, neglecting the needs of marginalised groups. This not only hinders the equitable development of resilient infrastructure but also deepens existing social divisions. Without inclusive and participatory processes that engage all stakeholders, particularly those from underrepresented groups, the development of infrastructure fails to recognise and address the full spectrum of community needs and opportunities for resilience, thereby perpetuating cycles of inequality and vulnerability.

For this reason, it's essential to ensure that data and processes are open, accessible, and inclusive. Transparent data collection and decision-making allow for a diversity of voices to contribute to infrastructure planning, fostering equity and enhancing resilience. This approach enables a holistic understanding of community-specific challenges and opportunities, thereby improving the effectiveness of infrastructure systems.

3 The aid of the AID

The integration of advanced Analytics, Informatics, and Data (AID) tools is crucial in facilitating infrastructure planning across interconnected sectors, embodying the nexus approach. This method enhances transparency and stakeholder trust, enabling informed and collaborative decision-making for resilient infrastructure.

There are examples of the nexus approach using integrated AID tools in action. In Amsterdam, the nexus approach is reflected through comprehensive urban management. The strategy encompasses various sectors such as environmental quality, water management, traffic flow, and urban planning, illustrating how interconnected systems contribute to a resilient and sustainable urban ecosystem (Amsterdam Smart City: A World Leader in Smart City Development). Similarly, Singapore's Smart Nation initiative exemplifies the nexus approach in infrastructure resilience. This initiative involves a wide range of applications, from traffic management and environmental monitoring to healthcare and public safety, demonstrating how integration across different sectors can create a more resilient and dynamic urban infrastructure (Woo 2017).

These examples underscore the essence of the nexus approach in infrastructure resilience. By leveraging AID tools, decision-makers can synthesize data across sectors, leading to insights that inform policies and actions beyond traditional urban infrastructure management. Public-facing dashboards in these initiatives democratize data, enhance digital literacy, and address access inequalities. Ultimately, the integration of AID, underpinned by ongoing community and expert consultation, supports negotiation and consensus-building between diverse stakeholders, ensuring integrated and resilient infrastructure priorities.

However, the effective application of these AID tools in a nexus approach necessitates guidance from domain specialists and community stakeholders to ensure that real-world complexities are adequately addressed. This systemic approach is vital for mapping and harnessing the interconnections between various sectors, thereby enhancing and complementing diverse types of human knowledge for sustainable and resilient urban development. A key challenge lies in addressing the gaps related to AID, which are crucial for achieving infrastructure resilience.

Significant gaps include data inadequacy, where the lack of accurate and comprehensive data hampers effective planning and decision-making. In addition, integrating data across various sectors remains a challenge due to inconsistent data formats and standards, which impedes synchronized efforts. Governance issues further complicate the coordination needed for resilient infrastructure, making it essential to develop cohesive policies that promote integrated planning.

Leveraging advanced data collection methods is essential to bridge these gaps. Accurate and reliable data will enhance the ability to identify vulnerabilities and plan effectively. Automation can streamline processes, reduce human error, and increase efficiency in managing infrastructure systems. Analytics play a critical role in interpreting large datasets, identifying trends, and providing actionable insights. AI enhances these capabilities by offering predictive insights and enabling proactive measures to mitigate risks. Together, these technologies will help build a robust infrastructure capable of withstanding and rapidly recovering from disruptions, ensuring continuous service delivery and community well-being.

4 Sustainability *nexus* AID programme: infrastructure resilience

The United Nations University (UNU) Sustainability Nexus Analytics, Informatics, and Data (AID) Programme is a pivotal initiative aimed at fulfilling the UN Agenda 2030. The programme, by addressing the digital divide and inefficiencies in data use, comprises three interconnected pillars: Data, Informatics, and Analytics. These pillars aim to enhance data exchange, processing capabilities, and decision-making tools for sustainable resource management.

The Infrastructure Resilience Module of the programme aims to promote nexus thinking through an interconnected systems approach to planning. Key aspects include:

- Interdisciplinary Collaboration and Capacity Building: The module promotes an interconnected systems approach, emphasizing nexus thinking across various sectors such as water, energy, and waste management. It focuses on enhancing the skills and knowledge of professionals and decision-makers in these areas.
- Promotion and Accessibility of Decision-Support Tools and Data: The module concentrates on making existing advanced tools and comprehensive data sets more accessible, particularly emphasizing their use in the Global South. This approach supports informed decision-making in developing resilient infrastructure systems.
- Global Network and Knowledge Exchange: The module operates as a platform for global collaboration, involving a network of academics, industry experts, policymakers, and UN agencies. It facilitates the sharing of information and best practices across different sectors and regions.

The development strategy and upcoming initiatives of the module are structured around several key elements:

- Member Expansion: The module aims to expand its membership by inviting experts with diverse nexus-related expertise. The current members are distinguished professionals chosen for their diverse sets of nexus expertise from various parts of the world.
- Regular Engagements and Knowledge Dissemination: Planned activities include annual meetings and bi-monthly online discussions to discuss state-of-the-art developments. These gatherings are platforms for members to exchange knowledge and foster collaborations.
- Educational and Advocacy Efforts: The module plans to integrate resilience concepts into educational materials and student projects, thereby fostering resilience thinking in future professionals. Additionally, it aims to produce publications and engage in advocacy to influence policy and practice in the field of infrastructure resilience.
- Promotion in the Global South: A key focus will be on promoting the use of advanced tools and data in the Global South, aiding in the development of resilient and sustainable infrastructure systems in these regions.

5 Infrastructure resilience AID tools

To systematically analyse and categorise the available tools, we can consider specific criteria such as their relevance to different infrastructure components, their scalability, and their integration capabilities in line with the nexus approach. For creating a comprehensive list, tools will be classified based on their specific application in infrastructure sectors. Below is the process of selecting the infrastructure resilience AID tools.

Data & Analytics Facility for National Infrastructure (DAFNI): Selected for its comprehensive capability to model the interconnectedness and resilience of infrastructure systems across multiple sectors. It supports sophisticated simulations of infrastructure behaviour under various scenarios, offering crucial insights for planning and policy-making.

Table 1 Infrastructure resilience AID tools

Type of tool	Tool name	Related infrastructure	URL
Comprehensive planning & analysis	DAFNI	Multi-infrastructure	www.dafni.ac.uk
Planning & analysis	CREAT	Water management	www.epa.gov/crwu/climate-resilience-evaluation-and-awareness-tool
Planning & analysis	SWC	Stormwater management	www.epa.gov/water-research/national-stormwater-calculator
Simulation & modeling	SWMM	Water infrastructure	www.epa.gov/water-research/storm-water-management-model-swmm
Network analysis	EPANET	Water distribution	www.epa.gov/water-research/epanet
Optimisation & planning	HOMER	Energy systems	www.homerenergy.com
Traffic management	TRANSYT	Transport and traffic management	trlsoftware.com/products/transyt
Network simulation	NS-3	ICT and network simulation	www.nsnam.org
Planning & analysis	EEM	Energy systems	www.nrel.gov
Network analysis	EVI-EnSite	EV infrastructure	www.nrel.gov/transportation/evi-ensite.html
Planning & analysis	Energy Dashboard	Multi-energy systems	www.energydashboard.co.uk/live
Simulation & modeling	SERA	Hydrogen infrastructure	www.nrel.gov/hydrogen/sera-model.html
Simulation & modeling	ALTRIOS	Railway infrastructure	www.nrel.gov/transportation/altrios.html

Climate Resilience Evaluation and Awareness Tool (CREAT): Chosen for its focus on water management, specifically in evaluating and enhancing the climate resilience of water infrastructure, particularly under conditions of decision-dependent uncertainty in adaptive planning (Erfani et al. 2020; Pachos et al. 2022).

Stormwater Calculator (SWC): This tool is essential for stormwater management, helping to design and implement systems that can handle increased rainfall and flooding, which are critical components of resilient infrastructure.

Storm Water Management Model (SWMM): Selected for its robust modeling capabilities in water infrastructure, useful in designing systems to manage stormwater runoff effectively.

Environmental Protection Agency Network Evaluation Tool (EPANET): Chosen for its ability to model water distribution networks, ensuring that these systems can withstand and recover from disruptions.

Hybrid Optimization of Multiple Energy Resources (HOMER): Included for its application in energy systems, allowing users to design and optimize microgrid systems that enhance energy resilience.

TRAffic Network StudY Tool (TRANSYT): Selected for its relevance to transportation and traffic management, enabling an adaptive planning and coordination of resilient and efficient transport networks specially for signal's optimum timing in urban intersections.

Network Simulator (NS-3): Chosen for its capability to simulate network performance in ICT, ensuring that communication infrastructure remains robust and interconnected, while incorporating fair resource allocation principles to enhance the effectiveness of infrastructure systems (Erfani & Erfani 2015a, b).

Engage Energy Modeling (EEM): This tool facilitates cross-sectoral energy system planning and simulation, helping stakeholders understand the impacts and trade-offs of various energy strategies. It is particularly useful for planning electricity generation and transmission assets allowing users to design and perform trade-off energy analysis (Zafar et al. 2022).

Electric Vehicle Infrastructure – Energy Estimation and Site Optimization tool (EVI-EnSite): A comprehensive tool for energy estimation and site optimization of EV infrastructure. It integrates site energy management, energy storage systems, and distributed energy generation, providing high-fidelity modeling for optimal design and control of charging infrastructure.

Energy Dashboard: This tool provides real-time data and insights on energy consumption, generation, and emissions, supporting multi-energy system management and planning.

The Scenario Evaluation and Regionalization Analysis (SERA): SERA Model is used for hydrogen infrastructure planning. It evaluates regional deployment scenarios and supports decision-making for hydrogen infrastructure investments.

The Advanced Locomotive Technology and Rail Infrastructure Optimization System (ALTRIOS): This tool is designed for the optimization of light-duty railway transportation systems, focusing on the integration of advanced vehicle technologies and infrastructure planning to support transportation resilience.

Table 1 outlines these tools for their specific infrastructure applications.

Not all the tools introduced above are ideally suited for the nexus approach due to varying scales and degrees of integration. However, the AID tools identified here are designed to enhance infrastructure resilience effectively and promote nexus approach through their integrated use. The infrastructure resilience group members[1] play a crucial role in promoting nexus thinking and decision-making. As climate and other uncertainties grow, the knowledge and capabilities provided by these tools will be key to developing evidence-based, robust infrastructure that can withstand and recover from disruptions. When these types of tools and platforms are combined, they support multi-stakeholder decision-making and trade-off analyses for optimised and resilient scenarios.

6 The way forward

As we look towards the future, the AID programme aims to address the existing gaps and areas needing improvement in the field of infrastructure resilience. Our primary objectives include enhancing the use of the tools and methodologies, building capacity, fostering a global community, and engaging in extensive outreach.

We will focus on identifying and addressing gaps such as data inadequacy and governance issues. By improving data collection, standardizing formats, and developing cohesive governance frameworks, we aim to support integrated planning and decision-making. Additionally, our programme will expand to include new sectors and regions, with particular attention to vulnerable areas in the Global South.

Capacity building is essential for achieving long-term resilience. We will develop training programmes and educational materials, and establish platforms for knowledge exchange to equip professionals and communities with the necessary skills and knowledge.

Building a strong global community of practice is crucial for the success of our programme. We will expand our network to include more experts and institutions worldwide, initiate collaborative projects, and support practical examples of integrated resilience planning.

Effective outreach and engagement are key to raising awareness and encouraging participation. We will launch public awareness campaigns and actively engage with stakeholders through regular meetings, consultations, and feedback sessions.

We invite the global community to join us in our mission to enhance infrastructure resilience. By contributing their expertise and innovative ideas, stakeholders can help us achieve our goals and create a more resilient and sustainable world.

As leaders of the Infrastructure Resilience AID programme, we are committed to addressing identified gaps, expanding our scope, building capacity, fostering a community, and engaging in effective outreach. Through these efforts, we aim to lead the way in promoting integrated and resilient infrastructure development.

[1] https://www.sustainabilityaid.net/infrastructureresilience

Acknowledgements The UNU Sustainability Nexus AID Programme is thankful to an international group of leading scientists for their valuable contributions since its inception. The Programme also acknowledges the partial financial support of Germany's Ministry of Education and Research (BMBF) and Global Affairs Canada (GAC).

References

Amsterdam smart city: a world leader in smart city development. Bee smart city
ASCE (2021) Infrastructure report card 2021. American Society of Civil Engineers, Reston
Brouwer F, Caucci S, Karthe D et al (2023) Advancing the resource nexus concept for research and practice. SNF 31:41–65. https://doi.org/10.1007/s00550-024-00533-1
Cabinet office (2011) Keeping the country running: natural hazards and infrastructure. UK Government
EPA (2023) Building climate resiliency with green infrastructure. United States environmental protection agency
EPA (2024) Flood loss avoidance benefits of green infrastructure for stormwater management. United States environmental protection agency
Erfani T, Erfani R (2015a) Fair resource allocation using multi-population evolutionary algorithm. Springer International Publishing, In Applications of Evolutionary Computation
Erfani T, Erfani R (2015b) An evolutionary approach to solve a system of multiple interrelated agent problems. Appl Soft Comput 37:40–47
Erfani T, Pachos K, Harou JJ (2020) Decision-dependent uncertainty in adaptive real-options water resource planning. Adv Water Resour 136:103490
Frischmann BM (2012) Infrastructure: The social value of shared resources. Oxford University Press, New York
https://www.sustainabilityaid.net/infrastructureresilience
IEA (2021) World Energy Outlook 2021. IEA, Paris
National infrastructure commission (2020) Anticipate, react, recover: resilient infrastructure systems. London
OECD (2017) Investing in climate, investing in growth. Organisation for economic co-operation and development
Pachos K, Huskova I, Matrosov E, Erfani T, Harou JJ (2022) Trade-off informed adaptive and robust real options water resources planning. Adv Water Res 161:104117
United Nations office for disaster risk reduction (UNDRR). (2019). Global assessment report on disaster risk reduction

United Nations (2018) World urbanization prospects: the 2018 revision. United Nations, Department of Economic and Social Affairs, Population division

Woo JJ (2017) Singapore's smart nation initiative - a policy and organisational perspective. National University of Singapore

World Bank (2019) Lifelines: the resilient infrastructure opportunity. World Bank Group

World economic forum (2020) The global risks report 2020

Zafar R, Nezhad AE, Ahmadi A, Erfani T, Erfani R (2022) Trading off environmental and economic scheduling of a renewable energy based microgrid under uncertainties. IEEE Access 11:459–475