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Adaptive transition of critical transport infrastructures

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ABSTRACT: Environmental and resource constraints are crucial for adapting Critical Transport Infrastructures (CTIs) to the ever-changing environment. Inadequate resources coupled with the implementation of non-resilient and unsustainable mitigation measures pose a considerable risk, potentially steering CTIs towards maladaptation. This paper investigates the interplay of CTIs' resilience and adaptive capacity under multiple hazards. In line with this, the resilience level of a bridge case study is estimated with the use of resilience indices. Beyond resilience assessment, the research scrutinizes the efficacy of potential mitigation measures designed to facilitate the adaptive transition of these critical assets. In a proactive approach to mitigate maladaptation risks, the chosen measures undergo a thorough evaluation using sustainability indices. This evaluation considers a comprehensive spectrum of criteria, encompassing societal, environmental, and economic factors. By blending resilience and adaptive capacity analyses with sustainability assessments, this paper aims to provide a holistic framework for fortifying CTIs against the uncertainties of a dynamic environment. Through a careful examination of both the challenges and opportunities, it strives to guide the implementation of resilient and sustainable strategies, ensuring the continuity and efficiency of critical transport infrastructures in the changing world.

1 INTRODUCTION

The urgent need for Critical Transport Infrastructures (CTIs) adaptation to the new demands and the extreme load conditions is guided by environmental and resource constraints (OECD, 2020). In 2022, the United Nations Office for Disaster Risk Reduction announce the six interconnected principles for resilient infrastructures in alignment with the objectives of the Sustainable Development Goals (SDGs) for achieving systemic infrastructure resilience. The principles ensure that infrastructures' management is based on 1) continuous learning, 2) proactively protection, 3) environmental integration; 4) shared responsibility; 5) protection by design and 6) adaptive transformation (UNDRR 2023).

Following a strategy for the adaptive transformation of CTIs, the exploit of lessons learnt, and the benefits of emerging technologies ensure for the proper allocation of resources and minimization of losses (Buurman & Babovic 2016); (Connelly et al. 2017); (Miao & Ghosn 2016); (Ghasemi & Nowak 2017); (OECD, 2020); (Bueb et al. 2021); (IPCC, 2022); (UNDRR, 2023).

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As information technologies emerge, big data are generated and need to be man– collected, transmitted, and processed to support decision-making. New generation sensors have been used broadly to enhance reliability (Achillopoulou et al. 2020); (OECD, 2020); (Makhoul et al. 2023a).

The probability of exceeding acceptable limits depends on many parameters and the ageing period (Cerar et al. 2017). The reliability of information lead to different strategies of maintaining the asset and taking measures. This paper develops a methodology to assess the adaptive capacity of an asset taking into account engineering, economic and social parameters.

2 ADAPTIVE TRANSITION

The adaptive transition of CTIs into more resilient and sustainable systems depends on their adaptive capacity (Werners et al. 2021); (UNDRR 2023). The adaptive capacity expresses the ability of infrastructures to efficiently adjust and cope with the progressively changed environment, as well as the shifts in the supply and demand (Adey et al. 2003). As such, monitoring the capacity of CTIs throughout their lifecycles, adaptive transformation can be achieved (ADB, 2021); (Mehryar et al. 2022); (UNDRR 2023).

2.1 *Adaptive pathways*

The strategic deployment and implementation of dynamic and flexible Adaptive Pathways (APs) is needed to manage efficiently the long-term impacts of climate change and financial instability. Within this context APs, represent a sequence of decision points, related to events, mitigation measures and risk levels through time to achieve specific objectives and goals (Bueb et al. 2021); (Werners et al. 2021); (IPCC, 2022); (Makhoul et al. 2023b). Therefore, APs can be beneficial for CTIs' adaptive transition by avoiding maladaptation (Bueb et al. 2021); (Werners et al. 2021); (IPCC, 2022); (Makhoul et al. 2023b).

2.2 *Data-driven resilience*

The resilience level associated with a pathway exhibits a robust correlation with several parameters encompassing the sequence of events, hazards, mitigation actions, financial and environmental constraints, infrastructure's structural integrity and functionality levels as well as risk levels (Bueb et al. 2021); (IPCC, 2022); (Makhoul et al. 2023b). Hence, the pathway's resilience level is data-based and fluctuates among the different actions' resilience levels.

Data-driven resilience quantification is highly contingent upon the risk level (Achillopoulou et al. 2020); (Afrin et al. 2023). Data, and actions associated with increased risk levels can result to maladaptive APs (Werners et al. 2021); (IPCC, 2022); (Makhoul et al. 2023b). The lower the risk level is, the more reliable the resilience level of AP can be. As such, to avoid CTIs' devaluation, the following AP should be represented by a series of actions characterized by increased reliability and resilience levels over time (Bueb et al. 2021); (IPCC, 2022).

2.3 *Reliability of data*

The holistic impact of uncertainties on CTIs is crucial for their efficient management and associates with the reliability of data (Frangopol et al. 2019); (Diamantidis et al. 2019); (Achillopoulou et al. 2020). Poor reliability can result to non-resilient and -sustainable actions leading to maladaptation of CTIs (Bueb et al. 2021); (Werners et al. 2021); (IPCC, 2022); (Makhoul et al. 2023b).

The uncertainties of CTIs decision-making policies throughout their life cycles may pertain to factors such as climate change effect, economic instability, probability of failure and/or asset disruption, mitigation measures effectiveness as well as the accuracy of models, analyses, codes, metrics and monitoring data (Frangopol et al. 2019); (Achillopoulou et al. 2020); (Makhoul 2022); (Afrin et al. 2023). Their quantification makes aware stakeholders of the risk level and can be achieved by statistical and probabilistic models; scenario analysis, pathways deployment and expert judgment when the data is limited (Diamantidis et al. 2019);

(Achillopoulou et al. 2020); (Pasman & Rogers 2020); (Malekloo et al. 2022). Model updating can also be employed to reduce further the uncertainties levels by aligning computational models with the most realistic data and predictions (Achillopoulou et al. 2020); (Malekloo et al. 2022); (Makhoul et al. 2023 a and b).

2.4 *Sustainability*

Sustainable solutions to the decision-making process of CTIs can be well informed by enhanced reliability levels as they derive from accurate data and predictions (Achillopoulou et al. 2020); (Makhoul et al. 2023b). On the contrary, sustainability is not always expressed by actions with high resilience levels (IPCC, 2022); (Makhoul et al. 2023b). Environmental compatibility, adequate structural integrity levels and prevention of CTIs' disruptions along with optimum use of resources are crucial to ensure sustainability in resilience solutions (UNDRR, 2022 and 2023); (Makhoul et al. 2023b). In line with this, to obtain long-term socio-economic and environmental benefits that enhance the adaptive capacity of CTIs, sustainability constraints need to be established (European Commission 2022); (UNDRR, 2022 and 2023); (Global Infrastructure Hub 2023); (Lei et al. 2023); (Makhoul et al. 2023b).

3 METHODOLOGY

In this research, the quantification of resilience, sustainability and adaptation levels of CTIs, such as highway bridges, is founded on the research by Stamataki et al. (2023) and integrates the APs framework introduced by Makhoul et al. (2023b). The sequential phases of the methodology, which is used for the evaluation of the mitigation measures through the assets' life cycle to assess the pathway with the optimal resilience level, the lowest resources cost, and the supreme socio-economic and environmental benefits, are illustrated in Figure 1.

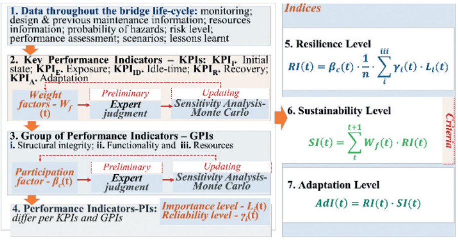


Figure 1. Adaptation space assessment methodology.

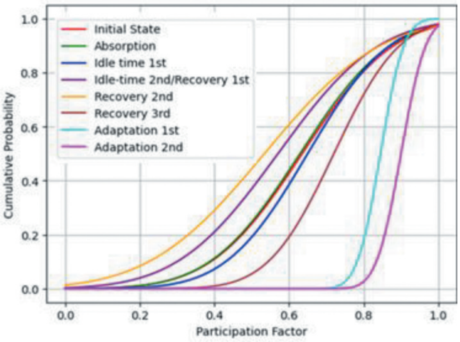


Figure 2. Probability of participation factor values over time.

3.1 *Data*

The methodology is data-driven, multi-criteria and comprises with seven phases commencing with the data acquisition. Data are not limited only to the maintenance information and design, but also to the lessons learnt throughout the life-cycle.

3.2 *Key performance indicators*

Key Performance Indicators (KPIs) that express the ageing periods of the asset's life cycle are employed to further organize and correlate the data. In general, there are five KPIs, though their number can differ from asset to asset. For example, the number of KPIs associated with idle-time (KPI_{ID}) and recovery period (KPI_R) initiation is related to the number of mitigation measures implemented in the case-study. To assess the contribution of the asset's ageing periods, Weight factors (*Wf*) are applied to each KPI. The preliminary *Wf* are established through experts' judgment, and their values are subsequently updated after the completion of the recovery periods. In cases where the asset demonstrates adequate levels of resilience and sustainability, reflecting an enhanced adaptive capacity, the *Wf* are recalculated based on a Sensitivity Analysis (*SensAn*).

3.3 *Resilience components*

Comprehensive research has been carried out concerning the resilience of CTIs, emphasizing their functionality and the interplay with structural integrity, as well as the resource requirements for their maintenance (Capacci et al. 2022). These three indicators are interdependent as inadequate levels of performance condition can trigger asset disruptions, whereas a lack of resources can progressively lead to safety and functionality problems. In line with this, the components of resilience considered in the adopted methodology are three and are related to i) the structural integrity, ii) the functionality and iii) the resources of the asset.

The components are expressed by Group of Performance Indicators (GPIs) that are considered complementary and are factored per KPI with the use of participation factors (β_c). The preliminary estimation of the participation factor for the resources component derives from a Life Cycle Cost (LCC) analysis as Stamataki et al. (2023) have already presented. A *SenAn* follows to determine the $\beta_c(t)$ per KPI based on the resilience thresholds as Stamataki & Achillopoulou (2023) have proposed. The criticality of the components on the overall resilience level arises from the type of distribution function of the factors. Throughout the life-cycle of the asset, the participation factors are also calibrated with a more sophisticated Monte Carlo Analysis (Figure 2).

3.4 *Parameters*

A set of Performance Indicators (PIs) is employed to associate the available data with the parameters that express each one of the GPIs. The total number of PIs (n) per component differ, whereas different PIs can be activated throughout the ageing periods of the asset. For example, the parameter of continuous monitoring is activated at the KPI corresponding to its initiation, while in cases of periodic monitoring, the parameter is deactivated. The assessment of each PI accounts for two variables i) the importance level and ii) the reliability factor as described in subsections 3.4.1 and 3.4.2 respectively.

The PIs pertaining to structural integrity are articulated with data such as a) the geometry and the type of the asset, b) material properties, c) damage index, d) structural health monitoring data, e) performance assessment, f) hazard occurrence, g) structural mitigation measures, g) mitigation impact and h) environmental limitations. Analogously, the PIs for functionality encompass a) design traffic capacity, b) traffic load changes, c) disruption, d) functionality monitoring data, e) functionality mitigation measures, f) hazard occurrence and extreme events, g) mitigation impact and h) environmental limitations. Finally, the resources component employs PIs such as monetary resources for a) maintenance and b) replacement, c) need for expertise staff, d) human resources, e) need for investment, f) financial limitations and g) bridge financial impact.

3.5 *Importance level*

The importance level (L_i) of each PI corresponds to the influence of the parameter in the resilience quantification. In total, the methodology comprehends four importance levels: 1-low, 2-moderate, 3-high and 4-very high. TheL_i may vary or remain consistent depending on the parameter and the ageing stage of the asset's life cycle. For example, factors such as failure of support or tendon loss are characterized by a consistently "4-very high" importance level per KPI due to their impact on the asset's safety and functionality levels.

3.6 *Reliability factor*

The methodology takes account of two different reliability levels with the use of reliability factors (γ_i). The first level pertains to reliable PIs with values equal or higher than 92.5%

($\gamma_i \geq 92.5\%$), while the second takes values below 92.5% ($\gamma_i < 92.5\%$), signifying non-reliable PIs. The factor is associated with the distribution function each PI follows, or the risk level and the probability of occurrence related to the PI ($\gamma_{i,PI}$), such as in cases of hazards, increase traffic demands and requirements for capital infusion. The γ_i is further updated based on the performance assessment of the asset in various scenarios ($\gamma_{i,p}$). The overall factor is anticipated to decrease over the exposure periods, while the implementation of mitigation measures and monitoring systems is expected to augment it.

3.7 *Resilience Index*

The overall resilience level of the asset is based upon the calculated resilience indices per KPI, *RI*(t), as presented by the equation in phase 5 of Figure 1. It derives from an overall average of risk, hazards, monitoring, components (structural, functionality, resources, operation) also taking into consideration the reliability level. The index ranges from 1 to 4, with lower values denoting a lower level of resilience. The critical level is at the middle of the scale corresponding that any further decrease of the RI can be related with safety, functionality and/or resources.

3.8 *Sustainability level*

Increased resilience levels did not always ensure high levels of sustainability. In the past decades, sustainable planning and management were not of high concern. Sustainability was promoted in 1987 WCED Commission's Report. The sustainability level is defined by Sustainability Indices, *SI*(t) as indicated by the equation in phase 6 of Figure 1. The estimation of the *SI*(t) takes advantage of the calculated *RI*(t) and the weighted KPIs. For a certain KPI the SI is calculated as the relative sum of the SI between two successive ageing periods.In this study, all pillars of sustainability are considered by including: 1) the environment through climate change, 2) the society through the population and traffic increase, and 3) the economy through the resources allocated to the infrastructure project.

3.9 *Criteria*

To ensure that the indirectly expressed sustainability level of the asset is well informed by the weighed RI, proper criteria and a classification scale ranging from 1 to 4 are selected. A rating of 1 denotes a non-sustainable level, 2 indicates the necessity for sustainability improvement, while 3 and 4 signify levels ranging from acceptable to sustainable sustainability. The selected criteria are related with the three pillars of sustainability i) society, ii) economy and iii) environment and take account the impact of the CTI throughout its life cycle.

3.10 *Adaptation Index*

The Adaptation Index (AdI) serves as a metric for assessing the adaptation level, and thus adaptive capacity of asset over its life cycle, in addition to evaluating the efficacy of different mitigation measures and policies. As the adaptive capacity should encompass both resilience and sustainability considerations the AdI is considered as their intersection and is determined based on the computed *RI*(t) and *SI*(t), as presented i by the equation in phase 7 of Figure 1.

4 CASE-STUDY

The bridge case study of this research the Hollandse Brug, the oldest prestressed RC highway bridge in the Flevopolder region of the Netherlands. The bridge plays a crucial role in connecting Almere, Amsterdam, and Schiphol Airport. Since its construction in 1969, many operational challenges led to the implementation of various mitigation measures throughout time. In 2007, as part of a refurbishment effort, a system of sensors was installed on the deck of the bridge for the continuous monitoring of strains, deflections, and temperatures (Achillopoulou et al. 2022); (Stamataki & Achillopoulou 2023); (Makhoul et al. 2023b). A Finite Element Analysis was performed to further investigate the performance and flexibility of the bridge under multi-hazards especially with climate change.

4.1 *Scenarios*

The hazard scenarios are based on the region's risk and account for a) traffic load changes and b) seismic events. According to NCEI (2023), in the next 50 years, the temperature increase in the region is expected to be slightly lower than the worldwide average, but still significant. Further to this, an augmented increase in the bridge's traffic volume, 247% greater than 1990, is predicted to take place by 2030 (IPCC, 2023). The earthquake occurrence in the Netherlands is classified as medium, meaning that in the next 50 years there is a 10% probability of such an event. In total four different hypothetical scenarios are considered as Table 1 presents. At the first stage of all the scenarios, the bridge is subjected to an initial temperature difference (ΔT) of 10◦C to consider the temperature increase due to global warming. The next stages of the scenarios include the occurrence of hazards related to traffic load changes (normal or increased) and seis-mic events (design or extreme). The final stage (4th) for all the scenarios, i.e., after the seismic event, restores the bridge to the initial considered traffic conditions (normal or increased).

Table 1. Multi-hazard scenarios.

Stage	1st	2nd		3rd		4th	
Hazzard Scenario	ΔT 10°C	Traffic *n*	*i*	Seismic event *d*	*e*	Traffic *n*	*i*
I	░	░		░		░	
II	▒	▒			▒	▒	
III	▓		▓	▓			▓
IV	█		█		█		█

* Symnols *n* and *i* are used for normal and increased traffic load and *d* and *e* for design and extreme seismic events.

4.2 *Simulation*

The bridge is 355m long with seven simply supported spans, featuring a 38m wide deck following its expansion in 2007. The structure comprises nine prefabricated prestressed girders and four cast in situ and post-tensioned transverse beams evenly distributed across the spans. The deck is supported by piers connected by elastomeric bearings, which offer both vertical stiffness and flexibility for anticipated horizontal deformations.

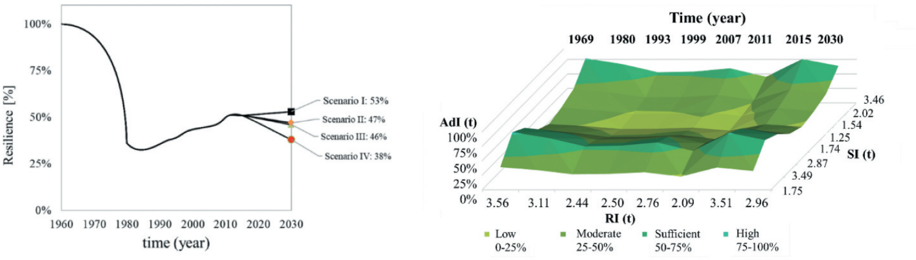
The model of the bridge was created with SOFiSTiK software. The dimensions estimated from existing drawings, and any missing data, such as transverse beam geometry, reinforcement arrangements, and prestressed tendons, were determined based on load combination results. The RC elements (slab, beams, piers) were simulated using 3D finite elements. Three axial and torsional springs were used for simulating the bearings.

5 RESULTS

The results of the four scenarios examined are shown in Table 2 in terms of the percentage of the structural elements, parameters or functionality been affected. The first scenario indicates that the damages in the girders, transverse beam or the bearings provoke a disruption of traffic with closing a part of the bridge for mitigation measures. The crack width seem to be unaffected by the increase of temperature and the designed traffic load. The second scenario indicates that even there are not extensive failures the risk of damage is increased since the percentage of elements passing the controls are decreased and approximately 10% of them are not sufficient to bear the loads. This automatically would cause a disruption on the bridge functionality by closing more lanes (based on the map of damages). Scenario III induces greater damages and risk of failure to the structural elements. From the analysis results, 83% of the structural elements are passing the acceptable thresholds, whereas 58% of the bearing do pass too. Lastly, Scenario IV prompts the severe damaged to be happened resulting in full closure of the bridge for mitigation measures and avoidance of losses.

Table 2. Multi-hazard scenarios' results.

Elements/ parameter	Scenario I			Scenario II			Scenario III			Scenario IV		
	failed %	damaged %	pass %	failed %	damaged %	pass %	failed %	damaged %	pass %	failed %	damaged %	pass %
Girders	2	3	95	5	5	90	3	14	83	3	22	75
Crack width	0	2	98	0	10	90	0	17	83	3	22	75
Transverse beam	0	7	93	0	14	86	0	14	86	0	18	82
Bearings	4	29	67	3	31	67	4	38	58	10	40	50
	opened %	closed %		opened %	closed %		opened %	closed %		opened %	closed %	
Lanes	62	38		38	62		38	62		0	100	



(a)

(b)

Figure 3. (a) Resilience indices (b) Adaptation space over time versus Resilience and Sustainability indices.

From the artificial data derived from the Finite Element Analysis, there is not significant decrease in the reliability of tendons to bear loads, therefore those elements didn't seem to have altered their importance level in the capacity of the asset. The rest of the structural elements sifted their importance due to the uncertainty and the risk for further damage.

The different scenarios seem to have an influence for the future resilience of the asset as shown in Figure 3a. It seems that only the first scenario manages to provide a resilience index just above 50% of the initial resilience. Damages on all the other scenarios range from 47-38% resilience levels. Specially for the extreme scenario IV, the resilience levels seem to have decreased to the level of the 1980s when the bridge could not further withstand the demands.

Although the resilience indices are changing, it seems that their influence to the sustainability, according to the current methodology is not significant. Figure 3b presents a 3D surface diagram providing a representation of the RI and SI changes over time. Versus the adaptation level of the asset. The adaptation level is expressed as a percentage of the relative AdI to the maximum potential AdI derived from the novel methodology considering the maximum RI and SI values.

It is remarkable that the highest SI value (3.49) is observed at the completion of the initial state period, while the RI experiences a slight decrease of 13% (from 3.56 to 3.11) indicating the start of the exposure period. At this stage, the adaptation level stands at a moderate level of 39%. The subsequent mitigation periods from 1993 to 2011 exhibit varying levels of low to moderate adaptation, ranging from 20% to 44%. The lowest AdI value of 20% corresponds to 2007 when traffic restrictions were imposed on the bridge.

To better understand the adaptation over the periods, the investment, operational but also the value of the asset is plotted in Table 3 over time. The value of the asset in monetary terms is calculated by considering the Effective Annual Interest Rate over the periods which is considered as 5% throughout the years, based on the Netherland data. The adaptation of the asset was in low levels in the 2000s when a big investment was needed to transform the asset again to ma bridge meeting the needs. This automatically increased the value of the asset, especially with increasing the demand for use by widening the deck and adding lanes ever since. Ever since the installation of SHM systems in 2007, the investment needed added tremendous value to the asset and made it more flexible to adaptation for the future, needing lower investment capital and steady operational cost.

Table 3. Asset's costs over time in Euro.

period name	**Initial state**	**Exposure**	**Idle time 1st**	**Idle time 2nd**	**Recovery 2nd**	**Idle time 3rd**	**Recovery 3rd**	**Adaptation**
period (years)	1969-1979	1980-1992	1993-1998	1999-2006	2007-2010	2011-2014	2015-2022	2023-2030
Age (years)	10	23	29	37	41	45	53	61
Asset value	2.63E+07	7.10E+07	6.54E+07	6.65E+07	1.12E+09	1.43E+09	3.47E+09	3.53E+09
Total Capital Investment per Period (TCIP)	6.22E+07	5.00E+07	1.65E+08	1.95E+08	2.01E+08	3.25E+08	9.00E+07	8.50E+07
Total cost per period (TCP)	6.59E+04	1.78E+05	1.63E+05	1.66E+05	2.81E+06	3.58E+06	8.68E+06	8.84E+06

6 CONCLUSIONS

The proposed methodology intricately captures the essence of adaptation capacity. Lower levels of adaptive space signal a pressing need for increased investment, while moderate to high levels signify a tangible enhancement of the asset's intrinsic value. In the face of unforeseen events and circumstances, the adaptation space remains at a moderate level.

As outlined by the methodology, the forecast for future adaptive space is notably high, indicating the bridge's robust capability to withstand hazards. This resilience is underpinned by the implementation of strategies grounded in a wealth of engineering expertise and historical data, ensuring a well-informed and proactive approach to fortifying the bridge against potential challenges and maladaptation strategies.

REFERENCES

Achillopoulou, D. V., Mitoulis, S. A., Argyroudis, S. A., & Wang, Y,. 2020. Monitoring of transport infrastructure exposed to multiple hazards: A roadmap for building resilience. *Science of the total environment*, *746*, 141001.

Achillopoulou, D. V., Stamataki, N. K., Psathas, A., Iliadis, L., Karabinis, A., 2022. Resilience Quantification based on Monitoring & Prediction data Using Artificial Intelligence (AI). *IABSE Cong. Nanjing 2022-Bridges Structures. Connect. Integration & Harmo*, *Nanjing*, *21-23 September 2022*.

Adey, B., Hajdin, R., & Brühwiler, E. (2003). Supply and demand system approach to development of bridge management strategies. Journal of infrastructure systems, 9(3), 117–131.

Afrin, T., Aragon, L. G., Lin, Z., & Yodo, N., 2023. An Integrated Data-Driven Predictive Resilience Framework for Disaster Evacuation Traffic Management. *Applied Sciences*, *13*(11), 6850.

Bueb, B., Tröltzsch, J., Reichwein, D., Oldenburg, C., Favero, F., Bodle, R., Teebken, J., Jacob, K. and Voß, M., 2021. Towards sustainable adaptation pathways. A concept for integrative actions to achieve the 2030 Agenda, *Paris Agreement and Sendai Framework. Conceptual & analytical paper* (No. UBA-FB–000590/3, ENG). Umweltbundesamt (UBA).

Buurman, J., & Babovic, V., 2016. Adaptation Pathways & Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy & Society*, *35*(2), 137–150.

Capacci, L., Biondini, F., & Frangopol, D., 2022. Resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks. Resilient Cities&Struct. 1(2), 23–41.

Cerar B., Allaix D.L. and Vervuurt A.H.J.M.(2017) Probabilistic analyses for determining the impact on the structural safety of bridges and viaducts, D 5.2 Impact analyses for bridges and viaducts, TNO.

Connelly, E. B., Allen, C. R., Hatfield, K., Palma-Oliveira, J. M., Woods, D. D., & Linkov, I., 2017. Features of resilience. *Environment systems & decisions*, *37*, 46–50.

Diamantidis, D., Sykora, M., & Sousa, H., 2019. Quantifying the Value of Structural Health Information for Decision Support.

European Commission, 2022. Guidance on Public Investment into Sustainable Infrastructure Projects.

Frangopol, D. M., Dong, Y., & Sabatino, S., 2019. Bridge life-cycle performance and cost: analysis, prediction, optimisation and decision-making. In *Structures & Infrastructure Systems* (pp. 66–84).

Ghasemi, S. H., & Nowak, A. S., 2017. Target reliability for bridges with consideration of ultimate limit state. *Engineering Structures*, *152*, 226–237.

Global Infrastructure Hub, 2023. *Sustainable Infrastructure*. Retrieved from: https://www.gihub.org/sustainable-infrastructure/, (assesssed 26/09/2023).

Intergovernmental Panel on Climate Change, IPCC, 2022. *Climate Change 2022: Impacts, Adaptation, & Vulnerability*. Contribution of Working Group II, Cambridge University Press, 3056 pp., doi:10.1017/9781009325844.

Lei, X., Dong, Y., & Frangopol, D. M., 2023. *Sustainability-informed intelligent management of aging civil infrastructure systems with emphasis on bridge networks.*

Makhoul, N., Achillopoulou, D. V., Stamataki, N. K., & Kromanis, R., 2023a. 12 Image Processing. *Data Driven Methods for Civil Structural Health Monitoring & Resilience: Latest Developments & Applications*, 279, Taylor & Francis.

Makhoul, N., Achillopoulou, D. V., Stamataki, N. K., & Kromanis, R. (2023b). Adaptive pathways using emerging technologies: Applications for CTI. Sustainability, 15(23), 16154.

Malekloo, A., Ozer, E., AlHamaydeh, M., & Girolami, M., 2022. Machine learning & structural health monitoring overview with emerging technology and high-dimensional data source highlights. *Strt. Health Mon*., *21*(4), 1906–1955.

Mehryar, S., Sasson, I., & Surminski, S., 2022. Supporting urban adaptation to climate change: What role can resilience measurement tools play?. *Urban Climate*, 41, 101047.

Miao, F., & Ghosn, M., 2016. Reliability-based progressive collapse analysis of highway bridges. *Struct. safety*, 63, 33–46.

Organisation for Economic Co-operation & Development, OECD, 2020. OECD compendium of policy good practices for quality infrastructure investment.

Pasman, H. J., & Rogers, W. J., 2020. How to treat expert judgment? With certainty it contains uncertainty!. Journal of Loss Prevention in the Process Industries, 66, 104200.

Stamataki, N. K., & Achillopoulou, D. V., 2023. Sensitivity analysis on resilience components throughout the lifecycle of an asset. IALCCE 2023 8th Intern. Symp. on Life-cycle Civil Eng., *Milan, 2–6/7 2023.*

Stamataki, N. K., Achillopoulou, D. V., & Makhoul, N., 2023. Evaluation of Resilience based on Resources & Adaptation Level in Critical Transport Infrastructures. *The 8th Smart City Applications International Conference, ESTP Paris France, 4–6 October 2023.*

United Nations Office for Disaster Risk Reduction, UNDRR, 2023. *Handbook for implementing the principles for resilient infrastructure*, https://www.undrr.org/quick/77508 (assessed 26/09/2023).

Werners, S. E., Wise, R. M., Butler, J. R., Totin, E., & Vincent, K., 2021. Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, 116, 266–275.