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# Digital technologies can enhance climate resilience of critical infrastructure

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## ABSTRACT

Delivering infrastructure, resilient to multiple natural hazards and climate change, is fundamental to continued economic prosperity and social coherence. This is a strategic priority of the United Nations Sustainable Development Goals (SDGs), the World Bank, the Organisation for Economic Co-operation and Development (OECD), public policies and global initiatives. The operability and functionality of critical infrastructure are continuously challenged by multiple stressors, increasing demands and ageing, whilst their interconnectedness and dependencies pose additional challenges. Emerging and disruptive digital technologies have the potential to enhance climate resilience of critical infrastructure, by providing rapid and accurate assessment of asset condition and support decision-making and adaptation. In this pursuit, it is imperative to adopt multidisciplinary roadmaps and deploy computational, communication and other digital technologies, tools and monitoring systems. Nevertheless, the potential of these emerging technologies remains largely unexploited, as there is a lack of consensus, integrated approaches and legislation in support of their use. In this perspective paper, we discuss the main challenges and enablers of climate-resilient infrastructure and we identify how available roadmaps, tools and emerging digital technologies, e.g. Internet of Things, digital twins, point clouds, Artificial Intelligence, Building Information Modelling, can be placed at the service of a safer world. We show how digital technologies will lead to infrastructure of enhanced resilience, by delivering efficient and reliable decision-making, in a proactive and/or reactive manner, prior, during and after hazard occurrences. In this respect, we discuss how emerging technologies significantly reduce the uncertainties in all phases of infrastructure resilience evaluations. Thus, building climate-resilient infrastructure, aided by digital technologies, will underpin critical activities globally,

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contribute to Net Zero target and hence safeguard our societies and economies. To achieve this we set an agenda, which is aligned with the relevant SDGs and highlights the urgent need to deliver holistic and inclusive standards and legislation, supported by coordinated alliances, to fully utilise emerging digital technologies.

## 1. Introduction

Climate resilience of critical infrastructure boosts economic growth and societal well-being to achieve the United Nations Sustainable Development Goals (SDGs) (Sachs et al., 2019). Deployment of emerging digital technologies, underpinned by multi-stakeholder alliances, is essential for accelerating progress toward more resilient infrastructure to contain and recover from multiple hazards in a sustainable manner.

The resilience of a system describes its ability to absorb and recover from disasters and adapt to new conditions (National Research Council, 2012). Delivering infrastructure, resilient to multiple natural hazards (Argyroudis et al., 2020), many of which are exacerbated by climate change, e.g. floods, landslides, sea-level rise, is fundamental to ensuring social and economic prosperity and achievement of the SDGs (Adshead et al., 2019). Critical infrastructure, such as energy and transport networks, is intricately interdependent (Vespignani 2010). Therefore, failure can cascade and amplify global environmental and socioeconomic impacts. Traditional infrastructure management relies heavily on visual inspection, manual measurements and expert judgement of an isolated infrastructure domain. These methods fall short in timely reacting to the rapidly evolving challenges of climate change, as they are fragmented, subjective and not designed to deal with compounding impacts and complex, interconnected systems. At the same time, we are witnessing the emergence of digital technologies, as formalized in the surge of Industry 4.0, e.g. Internet of Things (IoT), the establishment of digital twins, augmented and virtual reality, Artificial Intelligence (AI), Building Information Modelling (BIM) (Sacks et al., 2020), which impact most forms of human activity (WBGU – German Advisory Council on Global Change, 2019). Harnessing the potential of these tools and the generated data can enable the delivery and communication of automated, rapid and accurate assessments for building climate resilience in our infrastructure systems (Achillopoulou et al., 2020). Nonetheless, there are major challenges to the use of these technologies, including complex interdependencies, citizen privacy, and compliance with equitable principles, among others (Chester et al., 2021).

## 2. Climate change challenges traditional approaches to infrastructure resilience

Climate change is associated with effects that adversely strain existing critical civil infrastructure ecosystems (Forzieri et al., 2018), e.g. transport, energy and utility networks, which host our built environment, provide energy supply, and enable mobility of people and goods. More specifically, climate variability introduces more flash floods, windstorms, extreme temperatures, wildfires, and prolonged heat waves, with obvious implications for critical infrastructure planning, maintenance, and operation (Chester et al., 2020). In addition, climate change increases the risks from compound and cascading hazards and spatiotemporal variabilities of hazards in infrastructure networks. For example, sea-level rise exacerbates hydraulic stressors (Yesudian and Dawson, 2021), and hence, various mechanisms of coastal infrastructure deterioration, rendering them more vulnerable to other natural hazards that may occur at different time scales, such as earthquakes and fires. Therefore, preparedness and adaptation for individual hazards at asset level have tangible benefits for the asset and the infrastructure system (Aerts et al., 2014, McDaniels et al., 2008). Yet, there is little research on the resilience analysis of critical infrastructure to multiple and dynamic hazards (Koks et al., 2019).

Traditional risk assessments and diagnosis of infrastructure is commonly based on inspections, aided by conventional monitoring and analytics, therefore, do not provide an integrated approach to expedient decision-making. In addition, risk-based management for infrastructure is ill-suited for addressing 'low-probability, high-consequence' events, e.g. the 2011 Tohoku earthquake and tsunami, ignoring recovery after a 'beyond-design-life' situation. This is because available risk modelling and assessment commonly fail to account for such occurrences, whilst regulations and financial constraints rule them out. Furthermore, omitting important aspects, e.g. interdependencies, leads to an inaccurate appreciation of risk, stemming from compound events (Zscheischler et al., 2018). Limiting failures to a low annual probability is well established for hazards that remain invariant from year to year, e.g. hazards not related to climate change such as earthquakes. Nevertheless, for certain natural hazards, such as erosion and storm surge, the probability of infrastructure failure, e.g. ports, will increase annually (Vousdoukas et al., 2018) due to climate change, and, hence, the challenge is to integrate this into the design objectives (Chester et al., 2020).

Today, the delivery of climate-resilient infrastructure is hampered by myopia and ephemerality, mounting environmental and fiscal pressures (Jin et al., 2021). A central problem is our inability to grasp climate challenges, which are long-term and nonlinear, with potential feedbacks and tipping points, e.g. ice melting leading to irreversible environmental, infrastructural and social ramifications. In many cases, local governments fail to adopt resilience plans designed centrally by policymakers, and vice-versa, hazards pertinent only to specific areas of a country, are not always considered by policymakers. For example, floods and landslides might exacerbate in areas that have adverse geomorphology, nevertheless, such climate induced hazards might not be addressed by the national design regulations. Implementing climate resilience requires a holistic, cross-sectoral approach (Forzieri et al., 2016), which is often undermined by fragmented and siloed thinking (Hynes et al., 2020). As a result, stakeholders are unaware of the challenges and scientists lack the tools and data to make accurate infrastructure resilience predictions.

We argue that emerging digital technologies can solve some of these issues. For instance, digital and sensor technologies, data aggregation, and advanced simulation capabilities can automate these assessments. However, they are largely unexploited. Also, making critical infrastructure more resilient requires holistic standards and legislation, and well-informed life-cycle cost-benefit analysis for adaptation investments (Aerts et al., 2014). To achieve this, it is imperative to establish cross-sectoral, intercontinental collaborations, which will devise emerging digital technologies.

## 3. Enablers of climate resilience

In the era of smart infrastructure, the widespread adoption of emerging digital technologies disrupts the way we manage our infrastructure, by tackling issues and weaknesses of traditional management methods. For example, 5G-enabled technologies facilitate data mining and integration of heterogeneous information and evidence, almost in real-time for diverse infrastructure systems (Nguyen et al., 2021). These novel technologies pave the way to more accurate and automated decision-making for safer infrastructure, while providing end-users with means to communicate, visualise and interact with the ecosystem in which they reside. They enable better understanding and modelling of the spatiotemporal dynamics of hazards and infrastructure performance, therefore, enhancing climate resilience. For example, the accessibility of a substation, which is part of a power grid after a flood, can be facilitated using almost real-time 5G-enabled agent-based modelling for the affected and interdependent infrastructure systems (Battegazzorre et al., 2021), by deploying likely scenarios of functionality loss for the transport network.

Resilience analytics is a data-driven process that leverages resilience based on descriptive, predictive, and prescriptive modelling (Linkov and Trump, 2019). They provide means to visualise the performance of critical infrastructure, determine the impact of interdependencies to mitigate uncertainty, and ultimately facilitate prioritisation in decision-making. Analytics, strengthened by emerging digital technologies and data, incentivise climate resilience and sustainability more efficiently than traditional approaches by leveraging Big Data of different sizes, scales and sources, and aggregating it more quickly. For example, Big Data can underpin sustainable solutions to combat climate change, e.g. by facilitating clean energy solutions and by enabling the measurement of carbon emission levels due to e.g. traffic and building services (Giest, 2017; Seele and Lock 2017). Another example is the deployment of resilience analytics to advance the quantification, appraisal and comparison of management alternatives and restore an infrastructure system of assets back to functionality or operability (Thorisson et al., 2017; Hallegatte and Engle, 2019). Resilience thinking

**Table 1**
Emerging digital technologies and applications toward climate resilience of infrastructure.

| Emerging digital technology | Definition | Examples toward climate resilience |
|---|---|---|
| **Internet of Things (IoT)** (Russell et al., 2018) | The connection over the internet of digital and physical objects, e.g. smartphones, transport infrastructure, energy assets, by means of suitable information exchange, to enable data collection, communication, processing and actionable intelligence for a range of applications, services and decision-making. | ***Data collection:*** a cable-stayed bridge is monitored for ice accumulation, temperature variations, and wind loading.<br>***Communication:*** wireless conveyance of data (internet or other rapid transmissions).<br>***Processing:*** engineering algorithm and thresholds (**automated performance indicators**).<br>***Actionable intelligence:*** issue warnings, e.g. reduction of speeds, de-icing systems activated, swift functionality reinstatement. |
| **Artificial Intelligence (AI) and Machine Learning (ML)** (Spencer et al., 2019) | Adaptable intellect found in humans, which is simulated by machines, especially computer systems, that can learn and accumulate experience. | Utilizing Unmanned Aerial Vehicles (UAVs) for remote automated data acquisition (videos and photographs) and data processing and inspection using engineering algorithms to interpret the condition of infrastructure such as roads, railways and pipelines (**automation, rapidity**). |
| **Building Information Modelling (BIM)** (Davila Delgado et al., 2017) | The information technology for management and exchange of monitoring data, aiming to manage digital representations of all information related to a built asset during its entire life cycle. | ***Selection of monitoring systems***, e.g. fibre optics to measure strain and temperature, and photogrammetry to generate point clouds.<br>***Data processing***, using engineering algorithms and documentation.<br>***Modelling***, system showing selected monitoring entities and attribute sets.<br>***Data visualisation and interpretation****, on the* BIM model to gain geometrical context within the infrastructure asset, **rapid data-sharing**. |
| **Digital Twin (DT)** (CDBB (Centre for Centre for Digital Built Britain), 2018) | The digital replica of the physical assets, processes, and systems.<br>DT is broader than BIM in the sense that transmits data, monitors the asset in real-time and supports analytics, control and simulation functions by e.g. AI and ML processes. | Same methods as the BIM above, see example on the landmark Polyfytos bridge of Section 4 (Phase A).<br>Combined remote sensing systems are used to update frequently the DT. |
| **Agent-based modelling (ABM)** (Dawson et al., 2011; Cimellaro et al., 2019) | A computational model simulating the actions and interactions of autonomous agents, which can be complex infrastructures, individuals or groups, aiming to interpret behaviours based on characteristics and rules, and having the ability to learn and to adapt their behaviours. | ABM evacuation of road networks in the vicinity of coastal areas affected by storm surges could include the following: hazard simulation, agent-based model of human response and travel patterns, traffic simulation, agent vulnerability and risk analysis, congestion warnings and hence enabling **preparedness, rapid quantification of vulnerability/ losses** and **recovery.** |

encompasses those infrastructure factors that are most directly affected by a hazardous event across all relevant temporal stages and spatial domains. While various policy communities optimise or harden the system or part of their system, usually within the physical domain, a broader socio-ecological perspective emphasises the importance of systemic resilience, in which human-made physical systems function and interact with their ecological foundations, encompassed by society in a sustainable manner (Forzieri et al., 2016; Chester et al., 2021).

Proactively building resilience is more challenging due to the owners' reluctance to invest funds. Thus, legislation is often the only vehicle for incentivising climate adaptation in advance of hazards occurring. Legislation should be supported by digital data, technologies and methods to quantify the resilience dividends of climate prolepsis investments, across the infrastructure life-cycle (Akiyama et al., 2020), underpinned by clear, tangible and practical guidance. For example, regulators require high-fidelity hazard maps, supported by new digital technologies, such as AI combined with photogrammetry and satellite imagery, to improve design and flood risk assessment guidance for delivering climate-resilient infrastructure. In support of the Paris Agreement, numerous strategies (Pulido et al., 2018; Linkov et al., 2018a; Hill et al., 2019), roadmaps, initiatives (Williams et al., 2014), alliances, coalitions, and NGOs, have been launched, spring-boarding the SDG targets to be achieved by 2030, including climate neutrality by 2050. For example, the Coalition for Climate Resilient Investment launched at the UN Climate Action Summit in 2019, represents more than US $5 trillion in assets and is the first private sector-led initiative of its kind, aiming at bringing together different industries and leaders from across the finance and investment value chain to develop practical solutions and advance climate-resilience. In the same direction, 'Europe fit for the digital age', is an EU long-term investment in digital transformation and tools, which are enablers of the European Green Deal by 2050 (Tsakalidis et al., 2020). The latter will explore how the financial system can help increase resilience to climate and environmental risks, especially when it comes to physical risks and damage from natural disasters.

We are currently striving to design under deep uncertainty (Zscheischler et al., 2018; Chester et al., 2020), which is emanating from the lack of consensus on climate change modelling and alternative outcomes, along with unforeseen disruptions due to e.g. the COVID-19 pandemic (Hynes et al. 2020). We pursue the delivery of systemic approaches, considering interdependencies, adopt multi-hazard approaches and streamline nature-based solutions. Digital technologies can accelerate this endeavour.

## 4. Digital technologies incentivise climate-resilience

Emerging digital technologies can deliver more efficient, rapid and reliable resilience evaluations and enable better decision-making, based on actionable performance indicators before, during and after the occurrence of hazards. Table 1 shows technology that emerged recently and provides examples of how these technologies can enhance the climate resilience of critical infrastructure. Infrastructure resilience as shown in Fig. 1 can be represented through four distinct phases of the infrastructure life-cycle. These phases include planning and preparation before the hazard events, absorption and response during and immediately after the hazard occurrence, followed by recovery and adaptation to novel stressors (Ganin et al., 2016; Panteli et al., 2017; Argyroudis, 2021). The same figure shows the benefit of enhanced resilience to SDGs 9, 11 and 13.

During planning and preparation (**phase A** in Fig. 1) a gradual loss of operability ensues, e.g. due to ageing effects and asset deterioration. The latter may be accelerated, due to climate change that imposes extreme temperatures, wetter environments, and more frequent hazard occurrences. Traditional infrastructure inspection and screening at this phase are usually on-site and visual. Thus, they are periodical and non-automated, feeding static computer-based models, which provide a snapshot of the infrastructure condition and a one-off assessment (Pulido et al., 2018). Planning and preparedness for adverse events and stressors can be greatly enhanced by employing emerging digital technologies. Today, digital twins, i.e. the virtual representations of the physical infrastructure, in conjunction with AI, enable dynamic and adaptive modelling of hazard impacts on infrastructure, as well as automated and intelligent identification of deterioration and damage (Sacks et al., 2020).

A recent example of the extensive use of digital technologies in rapid decision-making is the assessment of the landmark Polyfytos bridge crossing the homonymous lake[1]. The resilience of the bridge and impact on the road network were evaluated based on visual inspections and collection of digital data by (a) high-definition photography with a camera mounted on a UAV processed with photogrammetry methods, validated by surveying measurements of the structure using a monitoring-grade total station and high-precision multi-hour static global navigation satellite system (GNSS) measurements of its stationary points. A digital twin was then generated with a point cloud spacing of 7 mm. When high accuracy was required for critical components (bearings and expansion joints), laser scanner measurements were deployed. (b) Persistent Scatterer Interferometry based on satellite imagery (Sentinel A & B), to provide continuous updates and information about the asset deformations and geometry (Markogiannaki et al., 2021). These digital technologies and data facilitated rapid decision making, by accelerating more accurate and hence reliable assessments, in comparison to traditional methods. Similarly, data analytics can be deployed for accurately predicting damage in infrastructure from natural and climatic hazards by fusing data and accurate measurements into model updating toward improved simulations (An et al., 2019). The above enable early warnings that can enhance the responsiveness of infrastructure operators before a critical level of performance loss is reached.

During **phase B** (Fig. 1), infrastructure absorbs and responds to hazard threats. These occur either abruptly, e.g. obstruction of railway operations due to acute flooding, or gradually, e.g. accumulation of scour due to successive floods. The loss is expected to be minimal if the assets are resilient. In this phase, crowdsourcing data from smartphones can be used for obtaining information regarding

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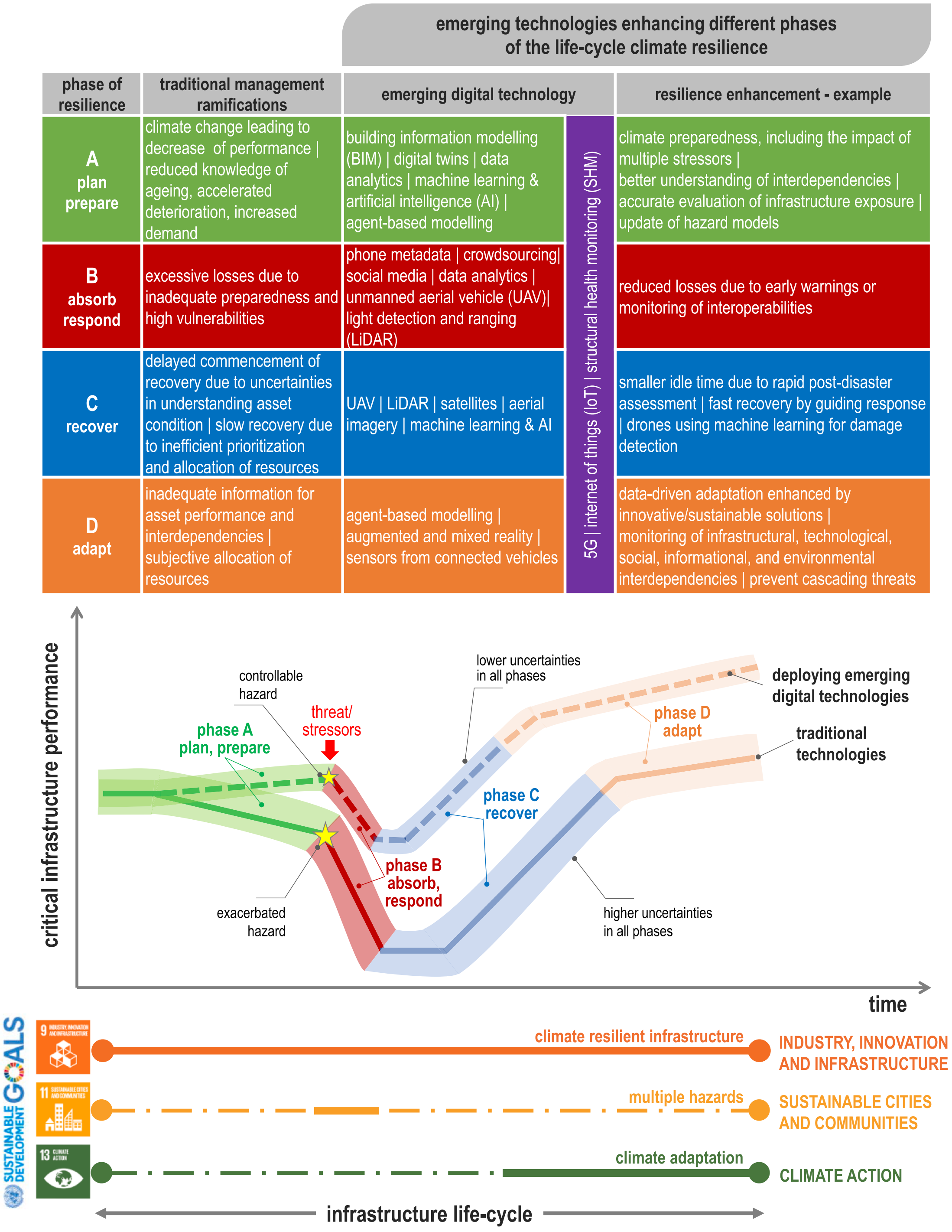
[1] http://www.infrastructuresilience.com/lake-polyfytos-bridge/



emerging technologies enhancing different phases of the life-cycle climate resilience

| phase of resilience | traditional management ramifications | emerging digital technology | | resilience enhancement - example |
|---|---|---|---|---|
| **A**<br>**plan**<br>**prepare** | climate change leading to decrease of performance \| reduced knowledge of ageing, accelerated deterioration, increased demand | building information modelling (BIM) \| digital twins \| data analytics \| machine learning & artificial intelligence (AI) \| agent-based modelling | 5G \| internet of things (IoT) \| structural health monitoring (SHM) | climate preparedness, including the impact of multiple stressors \|<br>better understanding of interdependencies \|<br>accurate evaluation of infrastructure exposure \|<br>update of hazard models |
| **B**<br>**absorb**<br>**respond** | excessive losses due to inadequate preparedness and high vulnerabilities | phone metadata \| crowdsourcing\| social media \| data analytics \| unmanned aerial vehicle (UAV)\| light detection and ranging (LiDAR) | | reduced losses due to early warnings or monitoring of interoperabilities |
| **C**<br>**recover** | delayed commencement of recovery due to uncertainties in understanding asset condition \| slow recovery due to inefficient prioritization and allocation of resources | UAV \| LiDAR \| satellites \| aerial imagery \| machine learning & AI | | smaller idle time due to rapid post-disaster assessment \| fast recovery by guiding response \| drones using machine learning for damage detection |
| **D**<br>**adapt** | inadequate information for asset performance and interdependencies \| subjective allocation of resources | agent-based modelling \| augmented and mixed reality \| sensors from connected vehicles | | data-driven adaptation enhanced by innovative/sustainable solutions \| monitoring of infrastructural, technological, social, informational, and environmental interdependencies \| prevent cascading threats |

**Fig. 1. Climate resilience of infrastructure enhanced by emerging digital technologies versus traditional management using conventional approaches.** The planning and preparedness (phase A), represent infrastructure performance for normal conditions, during which a gradual loss of operability ensues, e.g. due to ageing effects and asset deterioration. Absorption and response (phase B) are illustrated by the loss of functionality due to hazard events. The recovery (phase C) of the infrastructure functionality, includes the restoration of capacity and reinstatement of the operation. The adaptation (phase D) concerns future stressors, e.g. novel loads, climatically exacerbated hazards, which may take place before or after a hazard event. In all phases, emerging digital technologies significantly reduce aleatory and epistemic uncertainty. SDGs 9, 11, 13, which are underpinned by climate resilience, are represented by the three lines at the bottom of the figure across the infrastructure life-cycle. The continuous segments of these lines correspond to the periods where enhanced resilience influences the SDG directly and to a higher degree. The discontinuous lines refer to the instances where a lower impact is expected.

the condition of the infrastructure, such as post-flood water accumulation and end-user behaviour (Wang et al., 2018). Likewise, photos on social media before or during the development of critical events, anticipated or unforeseen, can facilitate management and emergency response, e.g. evacuation. Another example is the early warning systems triggered by monitored networks (Freddi et al., 2021), such as accelerometers used for rapid response and smart tagging of critical infrastructure assets, which can be facilitated by 5G technology.

In the recovery (**phase C**), digital technologies, such as UAV-enabled photogrammetry, can provide accurate real-time measurements of asset geometry, whilst high-definition photography can be used to monitor network functionality, and their interdependencies (Greenwood et al., 2019). Thus, they can facilitate infrastructure condition assessment for well-informed and rapid decision-making. They can also do this for inaccessible areas after disasters, unlike traditional approaches of manned emergency missions, which are of high risk, costly, and often impossible. Another example of how digital technologies can facilitate the recovery of energy systems, is the use of smart automated technologies that enable autonomous recovery mechanisms supported by IoT, e.g. automatic microgrids reconfiguration, which perform data-driven real-time automated diagnosis, isolate faulty components and redistribute power (Hare et al., 2016).

In adaptation **phase D**, agent-based modelling can be used to optimise designs, whilst augmented and mixed reality will enable operating infrastructure remotely (Kopsida and Brilakis 2020) and, therefore, reducing energy consumption. For example, the digital technologies deployed for the evaluation of the landmark bridge described above can be used during the recovery phase. They can enable building an accurate baseline model, which can then be used to evaluate deterioration and restoration scenarios, after diverse climate hazard occurrences, e.g. extensive droughts and floods. In the future, self-aware assets, with in-built technologies for monitoring infrastructure condition and interdependencies, based on the design for manufacture, assembly and operation strategies (DfMA) (Gao et al., 2020), will bring us closer to building resilience throughout their life-cycle, for instance, by reducing drastically the amount of waste generated in construction and the carbon footprint of the asset as a whole.

## 5. Challenges

However, there are also drawbacks of emerging digital technologies, as they increase vulnerability to cyber-attacks that in some cases may escalate to cyberwarfare, leading to security and citizens' privacy risks and misinformation. These technologies remain heavily reliant on the power supply and the interdependencies between their operators. Additionally, there is an involved tension in human–machine interaction during decision-making (Linkov et al., 2020). This is due to the distrust that the technologies have users' best interests at heart, which often stems from the challenges in explaining and interpreting digital data into actionable and human terms. The latter pose additional challenges and caveats of increasing infrastructure digitalization, which have to comply with the equitable principles and 'leave no one behind'. For example, the adoption of such technologies in developing economies might be slower. Yet, unlike physical infrastructure, digital technologies have the advantage of extensive scalability at very low costs. Thus, emerging technology is expected to proliferate rapidly once automation is achieved, an example of which is smartphones.

Even though resilience analytics may require significant data for advanced applications, a tiered framework (Linkov et al., 2018b) allows screening level evaluations of infrastructure dependency. The selection of the infrastructure assets and networks that will be twined and monitored may depend on e.g. primary engineering criteria, such as safety, cost, resilience and sustainability (Bocchini et al., 2014, Sharma et al., 2018). We expect that future prioritisation processes for building digital twins will include assets, networks and interdependencies, of the most critical, less redundant, more vulnerable and of lower resiliency assets, and infrastructure that has a greater environmental impact, leading to e.g. high CO2 emissions.

An acknowledged challenge of digital twins is the lack of full-scale benchmarks for the built environment, e.g. at a national level, to deliver climate resilience. Digital twins are, by definition, systems of systems, which can be decomposed into component-level and part-level digital twins. Hence, they become increasingly complex as they must reflect dynamic physical interdependencies under different hazard scenarios. In this respect, the systems of systems thinking necessitates information cloud architectures to federate, curate and maintain data. However, even though distributed ledgers (e.g. blockchains) are currently the most promising technology for addressing this challenge at different scales and localities (Kokoris-Kogias et al., 2018) that reduce information loss by deploying cloud permission exchanges, it will take at least a decade before such systems reach commercial application. In addition, federation, curation and preservation of data, generating, e.g. by digital twins, will come at a cost. The process is not naturally carbon neutral, just like physical infrastructure. Nevertheless, the effective use of data has the potential to compensate for the produced CO2 emissions toward Net Zero, achieving for instance substantially higher infrastructure performance. For example, using digital twins to predict traffic patterns and re-route autonomous vehicles to avoid traffic jams can save orders of magnitude more energy (Callcut et al., 2021), whilst data centres can be carbon–neutral by using renewable energy (Avgerinou et al., 2017).

## 6. Conclusion – Agenda for climate-resilient infrastructure

Traditional infrastructure management accounts for resilience to a limited extent, whilst sparsely exploits the full potential of digital technologies. Emerging digital technologies will facilitate the solution of a central problem in infrastructure resilience – balancing efficiency and resilience trade-offs (Trump et al., 2020). Many current infrastructure systems are more vulnerable to systemic shocks and cascading disruption since the practices on which they depend, overly prioritise system efficiency over resilience. More resilient systems may be less efficient, but they recover better from systemic disruptions. Building resilience does not mean abandoning efficiency, but rather maximising the long-term sustainability of socio-economic systems in the face of future disruptions. Emerging technologies pave the way to more accurate and automated decision-making for safer infrastructure, while providing end-users with means to communicate, visualise and interact with the ecosystem (Carluccio and Ní Bhreasail, 2019). The time is ripe for achieving the digital transformation of critical infrastructure, starting with the development of more rigorous and data-driven methods and tools for quantifying resilience.

We need more research to build adaptive capacity that incorporates deep uncertainties associated with climate change underpinned by digital technologies. For example, there are over 50 global models that can predict future climate change, however, their uncertainties are usually so severe that they can hardly be modelled as random variables. Also, there are open questions regarding the efficient use of digital technologies, because there is a lack of streamlined tools to integrate the knowledge attained from data with the experience gained by expert inspectors toward decision-making.

Next, we must embrace system complexity to minimise cascading failures resulting from unexpected disruptions, by decoupling unnecessary dependencies across infrastructure and making necessary connections controllable, visible and resilient (Hill et al., 2019). Today, we have a very limited understanding of the interdependencies between assets and diverse networks, which is the result of siloed and fragmented approaches that prevent the delivery of global solutions for combating climate change. Therefore, we urgently need to manage the system topology, i.e. nodes, links and the nature of their spatiotemporal connections. Hence, it is essential to design communication between interconnected parts of the infrastructure and add resources and redundancies in system-crucial components, to safeguard functionality. We need to create pipelines of sustainable infrastructure projects, aligned with long-term climate, development, and resilience goals (Pulido et al., 2018), rather than using expensive and fragmented hardening of parts of the system. These project pipelines should be the result of long-term planning, based on achieving multiple economic, social and environmental goals, coupled with regulations and legislation that promote climate resilience.

Standards, design codes and guidelines are vital in this regard. These could include resilience analytics, informed by infrastructure monitoring, management, deployment of digital data, related cloud architecture, as well as regulating digital technologies, particularly in relation to cybersecurity (Linkov and Trump, 2019). This requires mitigating relevant threats and cyberattacks, including, for example, misinformation and viruses that reduce the potential of emerging digital technologies. In this respect, cross-continental collaboration is of utmost importance for developing and facilitating the use of technologies for disaster responders. This is necessary as lessons learnt, know-how and synergies between emerging technologies, among stakeholders across the globe, can accelerate climate resilience. For example, the recent agreement between the US and European civil protection agencies foresees the exchange of information, e.g. satellite data, during major emergencies. Implementing this agenda requires coordinated collaborations and alliances between public and private sectors, developed and developing countries, inter-disciplinary science and policymaking to achieve and communicate the SDG-based transformation of critical infrastructure. Global organisations need to establish stronger strategies and provide guidance and coordination to facilitate the openness of knowledge and data. Governments must enact and implement legislation, encourage investment, and address market failures to create an enabling environment underpinning climate resilience. This must be complemented by private investment in emerging digital technologies for infrastructure, supported by research and development initiatives. The latter should be aligned with long-term investments in digital transformation, such as the EU's 'Europe fit for the digital age', an enabler of the European Green Deal.

Building resilience in our critical infrastructure through emerging technology is a vital strand of the Sustainable Development Goals (SDGs), as it contributes to climate-resilient infrastructure (SDG 9) and sustainable industrialisation, that makes the world safer from multiple hazards (SDG 11), whilst adapting quickly and efficiently to the planet's changing climate (SDG 13). In this evolving cross-sectoral effort, all SDGs support more resilient communities, countries and the planet (Sachs et al., 2019). These systems can only be resilient if they are inclusive (SDG 10), managed through good governance and strong institutions (SDG 16), and based on sustainable use of resources, leading to green-growth, low-carbon policies and climate neutrality (SDG 12). New technologies require reliable energy and power (SDG 7), telecommunication networks and supportive policies to foster innovation and competition. Infrastructure systems are becoming increasingly sophisticated and digitally interconnected, forming complex cyber-physical entities whose complexity needs to be adequately accounted for, including, for example, their interdependencies, which, if ignored, can lead to devastating cascading ramifications.

## Disclaimer

The views and opinions expressed in this article are those of the individual authors and not those of the U.S. Army, the European Commission or other sponsor organizations

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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