



# Evaluating digital technology applications and knowledge for climate action: A challenge-based decision framework

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## ABSTRACT

Digital technologies could offer solutions for climate change mitigation and adaptation; however, challenges such as data privacy, energy consumption, and digital inequality could hinder their adoption. This study develops integrated step-wise weight assessment ratio analysis (SWARA) and complex proportional assessment (COPRAS) methods under a spherical fuzzy (SF) environment to evaluate digital technology applications for climate mitigation and adaptation. To this end, seven key challenges were identified through a systematic literature review and evaluated by a panel of 10 experts. SF-SWARA results show that data privacy and security (weight = 0.28) and energy consumption and environmental impact (0.20) are the most influential challenges. Eight digital technology applications were ranked using SF-COPRAS according to the weighted challenges. The case study in Lithuania demonstrates that smart resource saver achieves the highest utility score (100), followed by virtual commutes (93.9). Moreover, the sensitivity analysis across 20 scenarios confirms that smart resource saver consistently remains the best option. Overall, the study shows that the spherical fuzzy multi-criteria decision-making (MCDM) approach effectively handles uncertainty in expert judgment, offering a robust tool for policy and planning in climate-tech adoption.

## Introduction

Climate change clearly affects all economic sectors worldwide. Human activities that release greenhouse gases (GHG) are a significant cause of climate change. Even if we significantly reduce GHG emissions globally, the impacts of climate change will still be significant in the future (Lyyanage et al., 2024). As the world is currently facing a climate crisis, mitigating climate change's effects and implementing more robust adaptation strategies are vital (Ratinen, 2021). However, the literature shows that climate change mitigation and adaptation are closely interconnected. For instance, Landauer et al. (2015) discussed the conflicts between these two strategies. They argued that addressing both in urban areas is essential because it helps manage trade-offs at different levels. Also, Jagers and Duus-Otterström (2008) point out that adaptation involves moral issues that differ from mitigation. Moreover, Moser (2012) noted that combining adaptation and mitigation policies could be beneficial.

With rising climatic risks and traditional methods of adaptation and mitigation facing limitations in scale and responsiveness, there has been a growing need for technology capable of processing large amounts of

data. Digital technology has been exceptionally effective in offering distinctive strengths in this area, providing real-time monitoring, forecasting, and optimisation across various sectors. For instance, technologies such as artificial intelligence (AI), machine learning, big data, and remote sensing provide faster and more reliable ways to monitor climate risks and predict their possible effects (Wang, 2023). These tools could assist decision-makers by providing large amounts of information to help create clear, actionable indicators. Digital technologies could boost our ability to respond to and predict climate-related issues by quickly and accurately analysing complex data (Balogun et al., 2020). Also, using digital technologies for climate adaptation is vital since they would boost national strengths (Munang et al., 2013). These technologies could benefit nations by building more sustainable cities and protecting communities from climate change impacts. Combining digital technologies with climate adaptation creates a unique opportunity for climate resilience and innovation (Akberdina et al., 2024; Balogun et al., 2022).

Although digital technologies could drive climate mitigation and adaptation, there are challenges to their adoption. Data privacy and security concerns, for instance, could limit critical environmental

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information sharing across platforms (Jasmy et al., 2024). Digital technologies' energy consumption and environmental impact could challenge their large-scale adoption (Azzouzi et al., 2021). Furthermore, technological reliability and equity issues are also challenging since not all regions have equal access to high-quality digital infrastructure (Vasilikis et al., 2023). Another critical challenge is the digital divide and accessibility, especially in low-income countries (Orozco-Messana et al., 2022). Moreover, the psychological and social impacts of digital technologies could challenge public acceptance and engagement (Tselapedi-Sekeitto et al., 2023). Ethical considerations, such as surveillance and data ownership, could also be challenging and require careful evaluation (Winter et al., 2025). In addition, governance and regulation challenges could complicate technology adoption with inconsistent policies and regulatory frameworks (Assad et al., 2023).

As mentioned, there are several challenges to the use of digital technology for climate mitigation and adaptation. Thus, the present study aims to develop an MCDM evaluation framework that integrates SWARA and COPRAS under spherical fuzzy sets. Based on expert evaluations, SWARA determines the subjective weight of the identified challenges, and COPRAS ranks the alternatives (applications in the present study) according to the weighted challenges. Therefore, the proposed framework can systematically address the complexities associated with technological adoption. In addition, the present study uses a spherical fuzzy environment to handle uncertainty and vagueness. The evaluation framework assesses applications against the identified challenges, helping policymakers and stakeholders identify the most impactful and feasible technologies for climate mitigation and adaptation. The main contributions of the present study are presented below:

The paper systematically reviews current literature to identify key issues involved in adopting digital technology for climate change mitigation and adaptation. It then develops a comprehensive evaluation methodology that combines the SWARA and COPRAS approaches within a spherical fuzzy framework to assess various digital technology applications in light of these issues. Finally, the methods are tested through a practical example from Lithuania.

The present study is organised as follows. Section 2 presents a step-by-step literature review. This section also discusses the applications and challenges of digital technologies for climate mitigation and adaptation. Section 3 shows the research method and its steps. In Section 4, the results are presented in detail, and in Section 5, sensitivity analyses are conducted. Section 6 discusses the results. In Section 7, a broad conclusion is given.

## Literature review

This section is a systematic review of the literature published between 2020 and 2025 on the role of digital technologies in climate adaptation and mitigation. Articles with the following keywords in their title, abstract, or keywords were selected at the first stage. Next, only peer-reviewed articles published in Scopus and web of science (WOS) were included to ensure high scholarly quality and reliability. Editorial letters, book chapters, review articles, academic theses, conference proceedings, replicated studies, and studies in non-English languages were omitted. The search term used was:

TITLE-ABS-KEY (“Metaverse” OR “virtual reality” OR “augmented reality” OR “digital twins”) AND (“urban climate change” OR “climate adaptation” OR “climate mitigation” OR “climate resilience” OR “carbon footprint”).

The search approach was designed to highlight digital technologies proven to be directly relevant to climate change adaptation and mitigation, such as those facilitated by virtual reality (VR), augmented reality (AR), digital twins, and the metaverse. These technologies were particularly highlighted for their key role in the literature on software used to model, understand, and shape behaviours related to urban climate patterns. This search method could be refined to target a specific set of technologies. However, future studies should expand their search

to include a broader range of innovations.

In the study, 40 articles met the inclusion criteria and were analysed to identify the applications and challenges of adopting digital technologies for climate mitigation and adaptation. The selected articles are summarised in Table 1, providing an overview of their methodologies, contributions, and identified research gaps. The reviewed studies were grouped thematically to clarify the diverse roles of digital technologies in climate-related applications, and are presented below:

### 1. Immersive and simulation technologies

Includes VR, AR, virtual environments, and immersive tools used for behavioural change, perception studies, training, and environmental simulation.

### 2. AI, machine learning, and data-driven environmental tools

Covers studies using machine learning, predictive analytics, and data-driven modelling to enhance environmental assessment, forecasting, and decision-making.

### 3. Digital twins for urban infrastructure and decarbonisation

includes applications of digital twins in transportation, buildings, energy systems, urban planning, and carbon footprint reduction.

### 4. Smart grids, energy management, and cyber-physical systems

Focuses on intelligent energy systems, load optimisation, renewable integration, and cyber-physical infrastructure for improving sustainability and flexibility.

### 5. Nature-based solutions and urban climate resilience

Includes digital models used to evaluate and enhance green infrastructure, climate adaptation strategies, and nature-based solutions in cities.

### 6. Building energy systems and sustainability assessment

Covers studies using digital tools to optimise building performance, lifecycle analysis, and energy efficiency.

### 7. Marine, ocean, and water systems management

Involves digital technologies applied to hydrological modelling, marine resource management, multi-risk disaster analysis, and coastal or flood resilience.

## Application of digital technologies for climate mitigation and adaptation

### Virtual commutes

Digital technologies could significantly reduce the need for commuting and carbon emissions (Pi et al., 2025). For instance, online education and remote work have decreased carbon emissions as people use transportation less. In fact, virtual collaboration tools like video conferencing have reshaped work structures and collaborations. These tools could boost productivity and lower environmental impact (Allam et al., 2022). Moreover, the digital twin technology could make public transport networks more efficient. For instance, mobility-as-a-service (MaaS) could adjust routes based on traffic patterns and reduce travel time (Orozco-Messana et al., 2022). Also, smart traffic control systems could optimise urban mobility and reduce congestion and personal vehicle needs (Luke et al., 2025). Another example could be decentralised co-working spaces, which are considered alternatives to traditional offices (Bühler et al., 2024). Therefore, the need for daily long-distance commuting would be minimised, meaning fewer carbon emissions.

### Smart resource saver

Digital technologies could be used across different sectors to optimise resource consumption. For instance, smart grids use real-time data to improve electricity distribution, reduce losses, and support renewable energy sources (Orozco-Messana et al., 2022). AI could also be used to create smart systems that respond to energy demand when people need it and adjust power use accordingly (Winter et al., 2025). Additionally, Industry 4.0 technologies help manufacturers use resources more efficiently. It could also reduce waste and make production more sustainable (Bühler et al., 2024). IoT sensors can detect water leaks quickly and

**Table 1**  
Summary of articles.

Author(s) and year	Group	Method(s)	Technology	Main research gap(s)	Main research aim(s)	Main result(s)
El Azzaoui et al. (2023)	3	Decentralised trust management, simulation	Digital twin, internet of vehicles (IoV), smart contracts	Lack of decentralised trust in IoV	Reduce carbon footprint and improve computation offloading	Efficient battery charging and reduced computation load
Vasilikis et al. (2023)	2	First-principles modelling, Machine learning	Digital twin, hybrid propulsion, carbon intensity assessment	Uncertainty in maritime carbon footprint evaluation	Improve the accuracy of fuel consumption predictions	Improved carbon footprint prediction with 2.5 % accuracy
Kim et al. (2023)	1	Physiological response measurement, Statistical analysis	Immersive virtual environment, VR	Lack of objective measures in thermal perception	Assess the impact of wood interiors on thermal sensation	Wood increases perceived warmth without temperature change
Mokas et al. (2021)	1	Discrete choice experiment, Econometric modelling	VR	Uncertainty in stated preference methods	Enhance certainty in discrete choice experiments	VR improves certainty and preference evaluation
Tselapedi-Sekeitto et al. (2023)	2	Comparative study, Survey analysis, Statistical methods	Telemedicine	Patient satisfaction and environmental impact of telemedicine	Assess the economic, social, and environmental impacts of telemedicine	Virtual care reduces emissions and lowers costs
Reitberger et al. (2025)	3	Geographic information system (GIS) simulation, Spatial analysis	Digital twin, Urban green infrastructure, CityTree model	Lack of predictive urban tree growth models	Assess the long-term impact of tree growth on solar radiation	Tree growth reduces solar radiation by 6.1 %
Luke et al. (2025)	3	Optimisation modelling, Techno-economic analysis	Digital twin, electric bus fleet, battery storage	Coordination of buses and storage for decarbonisation	Optimise fleet emissions and costs	98 % emissions reduction and USD 1.79 million savings over 10 years
Bartie et al. (2021)	3	Process simulation, Neural networks, Thermodynamic analysis	Digital twin, silicon photovoltaics, circular economy	Lack of life cycle analysis in PV waste management	Optimise resource efficiency in PV recycling	Identified pathways for high-purity material recovery
Fang et al. (2024)	3	Decision-making framework, lifecycle assessment	Digital twin, highway reconstruction, carbon footprint assessment	Limited city-wide carbon footprint comparison in highways	Develop a lightweight carbon footprint decision-support system	Digital twins improve highway carbon footprint management
Ahn et al. (2024)	2	Computational fluid dynamics (CFD), Machine Learning	Digital twin, AI, green space optimisation	Long simulation times for urban heat analysis	Improve the urban thermal environment using AI and digital twins	CFD simulation time reduced from 400,000 h to 1 h
Turan et al. (2022)	3	Finite element analysis (FEA), data analytics	Digital twin, sensors	High material waste in manufacturing processes	Optimise material consumption in thermoforming	50 % scrap reduction, 10 % material savings, and USD 2 million annual savings
Qian et al. (2024)	3	Carbon footprint accounting, multi-source data fusion	Digital twin, intelligent management platform	Lack of accurate carbon emission measurement in historic dwellings	Develop a low-intervention carbon footprint accounting system	Improved carbon accounting accuracy with a 15 % total error reduction
Zhong and Li (2024)	3	Statistical evaluation, evolutionary optimisation	Digital twin, renewable energy integration	Congestion management in urban power networks	Optimise PV energy integration and congestion pricing	Significantly reduced congestion costs and improved forecasting
Argyroudis et al. (2022)	3	Data-driven analysis, risk assessment	Digital twin, internet of things (IoT), AI	Lack of integration between digital technologies and resilience planning	Enhance the climate resilience of critical infrastructure	Improved decision-making for infrastructure resilience
Jiao et al. (2024)	4	Reinforcement learning, load optimisation	Digital twin, smart grids, renewable energy systems	Uncertainty in load management in smart cities	Optimise demand response strategies using AI	Enhanced sustainability of microgrid load management
Winter et al. (2025)	3	Life cycle assessment (LCA), data integration	Integral digital twin, product carbon footprint (PCF) assessment	Lack of integrated sustainability assessment in production	Develop a unified framework for product carbon footprint calculations	Improved transparency in carbon footprint data exchange
Desalegn et al. (2023)	2	Lifecycle impact assessment (LCIA), predictive modelling	Digital twin, IoT, wind energy systems	Limited accuracy in wind turbine environmental assessments	Improve life cycle assessments of wind energy systems	More accurate environmental impact evaluations of wind turbines
Stellacci et al. (2024)	6	Parametric modelling	Digital twin, Grasshopper 3D	Energy retrofit challenges in historic buildings	Evaluate retrofit solutions under future climate scenarios	Identified optimal retrofit strategies for historic buildings
van Thienen et al. (2024)	1	Carbon footprint analysis, lifecycle assessment	VR, metaverse	High carbon footprint of international research travel	Evaluate VR meetings as alternatives to physical meetings	VR reduces travel-related emissions
Ozel and Petrovic (2024)	5	Agent-based modelling (ABM), Simulation	Digital twin, urban forests, nature-based solutions	Lack of modular and extensible urban forest models	Develop a framework for urban forest monitoring and impact analysis	Improved tree growth prediction and CO <sub>2</sub> sequestration modelling
Lawrence and Hendershot (2020)	3	Data analytics, process optimisation	Digital twin, industry 4.0, IoT	Limited implementation of digital twins in aluminium processing	Optimise manufacturing processes for efficiency and emissions reduction	Enhanced process control with reduced waste and lower carbon footprint
Azzouzi et al. (2021)	4	Model-based engineering, stakeholder coordination	Digital twin, cyber-physical systems, Smart energy management	Lack of stakeholder coordination in energy system design	Develop a framework for stakeholder engagement in energy systems	Improved coordination and optimised multi-energy system design
Mengual Torres et al. (2022)	6	Artificial neural networks (ANN), data-driven modelling	Digital twin, AI-based energy efficiency analysis	High energy use and emissions in tropical hotel operations	Optimise energy use and carbon footprint reduction strategies	12 % energy savings and significant CO <sub>2</sub> reduction using AI solutions

(continued on next page)

Table 1 (continued)

Author(s) and year	Group	Method(s)	Technology	Main research gap(s)	Main research aim(s)	Main result(s)
Niall Buckley et al., 2021	6	Urban building energy Model (UBEM), simulation	Digital twin, renewable energy integration	Lack of neighbourhood-scale energy resilience planning	Develop zero-carbon urban energy strategies	Significant improvements in energy efficiency and carbon reduction
Buckley et al. (2021)	6	Energy performance modelling, carbon footprint analysis	Digital twin, solar PV, insulation retrofits	High carbon footprint of UK industrial infrastructure	Achieve carbon neutrality through energy efficiency measures	Up to 56 % energy savings with insulation and 16 % CO <sub>2</sub> reduction with PV
Bühler et al. (2024)	5	Computational modelling, resilience framework development	Digital twin, bioelectricity, earth-based materials	Lack of regenerative design in urban sustainability planning	Integrate earth-based materials and digital twins for resilient cities	A new paradigm for sustainable and self-regulating urban environments
Jiang et al. (2024)	1	Randomised controlled experiment, statistical analysis	VR, urban greenways	Limited understanding of vegetation effects on mental health	Assess VR exposure to urban greenways for stress reduction	VR exposure reduced stress and improved cognitive restoration
Pi et al. (2025)	1	Behavioural analysis, VR-based intervention study	Digital twin, VR, climate education	Lack of immersive tools for climate change awareness	Test the impact of VR time travel on pro-environmental behaviour	VR experiences increased engagement in climate action
Mignan (2022)	7	Multi-risk assessment, probabilistic modelling	Digital twin, virtual environment modelling	Limited frameworks for multi-risk disaster scenario analysis	Develop a standardised multi-risk assessment framework	Improved predictive modelling of cascading disaster events
Alabugin et al. (2023)	4	Mathematical modelling, big data analytics	Digital twin, zero-carbon electric power systems (EPS)	Lack of efficient mathematical modelling for EPS decarbonisation	Develop mathematical models to optimise zero-carbon EPS	Enhanced efficiency in EPS design for sustainability
Kaewunruen et al. (2024)	7	Climate change adaptation modelling	Digital twin, Bridge infrastructure	Limited digital twin applications for bridge climate adaptation	Improve bridge resilience to climate change using digital twins	Digital twins enhance bridge climate resilience planning
Qi (2024)	1	Thermal energy modelling, VR simulation	VR, green building design	Lack of real-time simulation for indoor thermal energy cycles	Optimise energy conservation and thermal comfort in green buildings	VR enhances green building sustainability
Assad et al. (2023)	4	Component-based design, machine learning	Digital twin, cyber-physical manufacturing systems	Limited energy flexibility integration in manufacturing	Embed energy flexibility in cyber-physical production systems	Enhanced energy management in smart manufacturing
Bowen et al. (2021)	1	Virtual exchange, collaborative learning	Virtual reality, remote learning in global health	High cost and ethical concerns in global health programmes	Develop cost-effective and ethical global health education solutions	VR enhances global health collaboration and ethical education
Jasmy et al. (2024)	2	AI-driven analytics, real-time tracking	AI, mobile application, carbon footprint assessment	Lack of real-time carbon footprint tracking systems	Develop an AI-driven system for individual carbon footprint tracking	Increased sustainability awareness and behavioural change
Tzachor et al. (2023)	7	Digital modelling, Marine spatial planning	Digital twin, ocean sustainability assessment	Limited digital twin applications in ocean sustainability	Leverage digital twins for marine resource management	Improved planning for ocean sustainability and conservation
Kaewunruen et al. (2020)	7	Life cycle assessment, carbon footprint modelling	Digital twin, subway infrastructure management	Lack of integrated life cycle assessment for subway station sustainability	Evaluate the sustainability and vulnerability of subway stations	Optimised life cycle management of subway stations
Orozco-Messana et al. (2022)	5	Digital twin modelling, climate adaptation assessment	Digital twin	Lack of modular solutions for urban regeneration	Develop sustainable modular solutions for cities	modular solutions enhance urban climate resilience
Vilaplana et al. (2024)	4	System dynamics, cost-benefit analysis	Virtualisation, digital twin, electrical substations	Scarcity of economic studies on virtualisation for substations	Assess the economic feasibility of virtualisation for substations	Virtualisation reduces capital expenditure by 20 % and operating expenditure by 60 %
Truu et al. (2021)	7	Hydraulic modelling, GIS-based analysis	Digital twin, urban drainage systems	Lack of integrated planning for pluvial flood resilience	Develop GIS-integrated decision support for flood planning	Enhanced urban flood resilience through digital twin modelling
Henriksen et al. (2022)	7	Hydrological modelling, machine learning	Digital twin, climate adaptation, water management	Lack of real-time water risk prediction tools	Develop a digital twin for climate risk adaptation	Improved water security and climate risk forecasting

adjust irrigation systems in water management. This technology saves fresh water while increasing agricultural productivity (Henriksen et al., 2022). Another example could be blockchain technology, which could be used for transparency in sustainable supply chains and promote circular economy practices that minimise waste (Bartie et al., 2021).

#### Future-ready cities

Tools like AI simulations, digital twins, and GIS spatial analysis have changed urban planning. These tools help design cities to adapt to climate change by considering energy efficiency, population density, and land use. Smart zoning rules and real-time environmental monitoring help ensure city growth without harming important ecosystems (Reitberger et al., 2025). Digitalisation also helps create 15-minute

cities. In these cities, urban services are close by, making it easier for people to access them. This setup reduces transportation emissions (Allam et al., 2022). Digital twin technology allows us to simulate and understand how different urban policies might work. This technology helps decision-makers create and test different scenarios before implementing plans (Luke et al., 2025). Another example could be participatory urban planning platforms, which let people engage in urban development and help them reach sustainable development goals (Argyroudis et al., 2022; Orozco-Messana et al., 2022).

#### Green tech for nature

Digital technologies could improve climate change resilience by integrating nature-based solutions. For instance, AI could help

determine the best locations for green infrastructure, like urban forests, wetlands, and bioswales (Ozel & Petrovic, 2024). Digital twin simulations could help better understand how afforestation projects impact city carbon storage and cooling over time (Tzachor et al., 2023). Also, monitoring systems that use IoT to track biodiversity health could ensure effective and sustainable urban planning. Moreover, remote sensing technologies can help monitor the health of urban greenery and allow for timely maintenance (Allam et al., 2022). Moreover, accurate weather forecasting models could be developed using AI to predict climate stressors (Ozel & Petrovic, 2024).

#### *Climate-proof communities*

By offering new financial and technological solutions, digitalisation could help communities impacted by climate change. For instance, AI could give accurate predictive analytics to help businesses and policy-makers create effective adaptation plans. Blockchain-based micro-finance and decentralised digital banking could benefit vulnerable people by ensuring access to credit and insurance if they are impacted by climate change (Allam et al., 2022; Argyroudis et al., 2022). Smart agriculture technologies, such as AI monitoring soil health, could also improve rural food security and economic stability (Turan et al., 2022). Moreover, digital marketplaces and e-commerce platforms help small businesses, especially those impacted by climate change, to access broader markets (Bartie et al., 2021).

#### *Smart disaster shield*

Advanced digital technologies have greatly improved disaster preparedness and early warning systems. These new tools use real-time satellite data, AI for weather forecasting, and networks of IoT sensors. Moreover, digital twin models could simulate natural disasters, and they would help decision-makers improve emergency response plans (Argyroudis et al., 2022). AI tools improve the accuracy of extreme weather forecasts, which can lower the number of injuries and reduce economic losses. For instance, Multi-risk digital frameworks, such as the generic multi-risk (GenMR) model, provide comprehensive risk assessments for cascading climate disasters (Mignan, 2022). Moreover, cloud-based communication platforms help emergency response teams work together in real-time to act quickly and effectively during disasters (Orozco-Messana et al., 2022). Additionally, blockchain technology systems make distributing aid fairly and efficiently during humanitarian efforts easier (Argyroudis et al., 2022).

#### *Resilient city design*

Digitalisation is changing how cities are designed and built to make them more resilient to climate change. AI helps decision-makers find the best places for climate-friendly infrastructure, like areas that can resist flooding and surfaces that reflect more sunlight (Orozco-Messana et al., 2022). Smart building technologies use IoT sensors to adjust ventilation, lighting, and insulation automatically. This technology helps save energy by responding to real-time weather changes (Zhong & Li, 2024). Also, predictive models help design city spaces that are friendly for walking and biking, which reduces the need for cars (Allam et al., 2022). Additionally, AI simulations evaluate how air temperature would impact mitigation strategies, ensuring that cities stay comfortable as the climate changes (Ahn et al., 2024).

#### *Digital heritage keepers*

Digitalisation is important for protecting cultural and heritage sites from climate change. High-resolution 3D scanning and digital twin technology allow for the virtual reconstruction of historical landmarks. This technology helps ensure their preservation despite environmental threats (Allam et al., 2022; Fang et al., 2024). AI tools can predict structural damage caused by climate change. This feature will help us take action to repair them early. VR and AR technologies create engaging experiences, helping the public stay connected with cultural heritage sites (Stellacci et al., 2024). AI could also be used to optimise

the maintenance of heritage and align it with sustainability goals (Qian et al., 2024).

#### *Challenges to adopting digital technologies for climate mitigation and adaptation*

##### *Energy consumption and environmental impact*

Adopting digital technologies for climate change mitigation and adaptation would increase energy demand, especially for artificial intelligence and high-performance computing. For instance, developing smart cities using digital twins would need massive data processing and high energy usage (Azzouzi et al., 2021). Although technologies like smart grids or AI-driven energy management are designed to decrease energy use, they require significant investments in infrastructure (Jiao et al., 2024). Another example could be cyber manufacturing systems developed to improve energy efficiency; however, they also introduce new challenges in balancing digitalisation and energy sustainability, such as increasing electricity demand in smart factories (Assad et al., 2023).

Moreover, zero-carbon electric power modelling could achieve energy efficiency using renewables. However, integrating renewables with technologies needs collaboration across different research fields, such as engineering, computer science, and environmental science (Alabugin et al., 2023; Zhong & Li, 2024). Digital technologies can help make historic buildings more energy-efficient. However, they also increase energy use in urban areas, especially in data centres and cloud computing (Qian et al., 2024). Recent research shows that digital twin simulations can aid green urban forestry planning by predicting tree growth and carbon absorption. However, simulations need a lot of computing power, which increases energy consumption (Ozel & Petrovic, 2024). Additionally, Industry 4.0 increases energy use since autonomous systems require more sensors, wireless networks, and cloud storage (Lawrence & Hendershot, 2020).

##### *Digital divide and accessibility*

Digital technologies need high-speed connectivity, sensors, and AI-driven platforms, which might not be available in rural areas, resulting in socioeconomic inequalities (Reitberger et al., 2025). For instance, phase change materials (PCMs) are used in building facades to help create climate-neutral buildings. Integrating digital twins with building retrofits could also show how cities with robust technological infrastructures can optimise energy efficiency and climate adaptation. However, these technologies are pricey and often found in more developed areas (Orozco-Messana et al., 2022; Stellacci et al., 2024).

Moreover, building information modelling is one of the best examples of digital twin applications in urban resilience. However, limited technical capabilities and expenses hinder their widespread use (Kaewunruen et al., 2024). Furthermore, digital transformation in transportation, such as the IoV, remains inaccessible to developing regions due to high costs and infrastructure limitations (Azzouzi et al., 2021). Therefore, inclusive policy measures are required to address the digital divide and inequalities so that the benefits of digitalisation are for all.

##### *Data privacy and security*

Digital solutions for smart cities, carbon footprint tracking, and predictive climate modelling may cause privacy concerns (Winter et al., 2025). Data ownership and ethical AI governance might also be at risk when adopting AI-driven sustainability apps (Jasmy et al., 2024). For instance, AI-powered carbon footprint assessment systems collect large volumes of user data, potentially exposing individuals to cybersecurity risks (Jasmy et al., 2024). Moreover, applying the metaverse in climate research raises security concerns since VR and AI-driven climate models can store personal and organisational data (van Thienen et al., 2024).

Furthermore, virtual protection, automation, and control applications could be used in electrical substations, but they might result in

digital grids' cybersecurity vulnerabilities if virtualised systems are attacked (Vilaplana et al., 2024). Furthermore, data sharing is a severe challenge to adopting digital technologies for sustainability, as it increases the risk of inconsistent data governance (Tzachor et al., 2023). Moreover, applying AI and digital twins in urban planning depends on real-time monitoring and data collection, causing ethical issues regarding privacy and data control (Turán et al., 2022).

**Governance and regulation**

A comprehensive framework of regulations is needed for effective governance in the digital era. Applying AI-based energy systems in smart manufacturing requires strict rules to ensure clarity, efficiency, and eco-friendliness. In other words, the lack of consistent policies for digital twins in climate mitigation and adaptation makes it harder to share data and plan urban areas effectively (Assad et al., 2023; Kaewunruen et al., 2020). However, even though digital twins are becoming essential for tracking carbon emissions, there is no common framework to ensure consistent energy efficiency assessments (Winter et al., 2025).

Furthermore, digital technologies can enhance the climate resilience of critical infrastructure; however, strong government support is needed (Argyroudis et al., 2022). This support will help ensure that new digital technologies work well with our goals for building resilience to climate change (Qi, 2024). Therefore, without a global regulatory framework, digitalisation efforts may become scattered. This situation can result in unfair adoption of smart technology and limit its positive environmental impact.

**Psychological and social impacts**

Digital technologies can enhance climate change education and present psychological challenges (Tselapedi-Sekeitto et al., 2023). For instance, digital twin technology in global health education has shown low user engagement, digital fatigue, and emotional disconnection from real-world problems (Bowen et al., 2021). Another example could be using VR to simulate green environments; however, people may think these digital experiences are enough and do not need to engage with the environment in real life (Pi et al., 2025).

Moreover, climate anxiety and reduced resilience might result from using AI too much for risk predictions (Jiang et al., 2024). Also, smarter energy grids and climate monitoring systems can create challenges for older people and those who are uncomfortable with technology (Ahn et al., 2024; Qian et al., 2024). Therefore, ensuring a balance between virtual experiences and real-world activism will be crucial as digital solutions become more integrated into climate strategies.

**Technological reliability and equity**

The success of using digital tools for climate adaptation depends on how reliable AI models and IoT systems are (Vasilikis et al., 2023). In manufacturing, cyber-physical systems, such as medical devices, raise concerns about system failures, sensor errors, and inconsistent real-time data (Assad et al., 2023). Moreover, digital twin applications for sustainability should deal with data quality and compatibility. These issues make it challenging to monitor climate impacts effectively (Tzachor et al., 2023).

Furthermore, using AI to optimise climate-adaptive building design raises concerns about algorithmic bias and model errors. These problems can result in poor planning for climate resilience (Qi, 2024). Additionally, innovative decision systems require constant updates in transportation, which can be costly and technically challenging for cities with limited digital infrastructure (Azzouzi et al., 2021). Therefore, these limitations show the need for rigorous model testing, clear AI guidelines, and inclusive technology policies.

**Ethical considerations**

The growing use of AI and digital twin technology in climate models raises concerns about data use, corporate influence, and just climate action (Bartie et al., 2021). For instance, some AI apps could track

personal carbon footprints; however, they may raise concerns about personal data privacy, behavioural surveillance, and environmental justice (Jasmy et al., 2024). Tracking emissions in industries using AI may raise concerns about misleading information about their environmental efforts, known as greenwashing. This situation happens when AI-generated sustainability reports falsely portray a company's environmental progress (Winter et al., 2025).

Additionally, low-income communities might not be included in AI-based sustainability programs, causing inequality in reaping the benefits of digital technologies (Orozco-Messana et al., 2022). Also, digital technologies could reduce carbon footprints, but data-driven policies are needed (Fang et al., 2024). Therefore, as digital climate solutions grow, it is essential to create transparent, inclusive, and ethical rules for AI. These rules will help ensure that climate actions are just and effective.

Fig. 1. Summary of the main digital technology applications and adoption challenges identified in the systematic literature review

**Research method**

The present study applied an integrated SF-SWARA-TOPSIS method to evaluate the applications of digital technologies in light of the challenges of adopting them for climate mitigation and adaptation. To this end, 10 decision experts were asked to evaluate alternatives using linguistic variables shown in Table 2. Afterwards, the SF-SWARA was applied to calculate the objective weights of challenges, and then the SF-COPRAS was used to rank applications.

**Preliminaries**

**Definition 1.** (Kutlu Gündoğdu & Kahraman, 2019) Let U a universe of discourse so that a spherical fuzzy set (SFS) is shown in Eq. (1):

$$\begin{aligned}
 A &= \{ \langle u, (\mu(u), \nu(u), \pi(u)) \rangle \mid u \in U \} \\
 \text{Subject to :} \\
 \mu(u) &: U \rightarrow [0, 1] \\
 \nu(u) &: U \rightarrow [0, 1] \\
 \pi(u) &: U \rightarrow [0, 1] \\
 0 \leq \mu(u)^2 + \nu(u)^2 + \pi(u)^2 &\leq 1 \quad \forall u \in U
 \end{aligned}
 \tag{1}$$

**Definition 2.** (Kutlu Gündoğdu & Kahraman, 2019) Let  $A = (\mu_a, \nu_a, \pi_a)$ , and  $B = (\mu_b, \nu_b, \pi_b)$  two SFSs. Eqs. (2) to 7 present some operators for SFSs.

$$\begin{aligned}
 A \cup B &= \langle \min\{\mu_a, \mu_b\}, \max\{\nu_a, \nu_b\}, \min\{1 - ((\min\{\mu_a, \mu_b\})^2 \\
 &+ (\max\{\nu_a, \nu_b\})^2), \min\{\pi_a, \pi_b\} \rangle \tag{2}
 \end{aligned}$$

Application of digital technologies	Challenges to adopting digital technologies
<ul style="list-style-type: none"> <li>• Virtual Commutes</li> <li>• Smart Resource Saver</li> <li>• Future-Ready Cities</li> <li>• Green Tech for Nature</li> <li>• Climate-Proof Communities</li> <li>• Smart Emergency Systems</li> <li>• Resilient Urban Design</li> <li>• Digital Heritage Keepers</li> </ul>	<ul style="list-style-type: none"> <li>• Energy Consumption &amp; Environmental Impact</li> <li>• Digital Divide &amp; Accessibility</li> <li>• Data Privacy &amp; Security</li> <li>• Governance &amp; Regulation</li> <li>• Psychological &amp; Social Impacts</li> <li>• Technological Reliability &amp; Equity</li> <li>• Ethical Considerations</li> </ul>

Fig. 1. shows a summary of applications and challenges found through a systematic literature review.

$$A \cup B = \langle \max\{\mu_a, \mu_b\}, \min\{\nu_a, \nu_b\}, \max\{1 - ((\max\{\mu_a, \mu_b\})^2 + (\min\{\nu_a, \nu_b\})^2), \max\{\pi_a, \pi_b\}\} \rangle \tag{3}$$

Proposed sf-swara-copras

Step 1. Decision matrix

Let  $D = \{d_1, d_2, \dots, d_m\}$  be a set of applications,  $I = \{I_1, I_2, \dots, I_n\}$  the set of indicators for digital challenges, and  $T = \{t_1, t_2, \dots, t_p\}$  a set

$$A \oplus B = \left( (\mu_a^2 + \mu_b^2 - \mu_b^2 \mu_a^2)^{1/2}, \nu_a \cdot \nu_b, ((1 - \mu_a^2)\pi_a^2 + (1 - \mu_b^2)\pi_b^2 - \pi_a^2 \pi_b^2)^{1/2} \right) \tag{4}$$

$$A \otimes B = \left( \mu_a \cdot \mu_b, (\nu_a^2 + \nu_b^2 - \nu_b^2 \nu_a^2)^{1/2}, ((1 - \nu_a^2)\pi_a^2 + (1 - \nu_b^2)\pi_b^2 - \pi_a^2 \pi_b^2)^{1/2} \right) \tag{5}$$

$$\lambda A = \left( (1 - (1 - \mu_a^2)^\lambda)^{1/2}, \nu_a^\lambda, ((1 - \mu_a^2)^\lambda - (1 - \mu_a^2 - \pi_a^2)^\lambda)^{1/2} \right), \lambda > 0 \tag{6}$$

$$A^\lambda = \left( \mu_a^\lambda, (1 - (1 - \nu_a^2)^\lambda)^{1/2}, ((1 - \nu_a^2)^\lambda - (1 - \nu_a^2 - \pi_a^2)^\lambda)^{1/2} \right), \lambda > 0 \tag{7}$$

**Definition 3.** (Kutlu Gündoğdu & Kahraman, 2019) Eqs. (8) and 9 present the spherical weighted arithmetic mean (SWAM) and the spherical weighted geometric mean (SWGM). Let  $\omega = (\omega_1, \omega_2, \dots, \omega_n)$ ;  $\omega_i \in [0, 1]$ ;  $\sum_{i=1}^n \omega_i = 1$ .

$$SWAM_\omega(a_1, \dots, a_n) = \left( \left( 1 - \prod_{i=1}^n (1 - \mu_{a_i}^2)^{\omega_i} \right)^{1/2}, \prod_{i=1}^n \nu_{a_i}^{\omega_i}, \left( \prod_{i=1}^n (1 - \mu_{a_i}^2)^{\omega_i} - \prod_{i=1}^n (1 - \mu_{a_i}^2 - \pi_{a_i}^2)^{\omega_i} \right)^{1/2} \right) \tag{8}$$

$$SWGM_\omega(a_1, \dots, a_n) = \left( \prod_{i=1}^n \mu_{a_i}^{\omega_i}, \left( 1 - \prod_{i=1}^n (1 - \nu_{a_i}^2)^{\omega_i} \right)^{1/2}, \left( \prod_{i=1}^n (1 - \nu_{a_i}^2)^{\omega_i} - \prod_{i=1}^n (1 - \nu_{a_i}^2 - \pi_{a_i}^2)^{\omega_i} \right)^{1/2} \right) \tag{9}$$

**Definition 4.** (Kutlu Gündoğdu & Kahraman, 2019). Eq. (10) presents the score function of SFSS.

$$S(A) = \mu_a * (\nu_a - 1) * (\pi_a - 1) \tag{10}$$

of experts who evaluate applications according to identified indicators. The decision matrix (X) is expressed by  $X = (x_{ij}^k)$ , for  $i = 1, \dots, m$ ;  $j = 1, \dots, n$ ;  $k = 1, \dots, p$ .  $x_{ij}^k$  represents the given support to the company (i) according to indicator (j) by the  $k^{\text{th}}$  expert.

Step 2. Aggregation

The  $SWAM_\omega$  is applied to construct the aggregated matrix  $Z = (z_{ij})_{m \times n}$ .

Step 3. SF-SWARA

Step 3.1. Calculating score value using Eq. (10).

Step 3.2. According to experts' support, indicators are ranked from the most to the least important.

Step 3.3. The significance of the indicators should be determined relative to the first indicator.

Step 3.4. The comparative coefficient ( $k_j$ ) should be calculated using Eq. (11).

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases} \tag{11}$$

In which  $S_j$  indicates the comparative significance of score values.

Step 3.5. Indicators' weight determination by Eq. (12).

**Table 2**  
Linguistic variables.

Linguistic Term	SFN
Absolutely High (AH)	(0.9, 0.1, 0.1)
Very High (VH)	(0.8, 0.2, 0.2)
High (H)	(0.7, 0.3, 0.3)
Slightly High (SH)	(0.6, 0.4, 0.4)
Medium (M)	(0.5, 0.5, 0.5)
Slightly Low (SL)	(0.4, 0.6, 0.4)
Low (L)	(0.3, 0.7, 0.3)
Very Low (VL)	(0.2, 0.8, 0.2)
Absolutely Low (AL)	(0.1, 0.9, 0.1)

$$p_j = \begin{cases} 1 & j = 1 \\ \frac{p_{j-1}}{k_j} & j > 1 \end{cases} \quad (12)$$

Step 3.6. Normalising weight using Eq. (13).

$$w_j = \frac{p_j}{\sum_{j=1}^n p_j} \quad (13)$$

Eqs. (1)–13 define spherical fuzzy numbers and the SWARA procedure.

- m, n, h: Membership, non-membership, and hesitancy degrees of a spherical fuzzy value (dimensionless, range 0–1).
- A: A spherical fuzzy set.
- Ai: The i th alternative in the decision problem.
- Cj: The j-th criterion (challenge).
- Ek: The k-th expert providing evaluations.
- Xijk: Linguistic evaluation given by expert Ek for alternative Ai under criterion Cj.
- Xij\_bar: Aggregated spherical fuzzy evaluation of alternative Ai under criterion Cj using SWAM.
- Sj: Comparative significance value assigned to criterion Cj by experts.
- kj: Comparative coefficient of criterion Cj, derived from Sj.
- qj: Preliminary weight for criterion Cj before normalisation.
- wj: Normalised final weight of criterion Cj such that the sum of all weights equals one.

Step 4. Indicators' value summation

The SF-COPRAS approach assesses alternatives using weighted indicators. Thus, indicators' values are summed using Eqs. (14) and 15.

$$\alpha_i = SWAM_w, \text{ for beneficial indicators} \quad (14)$$

$$\beta_i = SWAM_w, \text{ for non – beneficial indicators} \quad (15)$$

Step 5. Calculating the indicators' degree

The degree of indicators is calculated using Eq. (16).

$$C_i = S(\alpha_i) + \frac{\sum_{i=1}^m S(\beta_i)}{S(\beta_i) \sum_{i=1}^m \frac{1}{S(\beta_i)}} \quad (16)$$

Wherein  $S(\alpha_i)$  and  $S(\beta_i)$  are the score functions of benefit and cost indicators.

Step 6. Utility degree estimation

The utility degree for each alternative is computed using Eq. (17). The best alternative has the highest utility degree.

$$U_i = \frac{C_i}{C_{max}} * 100 \text{ for } i = 1, \dots, m \quad (17)$$

Eqs. (14)–17 compute the performance of alternatives under weighted criteria.

- Bij: Contribution of alternative Ai under criterion Cj for benefit-type criteria.
- Cij: Contribution of alternative Ai under criterion Cj for cost-type criteria.
- Bi: Total aggregated value of all benefit-type criteria for alternative Ai.
- Ci: Total aggregated value of all cost-type criteria for alternative Ai.
- Pi: Relative significance score of alternative Ai based on Bi and Ci.
- Ui: Final utility value of alternative Ai, normalised to allow ranking.

Case study

Lithuania has adopted digital and smart technologies to address climate change challenges. Consequently, it has achieved excellent results in energy efficiency and renewable energy utilisation, particularly in cities such as Vilnius and Kaunas, which have invested in IoT-driven infrastructure and AI-driven energy management (Melinske, 2024; Streimikiene & Kyriakopoulos, 2022). Lithuania has reduced its greenhouse gas emissions by approximately 58 % compared to 1990 levels, yet remains dependent on imported electricity, with over 70 % of total electricity consumption covered by imports in recent years. These conditions highlight both progress and persistent challenges, making Lithuania an appropriate setting for evaluating digital technologies supporting climate mitigation and adaptation (Streimikiene et al., 2021). Moreover, more remote work and online services in Lithuania

**Table 4**  
Spherical SWARA results.

Criteria	$s_j$	$k_j$	$p_j$	$w_j$
Data Privacy and Security	0.38	1.00	1.00	0.28
Energy Consumption and Environmental Impact	0.37	1.37	0.73	0.20
Technological Reliability and Equity	0.29	1.29	0.57	0.16
Digital Divide and Accessibility	0.28	1.28	0.44	0.12
Psychological and Social Impacts	0.28	1.28	0.35	0.10
Governance and Regulation	0.25	1.25	0.28	0.08
Ethical Considerations	0.21	1.21	0.23	0.06

**Table 3**  
Experts' opinions on the criteria.

	Energy Consumption and Environmental Impact	Data Privacy and Security	Governance and Regulation	Ethical Considerations	Technological Reliability and Equity	Psychological and Social Impacts	Digital Divide and Accessibility
E1	AH	AH	H	SH	M	L	SL
E2	L	H	SH	H	SH	SL	SH
E3	VH	H	SH	M	M	M	L
E4	M	L	L	SL	AH	AH	H
E5	SH	VH	VH	SH	SL	M	H
E6	AH	AH	VH	H	SH	L	SL
E7	L	M	L	VH	H	H	SH
E8	H	SH	M	L	VH	SH	AH
E9	SH	SL	SL	SL	H	AH	VH
E10	VH	VH	H	M	SL	SL	L

**Table 5**  
Aggregated matrix.

		Digital Heritage Keepers	Virtual Commutes	Smart Resource Saver	Climate-Proof Communities	Smart Emergency Systems	Resilient Urban Design	Future-Ready Cities	Green Cities
Energy Consumption and Environmental Impact	$\mu_i$	0.63	0.74	0.74	0.70	0.67	0.70	0.71	0.67
	$\nu_i$	0.38	0.27	0.27	0.32	0.35	0.31	0.31	0.35
	$\pi_i$	0.35	0.28	0.26	0.30	0.31	0.32	0.30	0.31
Digital Divide and Accessibility	$\mu_i$	0.72	0.73	0.60	0.67	0.69	0.73	0.64	0.74
	$\nu_i$	0.30	0.28	0.41	0.35	0.33	0.28	0.38	0.27
	$\pi_i$	0.28	0.27	0.36	0.34	0.31	0.27	0.33	0.27
Data Privacy and Security	$\mu_i$	0.73	0.72	0.67	0.63	0.68	0.67	0.70	0.71
	$\nu_i$	0.29	0.29	0.36	0.39	0.34	0.35	0.32	0.31
	$\pi_i$	0.25	0.30	0.31	0.33	0.32	0.31	0.31	0.28
Governance and Regulation	$\mu_i$	0.74	0.63	0.61	0.65	0.70	0.71	0.64	0.67
	$\nu_i$	0.28	0.38	0.41	0.37	0.32	0.31	0.38	0.34
	$\pi_i$	0.25	0.35	0.33	0.31	0.27	0.28	0.32	0.32
Psychological and Social Impacts	$\mu_i$	0.67	0.65	0.68	0.71	0.72	0.69	0.70	0.67
	$\nu_i$	0.35	0.37	0.33	0.30	0.30	0.33	0.31	0.35
	$\pi_i$	0.30	0.32	0.29	0.30	0.31	0.32	0.32	0.30
Technological Reliability and Equity	$\mu_i$	0.68	0.66	0.58	0.72	0.65	0.70	0.58	0.70
	$\nu_i$	0.34	0.36	0.44	0.30	0.38	0.33	0.44	0.32
	$\pi_i$	0.30	0.32	0.36	0.26	0.32	0.28	0.37	0.30
Ethical Considerations	$\mu_i$	0.71	0.66	0.63	0.67	0.64	0.72	0.68	0.69
	$\nu_i$	0.31	0.36	0.39	0.35	0.38	0.29	0.33	0.33
	$\pi_i$	0.29	0.29	0.33	0.30	0.34	0.27	0.29	0.29

**Table 6**  
The spherical SWARA-COPRAS output.

Alternatives	$\alpha_i$	$\beta_i$	$C_i$	$U_i$	Rank
Digital Heritage Keepers	0.127	0.176	0.248	77.75	8
Virtual Commutes	0.161	0.155	0.299	93.9	2
Smart Resource Saver	0.143	0.121	0.319	100	1
Climate-Proof Communities	0.139	0.134	0.298	93.54	3
Smart Emergency Systems	0.136	0.142	0.287	89.96	6
Resilient Urban Design	0.148	0.151	0.290	90.88	5
Future-Ready Cities	0.136	0.137	0.292	91.64	4
Green Cities	0.142	0.159	0.276	86.64	7

have reduced travel and commuting, thereby saving carbon emissions (Koutsogeorgopoulou, 2023). However, data centres and smart grids have increased energy consumption (Alonso Soto, 2025). Moreover, the digital divide is still a problem in rural areas and among elders, limiting their access to technology (European Commission, 2023).

Furthermore, although Lithuania has a strong national cybersecurity framework, there are still issues with data privacy and risks of AI-driven environmental monitoring and blockchain carbon trading (Štitiulis et al., 2017). Also, new regulations should be adopted in Lithuania to align with the new EU digital sustainability directives (Economy & Lithuania, 2024). Moreover, some Lithuanians might be hesitant to use AI and automation for climate control, even though Lithuania is a leader in digital sustainability. Improving cybersecurity, adapting policies, and ensuring digital inclusivity can further boost climate resilience and economic sustainability (European Commission, 2023; Streimikiene & Kyriakopoulos, 2025).

**Results**

The experts’ opinions on the importance of challenges to digital technology applications were collected in the first step. A panel of 10 experts contributed to the present research. Some criteria were considered for selecting experts to enhance the quality of the decision-making. Experts were divided into two groups: academic and nonacademic. Experts in both groups should have a good knowledge of digital technologies and sustainability, with at least 5 years of work experience in these fields, demonstrating their seniority. The experts supported the criteria using the linguistic variables shown in Table 3. It should be noted that challenges to digital technology applications are considered as criteria

for decision analysis in the present research. Table 3 shows the experts’ opinions on the criteria.

Table 2 was used to turn the linguistic variables into fuzzy numbers in this step. Afterwards, the SWAP operator is used to aggregate the individual matrices. In the present study, all experts are considered equal, so they were assigned equal weight. Table 4 shows the results of the SWARA under a spherical fuzzy environment.

According to Table 4, data privacy and energy consumption are ranked first and second, indicating that experts view these two challenges as the most critical barriers to digital technology adoption. Data privacy is about the security and ethical use of climate-related data. At the same time, energy consumption highlights the need to ensure that digital solutions do not put additional environmental burdens. After determining the criterion weights, the experts were asked to evaluate alternatives against the criteria using linguistic variables. After receiving individual opinions on other options, the SWAP operator aggregated them. Table 5 presents the aggregated matrix of experts’ views on different options according to the criteria.

Afterwards, steps 3 to 6 were done to rank alternatives according to weighted criteria. Table 6 shows the final ranking of other options using the spherical SWARA-COPRAS method.

In Table 6, the utility value represents the relative performance of each alternative expressed as a percentage. Utility = 100 shows the most preferred alternative under the given criteria weights. All other options receive proportional utility values.

**Sensitivity analyses**

Sensitivity analyses examine how changes to the most influential criterion would affect the alternatives’ ranking. To this end, Eq. (18) determines the criteria weights in each scenario.

**Table 7**  
The elasticity coefficient.

Criteria	$\alpha_c$
Data Privacy and Security	1
Energy Consumption and Environmental Impact	0.278
Technological Reliability and Equity	0.222
Digital Divide and Accessibility	0.167
Psychological and Social Impacts	0.139
Governance and Regulation	0.111
Ethical Considerations	0.083

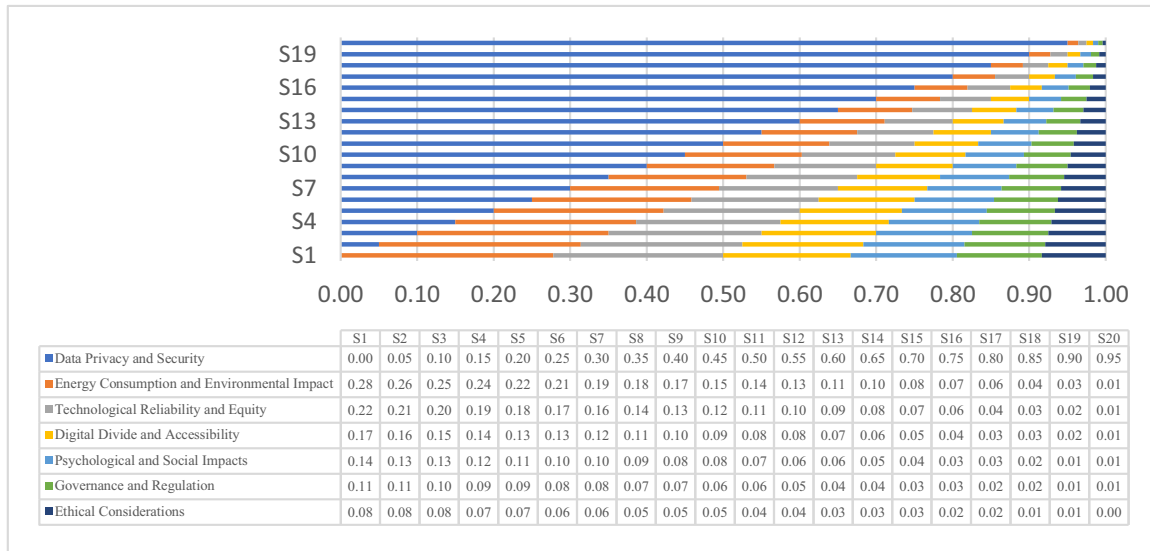


Fig. 2. Evolution of criterion weights across 20 sensitivity scenarios as the weight of “data privacy and security” increases.

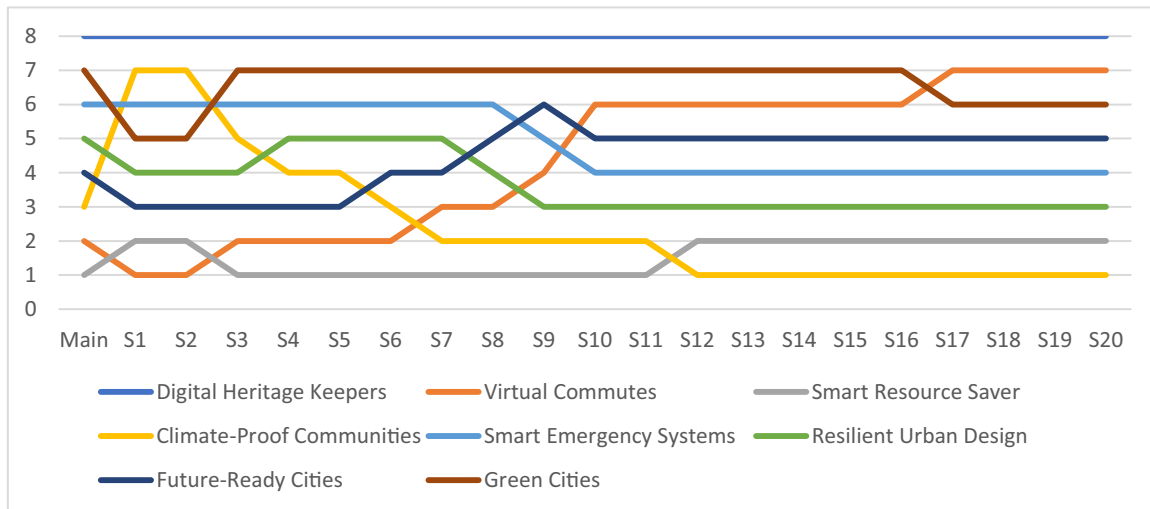


Fig. 3. Ranking of digital technology applications across 20 sensitivity scenarios based on the adjusted criterion weights.

$$w_c = (1 - w_s) \times \left( \frac{w'_c}{W'_c} \right) = w'_c - \Delta_x \alpha_c \tag{18}$$

Where  $w_c$  denotes the adjusted weights,  $w_s$  denotes the original value of the most influential criterion,  $w'_c$  denotes the original value of the changing criteria weights and  $W'_c$  denotes the sum of the original value of the changing criteria weights. The elasticity coefficient ( $\alpha_c = \frac{w'_c}{W'_c}$ ) shows the relative compensation of the changing criteria values according to the most influential criterion. It is set to one of the most influential criteria to ensure the overall weight ratio among criteria remains consistent throughout the analysis. New weights for all criteria are as follows:

$$w'_s \leq \Delta_x \leq \min \left\{ \frac{w'_c}{\alpha_c} \right\} \tag{19}$$

$$w_s = w'_s + \alpha_s \Delta_x \tag{20}$$

$$w_c = w'_c + \alpha_c \Delta_x \tag{21}$$

Eqs. (19)–21 test the robustness of results under weight changes.

- alpha: Elasticity coefficient controlling the adjustment of criterion weights in each scenario.
- wj\_original: Original normalised weight of criterion Cj.
- wj\_prime: Adjusted weight assigned to criterion Cj in a sensitivity scenario.
- sum\_w: Sum of original weights of all criteria affected by the adjustment.
- delta: Percentage change applied to the most influential criterion during sensitivity analysis.

Where  $\Delta_x$  shows the change and  $\sum w_s + \sum w_c = 1$ . “Data Privacy and Security” is the most influential challenge in the present research. The limit for this challenge is  $-0.28 \leq \Delta_x \leq 0.72$ . Table 7 shows the elasticity coefficient for all criteria.

The interval  $-0.28 \leq \Delta_x \leq 0.72$  is divided into 20 scenarios. A clear and gradual progression of weight changes is provided using 20 scenarios while keeping the sensitivity analysis interpretable. Fig. 2 shows new weights for the criteria.

Fig. 2 illustrates how the weights of all criteria evolve across 20 scenarios as the most influential challenge (“data privacy and security”) gradually increases. Although the weight of the leading criterion rises,

the relative ordering among the remaining criteria remains largely consistent. Afterwards, applications are ranked according to new weights for each scenario. Fig. 3 shows the ranking results for each scenario.

Fig. 3 presents the ranking of all alternatives under the 20 adjusted weighting scenarios. Each alternative is shown with a distinct colour. The figure demonstrates that “Smart Resource Saver” remains the top-ranked option in all scenarios, confirming its robustness. This pattern indicates that the proposed model produces stable results even under substantial variations in criterion weights.

## Discussion

Table 7 shows that “smart resource saver and virtual commutes” rank highest among the evaluated applications, with utility scores of 100 and 93.9, respectively. Moreover, these alternatives align with the most influential challenges: data privacy and energy consumption. Using digital technologies to save resources smartly is multifunctional, optimising energy and resources across sectors such as agriculture and manufacturing; therefore, it is crucial for climate mitigation and adaptation, which aligns with the obtained results. In addition, Fig. 2 demonstrates the robustness of this ranking by comparing results across 20 scenarios, in which Smart Resource Saver remained the top performer in all scenarios. This consistency shows the reliability of the proposed framework for decision support under uncertainty.

Moreover, the present study is more inclusive than previous research, as it simultaneously analysed various challenges and applications. For instance, Azzouzi et al. (2021) and (Winter et al., 2025) highlighted the operational complexity and ethical concerns of digital technologies; however, the present study concluded that energy efficiency and governance compliance are more influential once all challenges to adopting digital technologies are included. Also, as shown in Table 1, most research evaluated the applications or challenges in isolation or through sector-specific lenses. In contrast, this research provides a comparative and integrated assessment that includes various applications, challenges, and expert opinions.

Furthermore, the Lithuanian case study shows that the results apply to real-world policy situations. Lithuania has made noticeable progress in adopting digital technologies for climate mitigation and adaptation (Koutsogeorgopoulou, 2023; Mėlinskė, 2024). However, it still faces challenges, especially in rural areas, where digital access, cybersecurity, and data privacy protections may be limited. For instance, in Lithuania’s national reports, the high energy usage of data centres and the digital divide in rural areas are considered limitations to scalability and inclusiveness. Therefore, the most critical applications, such as Smart Resource Saver and Virtual Commutes, would directly correspond to Lithuania’s strategic priorities in energy management and digital service expansion.

In addition, the proposed evaluation framework, integrating SWARA and COPRAS within a spherical fuzzy environment, could efficiently handle uncertainty and complexity in decision analysis. The spherical fuzzy extension simultaneously considers hesitation, membership, and non-membership degrees, making a more reliable framework than conventional fuzzy (Kutlu Gündoğdu & Kahraman, 2019). The proposed framework is useful in areas such as adopting digital technologies, where information is often incomplete and subjective. The present study integrated various methods to address the gap in reliable tools for comparing socio-technical applications related to climate change and digitalisation.

## Conclusions

The present study developed a new evaluation framework that integrates the SWARA and COPRAS in a spherical fuzzy environment. This framework assesses challenges to adopting digital technologies for climate mitigation and adaptation. The present study identified the most

influential challenges and ranked the applications of digital technologies according to these challenges. The results show that Smart Resource Saver and Virtual Commutes are the best options in Lithuania because they provide strong resource management and help reduce emissions. The framework also helps reduce uncertainty and subjectivity using spherical fuzzy sets, making decision analysis more reliable. Furthermore, unlike previous models that often do not include the different challenges, this SWARA-COPRAS model provides an inclusive and flexible tool for policymakers and practitioners. The results showed how well the framework works, as it matched the top digital applications with the country’s strengths and existing technology gaps.

Moreover, governments and institutions should focus on adopting and expanding applications like Smart Resource Savers and Virtual Commutes. These applications could benefit society by supporting climate change mitigation and adaptation. Therefore, policies should improve infrastructure for better data security, lower energy use in digital operations, and promote digital access, especially in rural areas. Additionally, national policies should align with EU guidelines on digital sustainability and actively address emerging risks, such as cybersecurity threats and biases in AI systems. Moreover, policymakers should use evaluation frameworks to assess climate-tech investments and applications. These tools can improve transparency and traceability, ensuring that digital solutions promote climate action and social fairness.

Furthermore, the applicability of the proposed model, SWARA-COPRAS using spherical fuzzy sets, can be extended beyond Lithuanian boundaries and formulated in other nations, depending on their access to sufficient expertise. Also, developing the model in a different setting would be preferable, as it covers a wide range of stakeholders and could formulate a set of criteria aligned with various countries’ boundaries. Moreover, this model would also work beyond energy and climate and could be applied to any data-driven decision-making situation.

This study has several limitations. First, the number of experts involved in the evaluation was limited, which may influence the findings. Second, although spherical fuzzy sets reduce uncertainty in decision-making, the use of linguistic variables introduces subjectivity. Finally, differences in expert backgrounds may influence the weighting of challenges and the ranking of technologies. Future academic research should use the SWARA-COPRAS framework with spherical fuzzy sets for other countries, especially developing countries. Moreover, involving diverse stakeholders in decision-making would make the model more relevant to real-world situations. Furthermore, the results of the present study should be compared with those from other MCDM methods to evaluate the applicability of the proposed framework. Future studies could also empirically validate the framework by comparing model outputs with real performance data from implemented digital technology applications.

## CRedit authorship contribution statement

**Mahyar Kamali Saraji:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dalia Streimikiene:** Writing – review & editing, Supervision, Conceptualization.

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