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Digital Twin Models with ESG Methodology as a Tool for Transforming Solutions in the Transport-Energy Sector with Applications to Sustainable Tourism

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Abstract

The transport and energy sectors face significant challenges in achieving sustainability and efficiency. This paper explores the potential of digital twin (DT) models, coupled with Environmental, Social, and Governance (ESG) methodology, to transform solutions in these critical areas. Digital twins, i.e. virtual representations of physical systems, provide real-time data and insights for process optimization. ESG methodology, focusing on environmental impact, social responsibility, and good governance, guides decision-making towards sustainable practices. This paper investigates how digital twin models, integrated with ESG principles, can be used to: (i) optimize transportation networks: reduce traffic congestion, improve public transportation efficiency, and minimize fuel consumption, and (ii) enhance energy management, i.e. optimize energy production and distribution, integrate renewable energy sources, and reduce overall environmental footprint. Based on these insights, the combination of DT technology coupled with ESG methodologies is researched with respect to transformative opportunities for sustainable tourism, which can be applied across the transportation-energy sector by optimizing resource allocation, reducing emissions, and promoting social equity. The main finding is that digital twins, combined with ESG principles, offer a promising way to increase the tourism sector's sustainability by optimizing transportation and energy use, but successfully adopting these solutions may require changes in traveler behavior and careful consideration of many ethical and practical challenges.

Keywords: Digital Twins; ESG Methodologies; Transport and Energy Sectors, Sustainable Tourism.

1. Introduction

The transport and energy sectors are fundamental to modern society, but their reliance on traditional fuels and infrastructure creates significant challenges [1]. Environmental concerns, like greenhouse gas emissions and air pollution, necessitate a shift towards sustainable practices [2]. The transition towards decarbonized energy systems will generate disparate impacts across socio-economic groups, necessitating comprehensive analysis of potential inequities and the development of targeted policies to ensure an equitable energy transition [3]. Hence, ensuring equitable access to transportation and energy resources requires socially responsible solutions [4].

Digital technologies offer promising avenues for addressing these challenges. Digital twin (DT) models, virtual replicas of physical systems, are revolutionizing various industries by providing real-time data and insights for optimization [5]. In the transport sector, DTs can be used to monitor traffic flow, optimize public transportation schedules, and predict maintenance needs [6]. Similarly, within the energy sector, DTs can be employed to improve energy production and distribution efficiency, integrate renewable energy sources, and manage grid stability [7].

To ensure that these advancements contribute to a sustainable future, it is crucial to integrate environmental, social, and governance (ESG) considerations into decision-

making processes. ESG is a framework used to evaluate a company's performance and impact beyond just financial measures, balancing its impact on the environment, treatment of its employees, customers, suppliers, and the communities where it operates, and its leadership, stakeholders, and overall transparency and ethical behavior [8]. ESG methodology emphasizes responsible practices across these three interconnected domains [9]. By incorporating ESG principles, DT models can be harnessed to develop solutions that not only optimize efficiency but also minimize environmental impact, promote social equity, and prioritize responsible governance [10].

Significant research and development efforts are focused on advancing digital twin (DT) technologies. These efforts include improving sensor technologies for real-time data collection, enhancing simulation and modeling capabilities, and developing advanced analytics for extracting insights from complex DT models [11]. The digital twin model integrates the following sub-domains into a functional framework: physical entities, virtual models, services, digital twin data, and mutual connections (inter-relationships), as shown in Fig. 1. Furthermore, work is underway to address cybersecurity and data privacy issues surrounding DT implementation [12]. Additionally, integration with technologies such as artificial intelligence (AI), machine learning (ML), and cloud computing is continuously evolving [13].

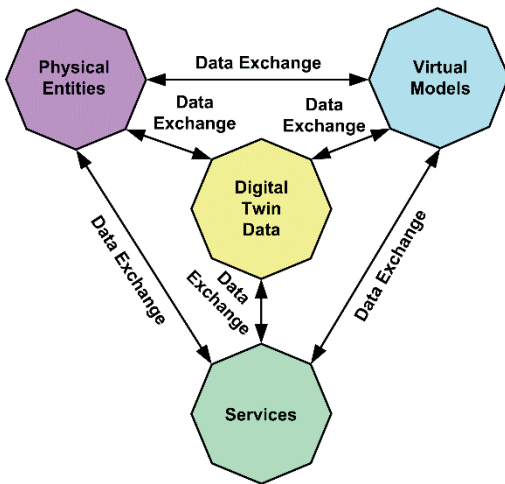


Fig. 1. The five-dimensional digital twin model representation [11].

Simultaneously, there is increasing emphasis on aligning technological advancements with Environmental, Social, and Governance (ESG) principles, and reducing the dependence on fossil fuels [14]. Researchers are exploring ways to utilize DT models to measure and improve ESG performance. This includes investigating carbon footprint reduction strategies, optimizing responsible resource use, and ensuring social equity in the development and deployment of these technologies [15]. Reference [16] underscores the importance of recognizing distinct stakeholder groups and examining how sustainable value is generated across different levels, encompassing diverse forms. This multifaceted analysis is illustrated in Fig. 2, which outlines both the stakeholder groups themselves and the corresponding mechanisms for creating sustainable value tailored to each group. In that respect, the triple bottom line concept has been introduced to measure the enterprises' adherence to sustainability principles [17]. Additionally, efforts are underway to establish standards and governance frameworks for transparent and accountable ESG reporting, as indicated in [18].

This research explores the transformative potential of DT models integrated with ESG methodology for the transport and energy sectors. We investigate how this approach can be leveraged to optimize transportation networks, enhance energy management, and ultimately contribute to a more sustainable future. In the following sections, the current state of the transport and energy sectors are explored, highlighting the need for sustainable solutions. The potential of DT models and ESG methodology is examined, followed by a detailed examination of how their integration can transform these critical sectors.

2. Transforming Transport with Digital Twin-ESG Solutions

Digital twin (DT) models integrated with ESG principles offer a powerful approach for optimizing and greening the



Fig. 2. Stakeholder groups and sustainable value creation process [15].

transport sector. This chapter explores some recent case studies showcasing how this combined approach is driving positive change into the transportation sector.

2.1. Road Transport

A study conducted by the University of New South Wales [19] examines how Siemens MindSphere, a cloud-based DT platform, is being used to optimize public transportation systems in a major European city. The DT model integrates real-time data from traffic sensors, buses, and trams. This data is used to monitor traffic flow, predict congestion, and optimize route planning. Additionally, the model considers social equity factors by analyzing accessibility for underserved communities. The study also reports a significant reduction in traffic congestion and emissions, along with improved service reliability and accessibility. In reference [20], a flexible mobility DT framework is designed, incorporating AI, cloud-edge-device technologies, and digital replicas of human drivers, vehicles, and traffic dynamics. This framework, implemented within Amazon Web Services, offers functionalities like data storage, modeling, learning, simulation, and prediction. A case study of a personalized adaptive cruise control system showcases the framework's ability to integrate driver behavior modeling, cloud-based driver assistance systems, and traffic flow management. The research presented in [21] proposes a DT for Badalona's (Spain) public transport system to gain deep insights into bus dynamics. Using a genetic algorithm with real-world data, the research has yielded a system that accurately replicates bus schedules and traffic flow, while also adapting to unforeseen situations thus accommodating the passenger comfort and satisfaction.

A study presented in [22] proposes a multi-level cooperative driving framework for urban arterials, accommodating a mix of connected vehicles, connected automated vehicles, and regular vehicles. The model is aimed to optimize the traffic flow to minimize fuel and energy con-

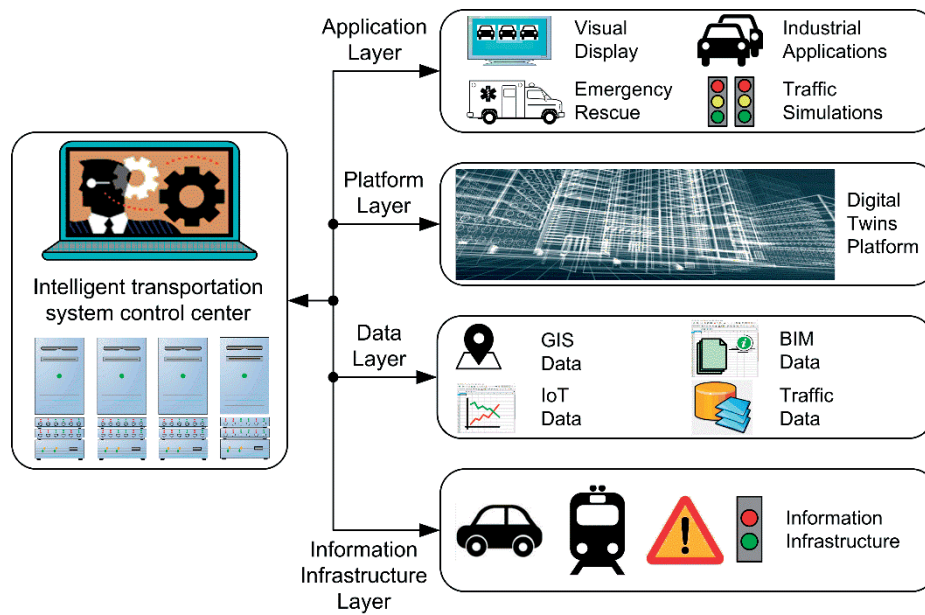


Fig. 3. Digital Twin-based smart transportation platform architecture from [25].

sumption by using centralized control, where communication infrastructure optimizes signal timing and provides general guidance, with distributed control for individual vehicle trajectories. Simulations on a real-world arterial show significant reductions in delays and fuel consumption across various traffic compositions and automated vehicle percentages. Sensitivity analysis confirms the benefits are robust to traffic volume fluctuations. Another innovative approach to smart mobility challenges using digital twins has been proposed in [23]. Leveraging digital replicas of urban environments and utilization of the so-called “meta-cities” architecture for smart mobility, the presented study aims to optimize traffic flow, reduce environmental impact, and improve emergency response through real-time monitoring and analysis.

Only the interaction of different aspects of sustainability makes the transport system of a tourist city future-proof and ensures long-term success and growth. Sustainability not only includes environmental issues, but also considers social aspects and key aspects of good and transparent corporate governance. For this reason, it is necessary to statistically collect traffic information and measure its parameters (e.g. by using an IoT network of distributed sensors), with the goal of successfully implementing corrections and making transparent and measurable decisions for the successful implementation of ESG sustainability parameters, especially for tourist locations that require measuring the traffic load in real time.

The city of Graz, Austria, is trialing a smart traffic monitoring platform to improve cycling infrastructure and support its climate goals. This GDPR-compliant system uses AI-powered video analysis to accurately distinguish between cars, cyclists, scooters, and other road users within the traffic model, thus overcoming limitations of traditional sensor-based solutions. The system transmits data via mobile networks for easy installation on the existing infrastructure. Graz aims to use the collected data, including traffic infringement information, to enhance

road safety and potentially expand the system city-wide. The project supports not only green initiatives but also the development of autonomous vehicles (AVs) and the EU’s Vision Zero goal by providing detailed traffic data [24]. The study presented in [25] analyzes how DTs can be applied to intelligent transportation systems and model traveler behavior under unexpected events, with the smart transportation platform DT architecture shown in Fig. 3. It integrates multi-source spatial and IoT data to construct virtual transportation scenes using 3D modeling and simulation tools. This study proposes an Internet of Vehicles (IoV) system that integrates DTs with blockchain technology to address data redundancy and vehicle data sharing issues. The study concludes that enhancing DT resilience directly translates to a more adaptable transportation system. A network traffic prediction algorithm for Vehicular Ad-Hoc Networks with fluctuating traffic flows is proposed in [26] to accommodate for the vast amount of data generated by Intelligent Transportation Systems (ITS). The algorithm combines Deep Learning methodologies for traffic prediction with Generative Adversarial Networks (GAN) to improve the traffic prediction accuracy, which is crucial for network management and security.

The challenge of the availability of tourist destinations is mainly related to the road transport infrastructure, which must meet the large and changing seasonal traffic demands. There is a great challenge of managing parking facilities in old urban centers that have a large increase in tourist arrivals, and on the other hand, increased demands on environmental sustainability. Due to new trends in tourism with highly mobile tourist demands, it can be surmised that a more accessible tourist destination will likely have better utilization of tourist capacities. For these reasons, tourist cities are looking for transport solutions that are increasingly complex due to the impossibility of expanding the old city infrastructure. Such new and sustainable traffic solutions are being developed in the direction of digitization and the introduction of artificial intelligence, especially in parking systems.

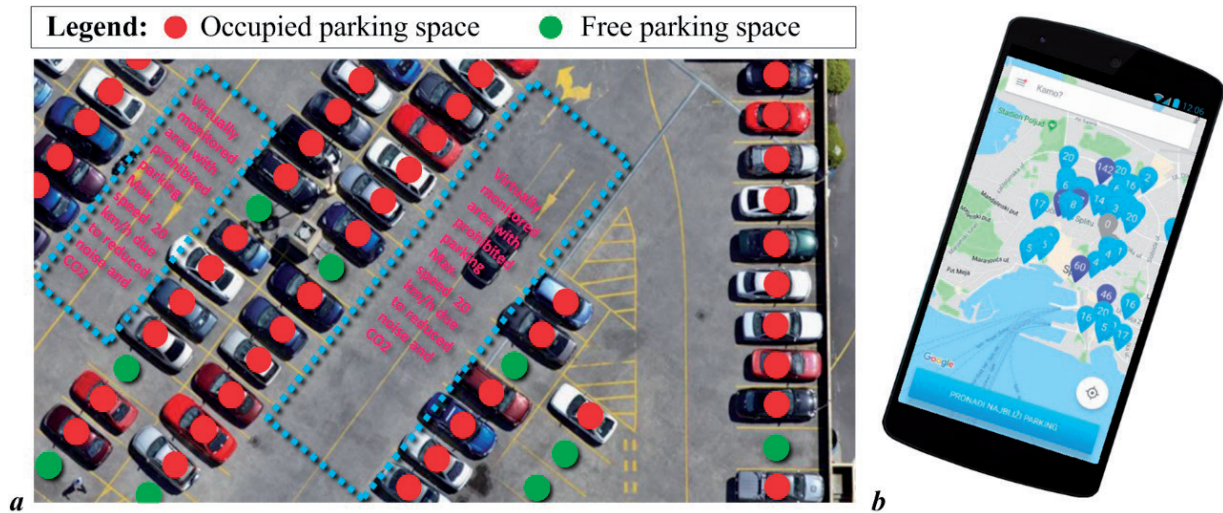


Fig. 4. The concept of digital monitoring of available parking capacities in real time with features of a smart directional system to increase the sustainability of urban traffic (a) and the user graphical interface (b) showing parking locations in the Split metropolitan area.

The city of Split is one of the first cities in Croatia to introduce a comprehensive digitization of the transport system due to overloading during the tourist season. Parking was defined as one of the primary problems, so the implementation of the digitalization of parking capacities was initiated recently, according to the concept of monitoring the occupancy of the parking infrastructure, as illustrated in Fig. 3. The digitalization of the parking infrastructure has been carried out by means of advanced sensors such as high-definition (HD) video and forward-looking infrared (FLIR) cameras whose data is collected in real time and processed to determine the currently available city-wide parking capacities, and those at the individual parking lots (see Fig. 3a). The parking space data within the centralized database will then be made available to subscribers within a mobile (smartphone) app, as illustrated in Fig. 3b. For more information about the digitalization project in question, the reader is referred to [27].

Traffic in cities is one of the greatest generators of CO₂ emissions and noise and searching for a free parking space generates up to 30% increase in traffic in urban areas. There are significant user traffic challenges such as: the fastest way from the point of movement to the point of long-term stopping, the nearest parking lot, the nearest electric charging station. By introducing innovative digital technologies, such as ITS (Intelligent Transport Systems) and a different organization of traffic, fuel consumption and CO₂ emissions can be reduced, drivers can be dynamically directed to available parking spaces and can thus avoid congestion and traffic jams, which could potentially reduce or solve traffic issues in today's cities, especially in tourist areas that are subject to seasonal traffic variations.

Study presented in [28] highlights the importance of social equity in the transition to electric vehicles (EVs). They analyze the availability and affordability of EVs that are cornerstone for greener road transport, and advocate for solutions that optimize the placement of EV charging stations, ensuring accessibility for all communi-

ties, including those in underserved areas. In that sense, future DT models could assist in analyzing the key factors like population density, travel patterns, and existing infrastructure to identify optimal locations for charging stations, promoting social equity, and encouraging wider EV adoption. This, in turn, would contribute to a cleaner transportation sector and would reduce greenhouse gas emissions.

2.2. Rail transport and autonomous virtual-line transport

Digital twins (DTs) are gaining traction in various sectors, offering benefits for product quality, process optimization, and resilience enhancement. In railways, DTs coupled with artificial intelligence (AI) show much promise for predictive maintenance, streamlining operations and reducing unexpected failures [29]. The research presented in [30] presents a new conceptual framework, RailTwin, or a railway Digital Twin (DT) that combines real-time data (insight), future predictions (foresight), and combined analysis (oversight) to enable automation and actions. This framework leverages various AI techniques like Deep Learning and Reinforcement Learning to achieve these functionalities. Research by the French National Railway Company (SNCF Réseau) [31] details their implementation of a DT model for railway infrastructure management. The model incorporates data from sensors embedded in tracks, switches, and overhead lines. This data is used to predict maintenance needs, optimize resource allocation, and minimize disruptions. The DT model also considers environmental factors by identifying energy-efficient routes and optimizing train schedules to reduce emissions. The SNCF Réseau study reports increased efficiency in maintenance activities, improved safety outcomes, and a reduction in the environmental footprint of their operations.

A study presented in [32] highlights how weather conditions, like wind and humidity, can affect train safety and energy consumption. By analyzing these factors through

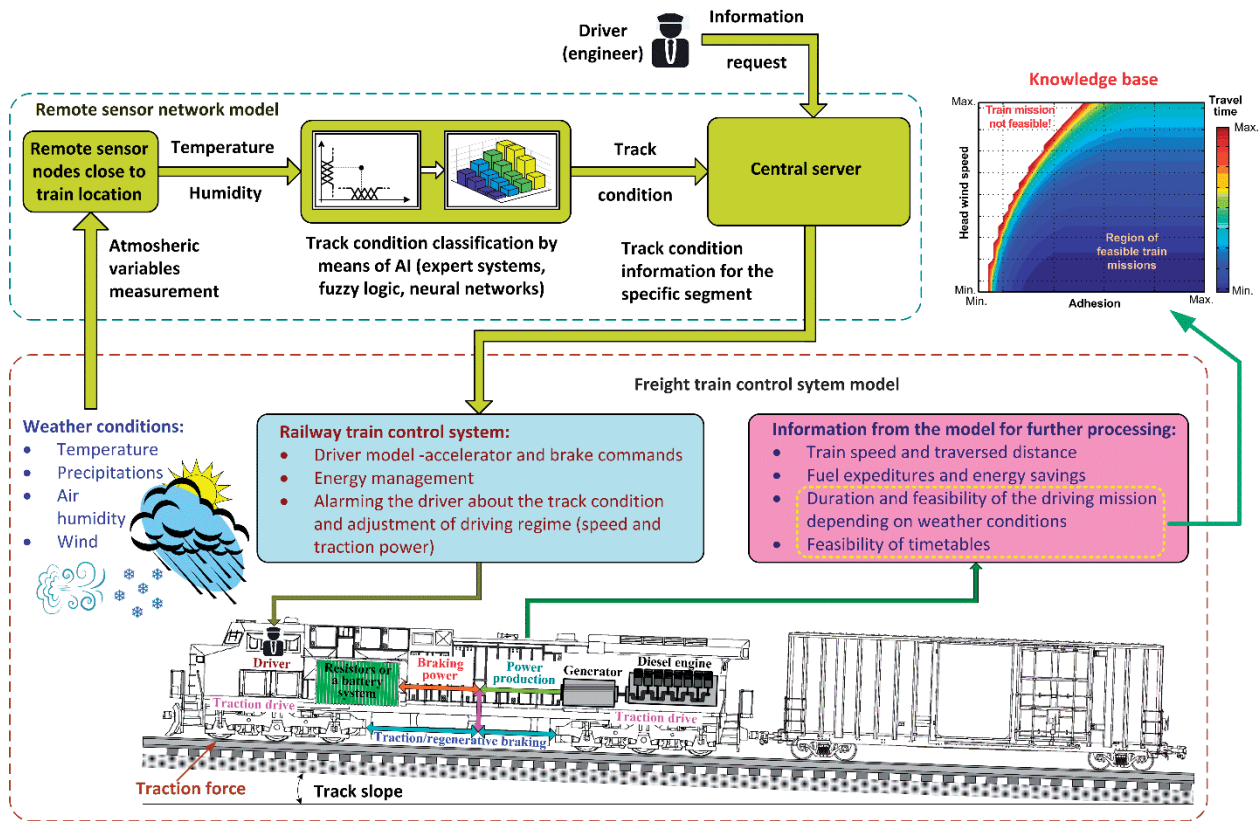


Fig. 5. Principal representation of train supervision system with information flow [32].

utilization of remote sensor networks, the study proposes a digital twin system equipped with AI features to predict challenging track conditions and adjust train driving missions and schedules accordingly (see Fig. 5). The study concludes that the presented approach could improve safety, optimize fuel usage, and contribute to a greener transportation sector through optimization of energy consumption with respect to micro-location weather conditions. Another example of utilization of AI for improved traffic safety can be found in [33] wherein a fuzzy logic algorithm is proposed to manage traffic during partial closures on a dual rail track, which is a common problem in railways and autonomous virtual-line transport (Fig. 6). The algorithm uses real-time queue data (from narrow-band IoT sensors) to schedule the traffic flows. Compared to conventional methods, this approach has been shown to effectively reduce vehicle congestion under irregular traffic conditions (see Fig. 6).

Smart railway systems, integrating 5G and AI, pose challenges for wireless network management. Wireless Digital Twins (DTs) offer solutions for the entire lifecycle of these networks, as indicated in [34], with key technologies for railway-oriented DTs including characterizing material properties, reconstructing 3D environments, AI-powered analysis, and deterministic channel modeling methods for radio signal propagation simulation. The DT-based planning tool in question has been demonstrated to have the industrial value and has been adopted by the China Railway Engineering Design and Consulting Group to implement different advanced functionalities. Research conducted in [35] presents an augmented

digital twin for railways, designed to enhance safety and efficiency in train operations by incorporating real-time derailment risk assessment. The digital twin combines a surrogate model, developed through extensive multibody dynamics simulations, with machine learning techniques to predict derailment risk based on factors like coupler force, speed, and track curvature. Successful implementation in a heavy haul case study demonstrates the augmented twin's potential to not only mitigate derailment risk but also support future advancements in reducing rail damage. More about next generation railway systems can be found in [36].

2.3. Other modes of transport

Digital Twins (DTs) are crucial for industries facing disruption from factors like rising costs and decarbonization mandates, and the whole maritime sector can significantly benefit from DT applications throughout the product lifecycle to tackle these challenges [37]. Modern seaport information systems leverage cutting-edge technology to analyze real-time data and are adopting Digital Twins as a key driver of Industry 4.0 integration. To that end, reference [38] paper examines the Digital Twin applications in global seaports, exploring implementation strategies, decision support, and challenges.

A collaboration between Maersk, a global shipping giant, and IBM showcases the potential of DT-ESG solutions in the logistics sector [39]. The project utilizes a DT model to track and optimize container shipments across the entire supply chain. The model integrates real-time data on

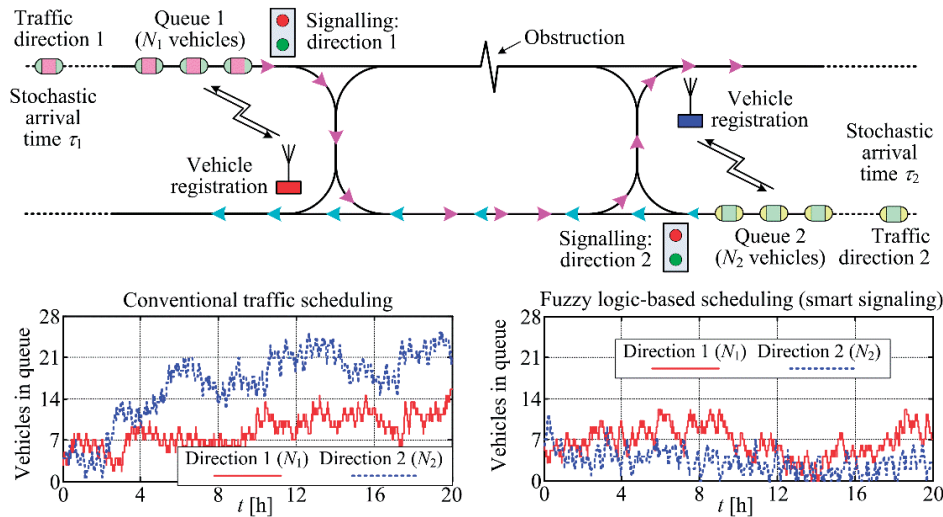


Fig. 6. Bidirectional autonomous virtual-line transport network segment under obstruction with signaling system and comparison of conventional and smart scheduling approach from [33].

location, fuel consumption, and emissions. By optimizing routes and logistics strategies, the project aims to reduce fuel consumption, minimize emissions, and improve overall supply chain efficiency. This case study demonstrates how DT-ESG solutions can contribute to a more sustainable maritime transport sector. To that end, reference [40] aims to improve efficiency and environmental compliance in maritime operations by using Deep Learning techniques on real-world data. A good survey of DT technologies and applications to future ports can be found in [41], along with some examples on how DT can contribute to energy efficiency and sustainability efforts by optimizing the use of port resources, facilities, and operations. The aerospace sector produces vast amounts of data that, with advancements in technology, can optimize the industry's processes. To achieve this, advanced system architectures and data models are needed to manage and integrate these diverse data sources. The study presented in [42] introduces an Airport Digital Twin concept, featuring a comprehensive data model used to streamline flight turnaround events. DT architecture in question has been validated at Aberdeen International Airport, Scotland, with the aim of reducing flight delays. On the other hand, airport ground delays can also significantly disrupt air traffic networks, so efficient ground handling is crucial to minimize delays and cascading effects. To this end, the study conducted in [43] presents a digital twin with agent-based modeling for Amsterdam Schiphol Airport's Pier H. It simulates ground handling activities and evaluates on-time departures under various scenarios, while also incorporating priority-based service rules, intelligent ground equipment to optimize service sequencing and resource allocation, along with an optimization model considers resource constraints and delays to achieve a cost-effective balance between airport demand and capacity. Results show that such strategies effectively reduce delays compared to the more traditional "first-in, first-out" (FIFO) approaches. A specialized DT platform has been proposed in [44] to conceptualize Urban Air Mobility (UAM) with unmanned aerial vehicles (UAVs) as a possible future transport solution, with the main obstacle currently being the integration of UAM into existing ground and air

traffic systems, which requires a digital twin framework for network design and management. This particular DT concept has been applied to the airspace of Bologna, Italy, and has been demonstrated to prioritize safe routes and optimize connections between origin and destination points within the DT simulation environment.

Airports are actively working to reduce their environmental impact through initiatives like Airport Carbon Accreditation and collaborative management, whereas many terminals are pursuing Green Building Rating Standards (GBRS) certification [55]. However, existing standards don't fully address all environmental aspects of airport operations. Therefore, the research presented in [45] explores integrating GBRS with a more holistic approach, highlighting potential challenges. The proposed holistic scheme could improve environmental management, coordinate partner efforts, address construction and operational impacts, and enhance overall accountability. An example of such a holistic approach to airline transport greening can be found in [46] wherein OLGA, a Horizon 2020 project, drives the aviation sector towards sustainability with its innovative solutions. Addressing environmental concerns like carbon-dioxide emissions, biodiversity loss, air quality, and waste management, OLGA optimizes energy efficiency holistically across airports and the aviation value chain.

A study presented in [47] explores factors influencing consumers' willingness to pay for sustainable practices at airports (e.g., biofuels, green construction) and their intention to mitigate climate change. A survey of 722 participants in the US examined how factors such as environmental concern and perceived value of sustainability impact these behaviors. The study found that positive response towards climate action, perceived value of sustainability, and personal beliefs about climate change all significantly influence willingness to pay for eco-friendly airports, which in turn translates to a greater willingness to take affirmative action. A rather comprehensive literature review on impact assessment literature for green airports can be found in [48].

3. Powering a Greener Future with Digital Twin-ESG Solutions in Energy Sector

The energy sector, especially when considering the Smart Grid (SG) paradigm presents another critical area where DT-ESG solutions can revolutionize how we generate, manage, and utilize energy resources. While there's no single definition, a smart grid (SG) generally combines technologies to connect and optimize the actions of all users within the electricity network. This includes generators, consumers, and so-called "prosumers", with the ultimate goal of SG to maintain a continuous, efficient, economic, and sustainable energy balance [36]. Figure 7. illustrates the variety of hardware, software, and communications systems involved in an SG. The Smart Grid Architecture Model (SGAM) provides a framework for understanding complex smart grid systems, as illustrated in Fig. 8. It consists of five layers (business, function, information, communication, and component) that facilitate information flow between domains and hierarchical zones of the energy system. Reliable information and communication technology resources are essential for timely coordination between these layers, which means that designing efficient energy systems involves complex decision-making. An Interactive Digital Twin (InDiT) is introduced in [49], as a tool that assists decision-makers in exploring design options, which translates user needs and preferences into an optimization model, considering factors like uncertainty and multi-criteria analysis.

With the rise of interconnected energy systems in smart cities, managing these networks effectively is crucial from the standpoint of reliability. The research presented in [50] proposes an energy management tool that utilizes advanced control and machine learning to optimize energy use across a city district, coordinating various energy sources while accounting for user-defined goals and high-level system constraints. The particular open-source framework allows for adaptation across different energy sectors, as demonstrated in case studies of integrating heating systems and electric vehicle charging stations in London. The study has indicated that such an approach empowers local governments to manage energy assets collaboratively and achieve environmental, economic, and resilience objectives, thus aligning well with ESG criteria.

The growing complexity of power systems with distributed energy resources (DERs) demands efficient data management for reliable operation, with Digital twins (DTs) offering a promising solution. To this end, the study presented in [51] proposes a methodology for modeling energy cyber-physical systems (ECPSS) using two DT types to cover for high-bandwidth (high response speed) and low-bandwidth (low response speed) events, while also supporting centralized decision-making. The concept has been validated using Amazon Web Services (AWS) as a cloud platform, demonstrating real-time implementation with high accuracy. In addition, digital twins (DTs) are revolutionizing modern industries by creating real-time digital replicas of physical systems, while the growth of the Internet of Things (IoT) in power grids provides the data needed for DT implementation, as proposed in [52]. This particular study proposes DT applications across

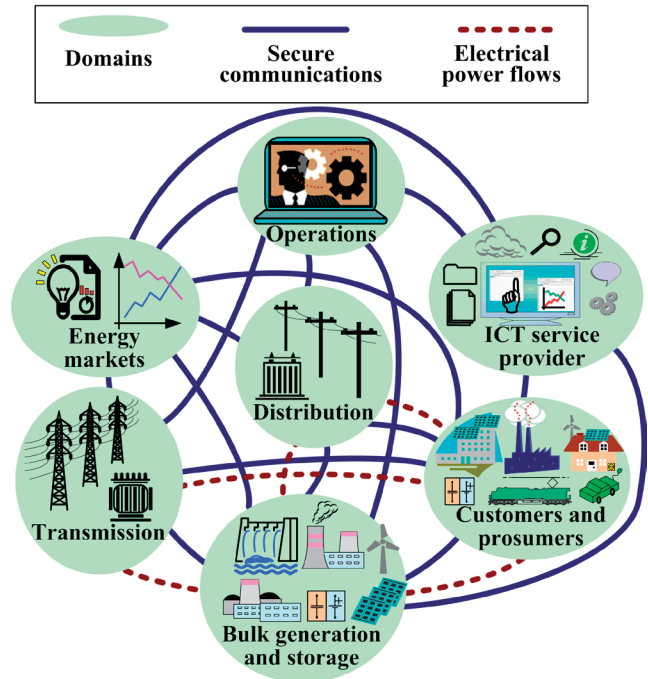


Fig. 7. Conceptual model of Smart Grid [36].

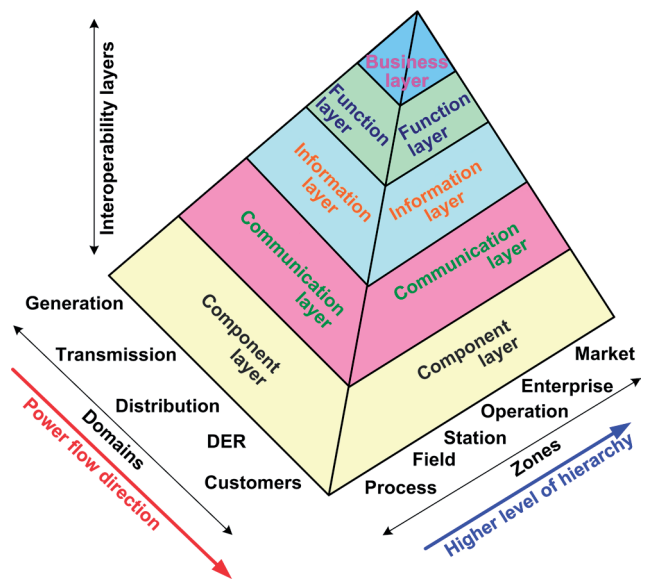


Fig. 8. Conceptual representation of smart grid architecture model (SGAM) [36].

various power system domains within smart cities, including transportation systems, smart grids, and micro-grids, with real-time data analysis from DTs being able to address challenges like traffic management in transportation and remote data transfer in power grids. Security considerations for Machine Learning (ML)-based DTs are also discussed and a comprehensive guide for developing and deploying DTs for diverse power system applications has been presented as well.

Within the future smart energy systems, complex power plants demand robust DT architectures for optimized reliability, availability, and cost-effectiveness, as proposed in [53], wherein a comprehensive DT architecture has been

developed for power plants, adaptable to similar engineering systems. The architecture in question integrates physics-based models, sensor data analysis, localized simulations, and a digital thread, fulfilling established DT requirements. The study has demonstrated its effectiveness for the case of anomaly detection for utility gas turbines in an operational power plant, thus also showing potential in improving the overall energy production resilience.

A review presented in [54] explores how Digital Twins (DTs) can be applied to Smart Energy Systems (SES) in the age of Industry 4.0. It investigates how DTs can address challenges in energy service provision and contribute to a more agile and intelligent energy sector (Energy 4.0). The review has included: (i) a description of the current DT applications in SES, (ii) identification of key DT applications, challenges, and implementation factors for Energy 4.0 management, and (iii) description of various approaches for deploying DTs within SES, thus providing a managerial guideline for practitioners considering future DT adoption.

Digitalizing the process and energy sectors with Energy Digital Twins (EDTs) promises significant advancements in energy management, optimization, maintenance, design, and renewable integration, as outlined in the review paper [55]. This review proposes a multi-dimensional EDT classification framework, outlining lifecycle applications, and suggesting how EDTs can reduce the environmental footprint of industrial sites and local areas, along with listing key challenges for future EDT adoption. The study presented in [56] explores using digital twins with 3D data, IoT, AI, and machine learning for intelligent energy management in a residential district. The case study focuses on Rinascimento III in Rome, a self-renewable energy-powered complex. It evaluates energy efficiency interventions using dynamic analysis algorithms to optimize energy use while maintaining resident comfort, with the goal of increasing self-produced renewable energy and achieving near-zero energy building standards, thus aligning well with the ESG criteria for future smart cities.

An example of challenges faced by future city designers is prioritizing building upgrades for energy reduction. While traditional benchmarking helps identify good and bad performers, it lacks details for actionable plans. To this end, the study presented in [57] proposes using smart meter data to create daily energy benchmarks for different building use periods. Unlike annual benchmarks, these segmented metrics reveal variations in efficiency throughout the day, week, or month, thus allowing for more targeted efficiency strategies and preparing for digital twin platforms that manage energy across entire building portfolios in near-real-time. A conceptual model for a Smart City Digital Twin (SCDT) specifically focused on disaster management is presented in [58], integrating sensors and simulations across various city systems that may be crucial for community management in disaster situations.

In conclusion, smart cities are seen as a solution to sustainability challenges, but face development hurdles, wherein Digital Twin Cities (DTCs) can be regarded as a transformative approach, with DTCs leveraging tech-

nologies such as IoT, AI, and blockchain to create digital replicas of cities, enabling better urban governance [59].

4. A Case for Sustainable Tourism using Digital Twins and ESG Methodologies

The global challenge of sustainable development requires a multi-dimensional approach, considering many aspects such as culture, structure, technology, and stakeholder collaboration. A key strategy is systems renewal, which involves prioritizing human needs and aiming for significant improvements in eco-efficiency. This requires strategic innovation and transdisciplinary collaboration to achieve viable results, especially when the transport-energy sector is considered due to its significant environmental impact [60]. This chapter will provide an overview of current efforts in sustainable development for the case of the tourism sector, which is highly dependent on both the transport and energy sector, with emphasis on digitalization, digital twins, and adherence to ESG methodologies.

Tourism's growth, especially in developing countries, has led to increased energy consumption, primarily from air travel, which has significant environmental consequences, necessitating the integration of energy use into sustainable tourism discussions [61]. The hotel industry, a major energy consumer within the tourism sector, often wastes energy due to a focus on comfort and competition. According to [62], there is a significant opportunity for hotels to implement renewable energy technologies and improve energy efficiency. Tourism transportation's impact on climate change also represents a crucial concern. Namely, a business-as-usual scenario will lead to undesirable consequences, making climate mitigation goals unattainable. Therefore, it is essential to consider long-term, macro-scale scenarios to understand both desirable and undesirable elements for the future of tourism transportation [63]. Statistical analysis has revealed a positive correlation between environmental indicators and tourism activity [64], with transportation used by tourists, especially road and air travel, having a negative impact on the environment. Promoting natural parks and encouraging more sustainable transportation methods can help balance these effects.

Sustainable tourism should not only consider local activities but also address the environmental impact of travel, especially in developed countries [65]. Therefore, reducing reliance on cars and planes is essential, posing a challenge for future tourism development. To achieve sustainable tourism transportation, behavioral change is necessary, as technology alone may not be enough to mitigate climate change. Models incorporating psychological economics and product diffusion theories can help evaluate the long-term policy impacts and promote sustainable travel choices [66]. Sustainable transportation also requires understanding of the psychology of travelers [67], because individual mobility decisions are influenced by both internal factors (attitudes, preferences) and external factors (price, speed). Therefore, transport policies can be more effective by considering these psychological aspects. In that sense personalized systems can incentivize sustainable travel behavior by learning individual pref-

erences and promoting alternatives. According to [68], using control theory approaches in combination with domain knowledge in developing new travel planning strategies, these novel systems can effectively influence choices like departure times, potentially reducing overall travel time and promoting sustainability.

Digital twin (DT) technology, emerging from AI and IoT, has the potential to improve smart and sustainable tourism by predicting system responses. However, challenges such as regulatory compliance, stakeholder communication, and data security need to be addressed, so a documentation framework applying big data governance to the digital system is proposed in [69] to ensure accountability and trust in these novel concepts. Digital twins can also be used to enhance management, virtualize testing and maintenance, and maximize efficiency gains in smart cities by focusing on practical applications like GIS and BIM fusions, which can aid urban designers in placemaking and consultation [70]. Digital twins of the urban ecosystem are also a popular and mainstream trend in the digital development of territories worldwide [71], with their use within the urban ecosystem allowing the municipal authorities to obtain effective levers of management, and to enhance the quality of life within the city. Digital twins can also utilize Big Data to create virtual representations of regions and analyze visitor activity thus enabling smart and sustainable tourism [72]. However, this also requires addressing regulatory compliance and stakeholder communication. It also requires resolving issues of Big Data governance, whose framework comprises policies, guidelines, and procedures to effectively manage large volumes of structured and unstructured data, enabling efficient data discovery, collection, processing, analysis, and storage (Fig. 9). One such conceptual framework for designing and implementing a Digital Twin in smart and sustainable tourism is shown in Fig. 10. It comprises four key steps: identification of big data sources, data management, Data interpretation, and decision-making.

The rapid advancement of 5G communications technology has already highlighted its limitations and the need for the next generation (6G) technology. As suggested in [73], the coupling of the 6G technologies with digital twins and immersive realities has the potential to impact smart cities and contribute to sustainable development goals. The ultra-reliable low-latency communication enabled by 6G will be crucial for autonomous vehicles, optimizing traffic flow, and reducing congestion, leading to lower fuel consumption and emissions [74]. In the energy sector, 6G will facilitate more reliable and more responsive smart grids, enabling real-time monitoring and control of energy generation and distribution, promoting the integration of renewable sources and enhancing energy efficiency [75]. Moreover, 6G will empower the tourism industry by supporting immersive technologies and personalized experiences [76], while fostering sustainable practices through efficient resource management and reduced environmental impact [77].

In that context, the utilization of digital twins with advanced 5G/6G communications technologies can improve sustainability in natural resource monitoring by predicting and promptly addressing potential energy waste and maintenance issues, thus enhancing profitability and preserving environmental resources [78], which is key for sustainable tourism. Digital twins, combined with information and communication technologies and data analytics like artificial intelligence, can help conserve physical resources in the infrastructure industry by enabling new ways of designing, constructing, operating and monitoring infrastructure assets [79]. Moreover, digitally enhanced disaster risk reduction practices that promote civic engagement and evidence-based decision-making can help areas suffering territorial imbalances to achieve sustainable development. The concept of Territorial Digital Twins (TDTs) illustrates the potential benefits of networking distributed information resources in Italian inner mountain areas [80].

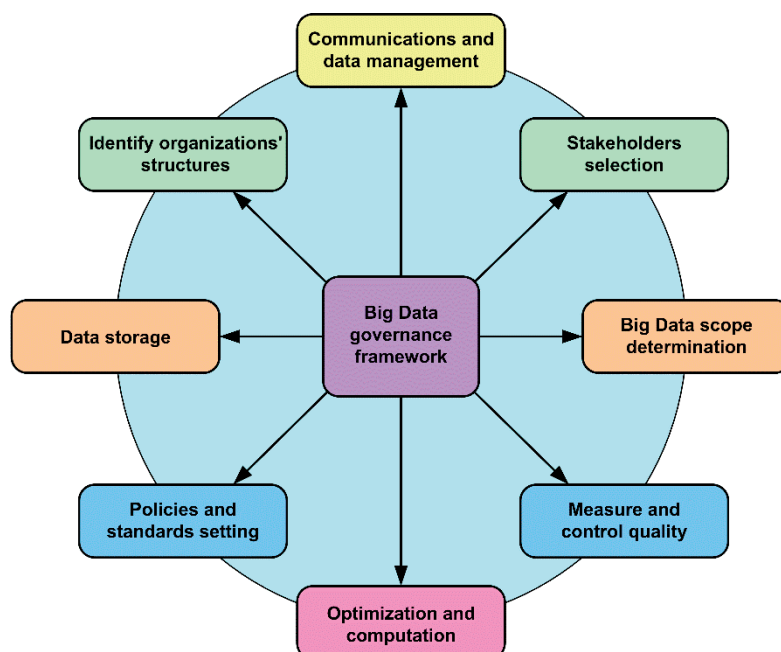


Fig. 9. Big Data governance framework proposed in [72].

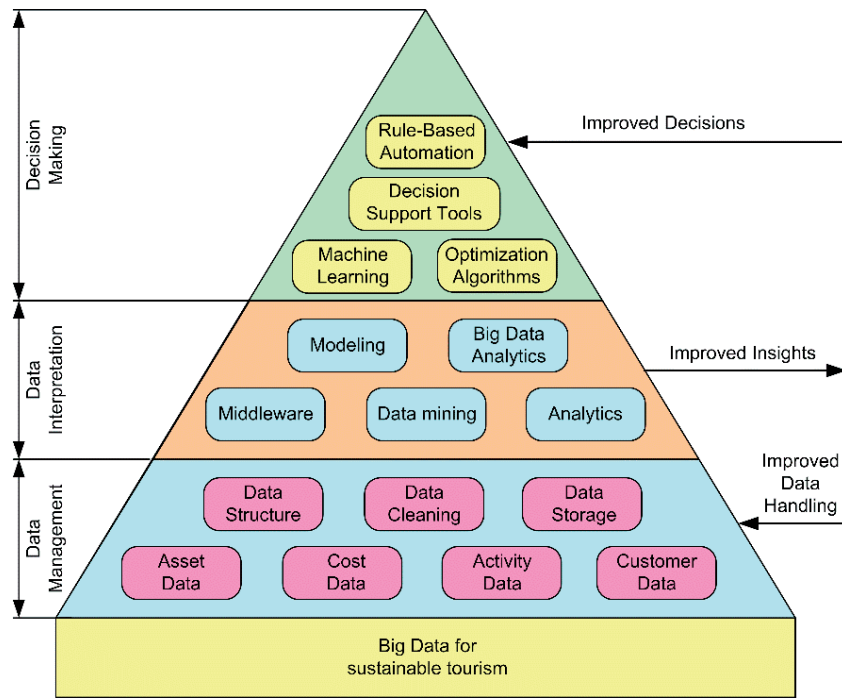


Fig. 10. Conceptual framework of Digital Twin for smart sustainable tourism proposed in [72].

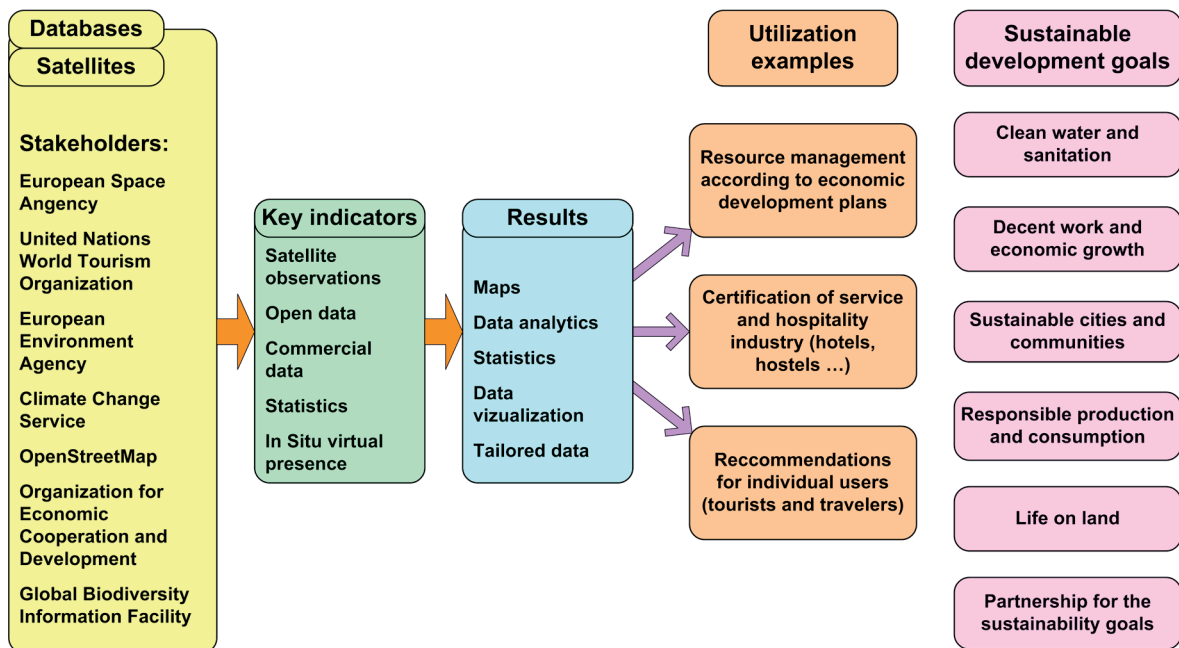


Fig. 11. Conceptual framework of ESA/Murmuration Co. solution for monitoring the impact of tourism on the environment based on satellite data [86].

The concept of lifestyle can be integrated into travel models to better understand behavior. Lifestyles, shaped by opinions, social status, and preferences, influence travel choices beyond just price and convenience, and, thus by considering lifestyles as dynamic rather than static can offer insights into promoting more sustainable travel patterns [81]. Regarding the use of 5G/6G technologies, mobile phone applications can be used to promote sustainable travel behavior. While there are indications that such behavior change support systems can be effective,

more robust studies are needed to draw definitive conclusions [82]. Understanding the triggers for sustainable behavior while traveling is crucial for the tourism industry. Research on Canadian tourists found that sustainable consumers often exhibit altruism, frugality, and pro-ecological behavior in daily life, but these behaviors may not always translate to their travel habits [83]. Tackling complex socio-technical systems, particularly in tourism, requires design-driven innovation beyond e-commerce advancements, which is crucial due to tourism’s impact

on a global and local scale, and the need for a sustainable, regenerative approach. Realizing this goal requires creating holistic solutions that consider stakeholders, leverage data, and create both digital and physical products to enhance sustainable travel experiences [84].

When analyzing the technical regional sustainable reports, it was concluded that it is not possible to comprehensively analyze and compare the data by region for the following reasons: Regions used different sources to analyze the same indicator and had different preferences in the choice of source to be used (European or national/regional sources); and the units of measurement used are not always consistent (some regions prefer absolute numbers, while others use percentages or rates, etc.) [85].

The European Space Agency and the French company Murmuration from Toulouse are developing a solution for monitoring the impact of tourism on the environment based on satellite data (Fig. 11). The solution provides environmental monitoring and forecasting KPIs for the tourism industry on air quality, green areas, urbanization, and water resources, which are collectively expressed as the Tourism Sustainable Development Index (TSDI) [86]. The services are intended for decision makers who want to understand, monitor, report and act on the environmental impact of the tourism industry. The main functions are to provide indicators based on satellite Earth observation data, combine these data into a comprehensive set of indicators that will then be used together with additional data sources and external databases to assess the sustainability of tourism and the impact of these activities on the environment [87]. The indicators will enable decision makers to comply with increasing regulatory requirements for monitoring, controlling, and acting in accordance with the environmental impact of the tourism industry.

In tourist regions with large tourist traffic, it is necessary to create solutions with a system of indicators that can be mapped on multiple scales, and which can help in locating and describing pressures on the environment, thus promoting environmentally friendly destinations or to identify land management policies that can improve the interrelationship between ecosystems and tourism. To produce the above information, Murmuration Co. integrated biophysical, climatic and tourist sector indicators. Table 1 summarizes the indicators that can be monitored by collecting and analyzing data from the European Space Agency's satellites.

5. Discussion

The integration of digital twins (DTs) and Environmental, Social, and Governance (ESG) methodologies presents a transformative opportunity for the tourism sector, which is heavily reliant on the transportation and energy sectors, both significant contributors to environmental impact. DTs, powered by artificial intelligence (AI) and the Internet of Things (IoT), offer a promising avenue for achieving sustainability goals by optimizing resource allocation, predicting system responses, and facilitating data-driven decision-making.

In the transportation domain, DTs have shown potential for optimizing traffic flow, public transportation systems,

and infrastructure management, leading to reduced emissions and improved energy efficiency. Furthermore, integrating DTs with blockchain technology can address data redundancy and enhance security in vehicular networks, fostering a more resilient and sustainable transportation ecosystem. However, the successful implementation of DT-driven solutions requires careful consideration of regulatory compliance, stakeholder communication, and data security issues. The energy sector also stands to benefit significantly from DT-ESG integration. DTs can be leveraged to optimize energy production and consumption in hotels, a major energy consumer within the tourism industry. Additionally, DTs can facilitate the integration of renewable energy sources and enable intelligent energy management systems for smart cities, contributing to reduced carbon footprints and increased energy efficiency.

Table 1. Overview of proposed indicators to be monitored by collecting and processing European Space Agency's Earth observation satellite data [87].

Indicator	Description
Air	Groups all information for assessing and monitoring air conditions
Biodiversity	Brings together all indicators for assessing and monitoring the state of biodiversity
Climate	Integrates all indicators for assessing and monitoring weather and climate conditions
Human activity	Integrates all indicators for assessing and monitoring the impact of tourism on the environment
Land	Groups all indicators for evaluating and monitoring the state of the ground
Water	Groups together all indicators for assessing and monitoring the state of water resources

However, the adoption of DT-ESG solutions faces several challenges. The transition to sustainable transportation requires not only technological advancements but also a fundamental shift in traveler behavior and preferences. Understanding the psychological aspects of travel choices is crucial for designing effective policies and incentives that promote sustainable practices. Additionally, ensuring equitable access to sustainable transportation options and aligning technological advancements with ESG principles remain critical areas for future research and development.

Digital twin technologies hold significant potential for personalizing incentives and providing real-time feedback to tourists on their environmental impact. For example, a DT-powered app could track tourists' behaviors and preferences such as through historical data, using those data for designing tailored incentives that promote sustainable choices. Moreover, it would be possible to provide instant (real-time) feedback on the environmental impact of their actions, such as those related to transportation and energy use, which can empower tourists to make more sustainable decisions. Naturally, in all those instances it would be crucial to address privacy concerns and ensure transparency in data collection and usage. This can be done by data minimization, i.e. collecting only the data that is nec-

essary for the intended purpose and data anonymization and pseudonymization. Implementation of strong security protocols to protect data from unauthorized access, use, disclosure, disruption, modification, or destruction would be mandatory. This includes encryption, access controls, and regular security audits, and limited data retention, including policies and secure disposing of data when it is no longer needed. Implementing digital twins in the tourism sector also requires careful consideration of various regulations, primarily those pertaining to data protection and privacy, as discussed above. The General Data Protection Regulation (GDPR) [88] introduced in the EU has a global impact and sets strict rules for collecting, processing, and storing personal data. Key aspects include obtaining explicit consent, ensuring data security, and granting individuals rights to access and control their data. While not legally binding, adhering to industry standards and best practices for data governance and security can help build trust and demonstrate a commitment to responsible data handling.

6. Conclusion

This paper outlines the transformative potential of integrating digital twin (DT) models with ESG principles to achieve significant advancements within the transport and energy sectors. By leveraging real-time data and insights generated by DTs, decision-makers can optimize processes, promote resource efficiency, and ensure social equity in these critical domains. Such a strategy is essential for driving global sustainability efforts and addressing our planet's most pressing environmental challenges. While this combined approach offers substantial benefits, its successful implementation hinges on addressing several key challenges. Ensuring the availability, quality, and security of vast amounts of data within the complex DT ecosystem is of paramount importance. Additionally, developing universal standards and governance frameworks will foster compatibility between various DT systems and enhance transparency in ESG reporting. Overcoming these obstacles will unlock the full potential of DT-ESG integration.

In conclusion, the integration of digital twin (DT) technology with environmental, social, and governance (ESG) principles offers a promising pathway towards a more sustainable and resilient tourism sector. DTs have the potential to revolutionize transportation and energy management, two critical components of the tourism industry, by optimizing resource allocation, reducing emissions, and promoting social equity. However, the successful adoption of DT-ESG solutions requires addressing challenges related to data governance, regulatory compliance, stakeholder collaboration, and traveler behavior. Future research should thus focus on overcoming these challenges and further exploring the applicability of DT-ESG solutions across diverse industries and domains. Moreover, when discussing the pivotal role of policy in facilitating sustainable tourism development, one of the key limitations may be the reliance on secondary research. Future research should thus also prioritize the collection and analysis of original data, potentially by focusing on specific case studies, for instance by calculating the total en-

ergy savings realized after implementing a smart energy-transport system at the particular tourist destination. This would provide tangible evidence of the policy's impact and further validate the benefits for both tourists and the local population, thus ultimately contributing to a more holistic understanding of sustainable tourism practices.

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