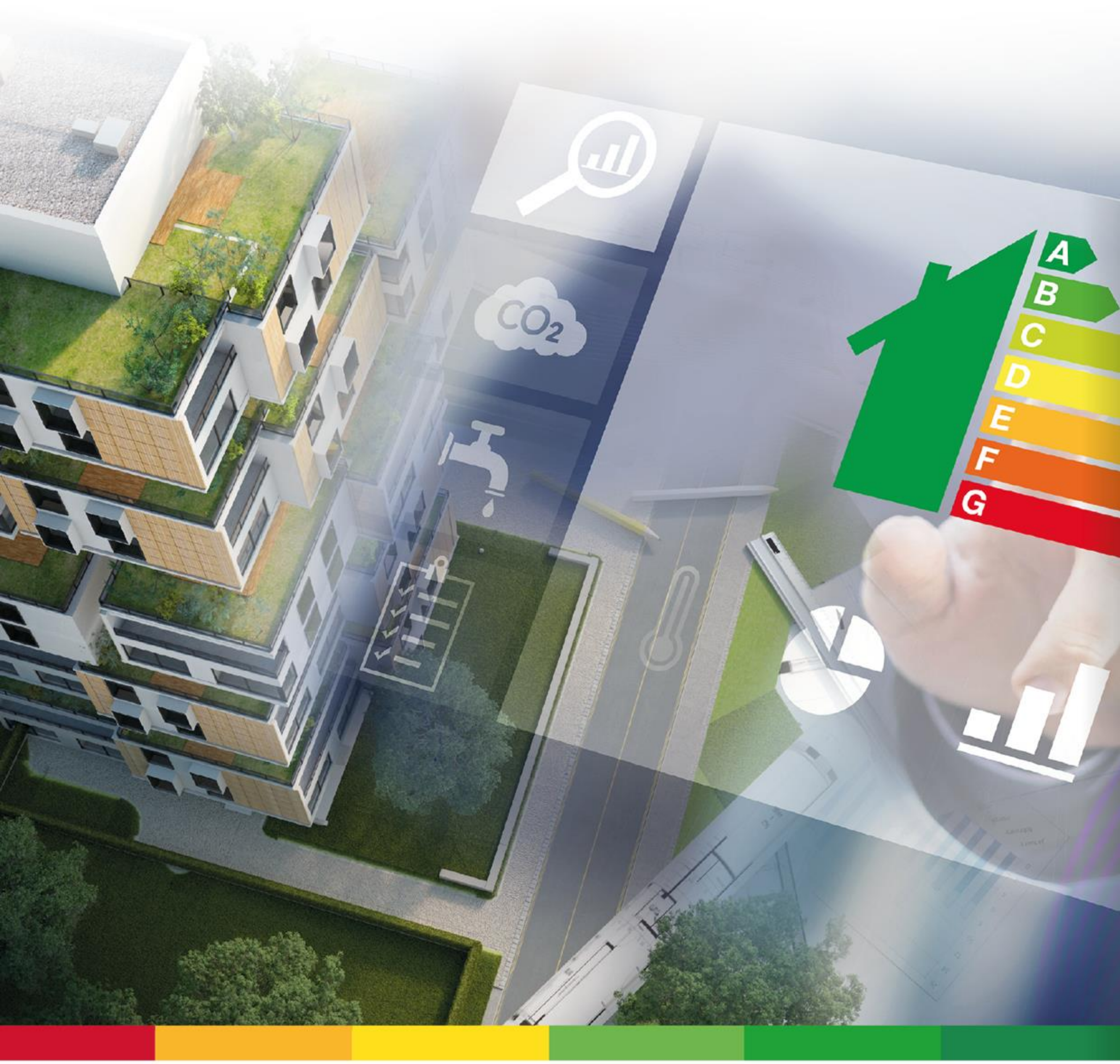
Smart living EPC

D3.2 Operational assessment methodology in complex level



This project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement number 101069639. The European Union is not liable for any use that may be made of the information contained in this document, which is merely representing the authors' view.

Project Acronym:	SmartLivingEPC
Project Full Title:	Advanced Energy Performance Assessment towards Smart Living in Building and District Level
Grant Agreement:	101069639
Project Duration:	36 months (01/07/2022 – 30/06/2025)

Deliverable 3.2

Operational assessment methodology in building level

Work Package:	WP3 SmartLivingEPC Framework Operational Methodology
Task:	T3.4 Building complex assessment Operational methodology T3.5 SmartLivingEPC operational rating calculation methodology
Document Status:	Final
File Name:	SmartLivingEPC_D3.2 Operational assessment methodology in building complex level v1
Due Date:	31.08.2023
Submission Date:	10.11.2023
Lead Beneficiary:	UDEUSTO

Dissemination Level	
Public	☒
Confidential, only for members of the Consortium (including the Commission Services)	☐

Authors List

Leading Author				
First Name		Last Name	Beneficiary	Contact e-mail
Borges		Cruz	Deusto University	cruz.borges@deusto.es
Mugarra		Aitziber	Deusto University	aitziber.mugarra@deusto.es
Kachala		Tamara	Deusto University	tamara.kachala@deusto.es
Ferrón		Leandro	Deusto University	l.ferron@deusto.es
Co-Author(s)				
#	First Name	Last Name	Beneficiary	Contact e-mail
1	Samy	Iousef	QUE	s.iousef@que-tech.com
2	Pinelopi	Valiouli	IsZEB	p.valiouli@iszeb.gr
3	Eider	Iribar	GOI	eider.iribar@goiener.com
4	Paris	Fokaides	FRC	eng.fp@frederick.ac.cy

Reviewers List

Reviewers			
First Name	Last Name	Beneficiary	Contact e-mail
Paul	Waide	WSEE	paul@waide-europe.eu
Bishnu	Babu	R2I	bishnu.babu@r2msolution.com

Version History

v	Author	Date	Brief Description
0.1	Leandro Ferrón (UDEUSTO)	28.07.2023	First draft version of the document
0.2	Leandro Ferrón (UDEUSTO)	18.09.2023	Updated based on comments from contributing partners
0.3	Samy Iousef (QUE), Pinelopi Valiouli (IsZEB), Eider Iribar (GOI)	06.10.2023	Quality check, suggestions for improvement and minor change
0.4	Leandro Ferrón (UDEUSTO)	18.10.23	Updated based on comments from partners, Version for Review
0.5	Paul Weide (WSEE), Bishnu Babu (R2I), Samy Iousef (QUE), Pinelopi Valiouli (IsZEB), Eider Iribar (GOI)	20.10.23	Quality check, suggestions for improvement and minor changes
0.6	Leandro Ferrón (UDEUSTO)	23.10.2023	Updated based on comments from partners

0.7	**Aggeliki Veliskaki (CERTH)**	**25.10.2023**	**Format improvements**
0.8	**Paris Fokaides (FRC)**	**05.11.2023**	**Quality check and minor corrections**
1.0	**Leandro Ferrón (UDEUSTO)**	**09.11.2023**	**Available for submission**

Copyright

Executive Summary

This deliverable comprises five chapters, each contributing valuable insights to the development of an operational methodology for scaling complex buildings. Chapter 1 serves as an introduction, outlining the objectives and scope of the deliverable. Chapter 2 delves into the concept of Operational Rating. The baseline, representing the average energy use for a group of buildings of the same function, is essential in this rating approach. Additionally, the technical underpinning of the Operational Rating is illustrated through relevant equations. Chapter 3 explores the advancements in novel technologies such as information and communications technology (ICT), internet of things (IoT), Big Data, cloud computing, wireless sensors, and artificial intelligence (AI). These technologies are identified as accelerators in the development of neighbourhoods' energy conservation systems. Furthermore, a preliminary taxonomy of Operational Assess Rating Indicators is presented in section 3.2. In Chapter 4, a detailed discussion addresses the challenges of operating digital twins in the urban context. These digital twins serve as virtual models of physical assets in cities, enabling data analysis and simulations to support informed decision-making. The concluding chapter summarizes the primary findings and contributions of the deliverable. It also lays the groundwork for future directions to advance the project's development. Overall, this deliverable provides valuable insights and establishes a foundation for further research and development in the area of operational energy rating for building complexes. The integration of cutting-edge technologies and digital twin practices opens new possibilities for enhancing energy efficiency and sustainability in urban environments. By addressing the challenges and leveraging the opportunities presented in this deliverable, future endeavours in the project will be well-positioned to make substantial contributions to the field of smart sustainable cities.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

Term	Description
AI	Artificial intelligence
AMR	Automatic meter reading
AR	Augmented Reality
BMS	Building Management System
CBECS	Commercial Buildings Energy Consumption Survey
DT/UDT	Digital Twin/Urban Digital Twin
EPC	Energy Performance Certificate
GHG	Greenhouse gas emissions
GPS	Global Positioning System
HEMS	Home energy monitoring systems
HVAC	Heating, ventilation, and air conditioning
ICT	Information and communications technology
IoT	Internet of things
LCC	Life Cycle Analysis
MEMS	Micro-Electro-Mechanical Systems
NEMS	Nano-Electro-Mechanical Systems
NFC	Near Field Communication
RFDI	Radio frequency identification
SD	Sustainable Development
SRI	Smart Readiness Indicator
USS	Urban Social sustainability
VR	Virtual Reality

1 Introduction

The project aspires to develop a new rating scheme applicable at the neighbourhood scale, which is based on the assessment of individual building units and on additional building complex parameters with the aim of energy performance certification of building complexes. In this task the operational energy aspects at building block scale will be considered. Infrastructure and smart sensors for the measurement of the actual performance at the neighbourhood scale will be documented, and practices for the analysis of the measurements will be defined. The evaluation and rating scheme at the building complex scale will also be identified.

Digital twin practices at neighbourhood scale, and the integration of measurement findings from smart sensors for building complexes will be defined. Task 3.4 gives a resumé of standardized procedures for the measurement, processing and reporting of energy consumption data at the complex scale, as well as the assessment of this data for the definition of the operational rating of building complexes.

1.1 Objectives

The main objective of this deliverable is:

The development of a new rating scheme applicable at the neighbourhood scale, based on the assessment of individual building units and on additional building complex parameters.

It has as secondary objectives:

- Shifting from the unit building scale to the complex building scale,
- Exploring the interaction between buildings,
- Identifying energy-consuming services unique to neighbourhoods,
- Creating a neighbourhood certificate.

1.2 Scope of the deliverable

As we move into an era where building units will be able to interact energetically through smart grids but also through energy communities, energy performance classification on a neighbourhood scale is expected to become particularly important in the coming years. The SmartLivingEPC will launch and introduce a new energy performance classification methodology applicable at the neighbourhood level, which on the one hand will be based on the categorization of individual building units, on the other hand will consider the energy infrastructure and services on a district scale, as well as the interaction of buildings. The end result is expected to be a methodology to issue a certificate that includes performance at the neighborhood level, which will save energy at that scale.

2 Thinking from the individual building to the building complex scale

2.1 Neighbourhoods operational rating assessment

An analysis of current Neighbourhood Sustainability Assessment Tools and Urban Sustainability Frameworks was presented in deliverable D2.2. Building upon this foundation, this section will provide insights into the concept of Operational Rating. Operational Ratings quantify the energy performance of buildings in terms of adjusted metered energy consumption per unit of conditioned floor area, with the baseline typically representing the average energy use for a group of buildings of the same function (e.g., office buildings). In this context, the EU ENERGYSTAR programme [1] serves as a prominent example of an Operational Rating. This program compares metered energy data from at least a full year of operation with baseline consumption data that accounts for variables such as occupancy, weather, conditioned floor area, and hours of operation. Operational Ratings are effective in comparing the performance of a building over time or comparing the performance of different building portfolios.

The technical underpinning of the Operational Rating is illustrated in Equation 1. The energy performance of both the rated building and the baseline building is assessed based on energy bills. The numerator represents the energy bills of the rated building over a minimum period of 12 months, while the denominator represents the average energy bills of the baseline building adjusted for climate and specific operating parameters. The metered energy performance of the baseline building is adjusted to align with the climate and operating conditions of the rated building (neutral dependent).

$$\text{Operational Rating} = \text{Operational EnPYo} = \frac{\text{EPrb,eb}}{EPbb,aeb}$$ **Equation 1**

Where:

EPrb,be is the energy performance of the rated building determined from utility bills. Electricity, gas, and other fuels measured at the meter are converted into common units, such as source energy or cost.

EPbb,aeb is the energy performance of the baseline building with the same conditioned floor space as the rated building, but adjusted for the operating conditions of the rated building. ENERGYSTAR achieves this through statistical analysis of CBECS data.

Operational Ratings can serve as a valuable tool for directing an organization's focus on energy management, and it have the potential to save 15 to 30% of energy consumption. But there exists a significant variance in energy use per square meter among buildings of the same type within a country or even a city. While certain analyses, notably correlations with building age and size, explain a portion of this variation, a substantial spread remains even after incorporating statistically significant variables into the model. It is important to note that this represents the range diffused enough in the marketplace to be observable in a statistical analysis, rather than the full range of possible efficiency observations. The issue of unexplained variability, as observed in a variety of studies, is a recurring challenge. Different authors attempt to account for variations in energy use through statistical analysis; however, significant unexplained variance persists in every case.

An additional concern when relying solely on Operational Ratings can be illustrated through the concept of Net-Zero Energy Buildings, which has garnered increasing attention among policymakers. Surveys have identified hundreds of net-zero buildings worldwide; however, these surveys often overlook the existence of hundreds of millions of net-zero buildings that have been in use for years. These structures, utilized for commercial and residential purposes in rural areas, are unconditioned and lack access to electricity. While an Operational Rating of zero energy use may appear highly efficient, it fails to account for the insufficient level of energy service provided. To maximize effectiveness, Operational Ratings should be employed within an energy management system, enabling comprehensive analysis and subsequent action.

3 Actual energy performance at neighbourhood scale: Infrastructure and smart sensors

One of the overarching strategies of the leading environmental programs is called "resource efficiency and climate responsibility". With this strategy, smart sustainable neighbourhoods and cities aim to reduce greenhouse gas emissions (GHG) to a level below 1 ton per inhabitant by 2030 and to become fossil fuel-free and climate-positive by 2050 as ambitious environmental goals. The core of this strategy is the reduction of energy consumption and carbon footprint as well as the use of digitalization and new technologies to make it easier for citizens and businesses to be environmentally friendly. In this context, novel technologies like information and communications technology (ICT), internet of things (IoT), Big Data, Cloud computing, wireless sensor, and artificial intelligence (AI), among others, have accelerated the development of neighbourhood energy conservation systems. These innovations, along with advanced networks, policies and infrastructure, have the potential to revolutionize energy use and encourage public participation in conservation efforts. The integration of big data technologies allows for a deeper understanding of urban behavior, reducing risks and uncertainties in decision-making and enhancing interconnectivity among city components. Through an analysis of the consulted literature, we can identify the four main strategies of the resource efficiency and climate responsibility associated with smart energy and the smart environment:

- <u>Smart grid and advanced metering infrastructure</u>: The objective of smart energy is to create highly efficient energy systems that rely more on renewable and local energy sources, enabled by new technologies and less dependent on fossil fuels. Key components in this area are the smart power grid and advanced metering infrastructure, including smart meters. The smart power grid uses hardware, software, and network tools to route power efficiently to consumers, reducing excess capacity and enabling real-time demand-side management. It collects data from a Wi-Fi-enabled sensor network to analyze power supply from diverse sources for better decision-making and process control. Advanced metering infrastructure consists of solid-state meters that remotely provide electricity use details to utilities and consumers, facilitating two-way communication. This system involves sensors on access points and power systems, remote controls, and communication technologies within electricity networks. The smart grid's operational functioning integrates ICT systems, data, and back-office processes, enabling front-end engineering, middleware, and computing systems for data collection and decision analytics. This infrastructure is part of the IoT system in smart sustainable neighbourhoods, with an operations center monitoring a whole and processing real-time data for decision-making and problem-solving, related to energy and the environment.

  The tactics needed for executing the smart grid and advanced metering infrastructure strategy are:

  - Support projects of smart grid technologies.
  - Subsidized projects that support energy-efficiency technology adoption.
  - Allow the decentralization of energy production.
  - Encourage energy production from renewable sources.
  - Promote the multiplication of grid distribution networks.
  - Subsidize projects that integrate renewable energy in power distribution networks.
  - Develop and implement integrated renewable solutions which involve the use of modelling, simulation, analytical, and management tools to enable a wide deployment of renewable energy.

  Deploy and implement a large-scale smart grid system that implies:

  - Smart homes/buildings and demand response.
  - Distributed energy systems.
  - Energy storage for the grid and consumers.
  - Smart primary substations.
  - Smart grid as part of innovation lab.
  - Integration and use of electric vehicles.
- <u>Smart buildings</u>: The Building Management System (BMS) aims to maintain predefined parameters and control functionality in buildings using smart metering and advanced visualization tools. It continuously monitors real-time data on equipment performance and uses it to optimize building performance and

identify energy efficiency opportunities. To execute the smart building strategy, the following (or similar) pathways would be beneficial:

- Subsidizing design projects that promote efficiency technology adoption among building owners and urban developers.
- Rewarding owners and operators of best-in-class buildings.
- Providing funding schemes to encourage building automation system investments.
- Developing and implementing assessment tools for energy-efficient buildings.
- Regulating the use of automation measures in building construction and new development projects.
- Utilizing decision-support systems for large-scale energy efficiency improvements in existing buildings.
- Collaborating with utility companies to evaluate energy efficiency potential in different building vintages and reduce energy use based on construction date market segmentation.
- Implementing data-driven approaches for strategic building energy retrofitting, analyzing actual energy consumption, energy performance certificates, and reference databases.
- Installing BMS in new and retrofitted municipal, commercial, and industrial buildings to monitor and optimize supervised subsystems' use.

- Smart home appliances and devices: Smart homes enable remote control of appliances and devices via smartphones and the internet, offering convenience and cost savings. Smart appliances and devices have built-in intelligence and communication capabilities for automatic or remote control based on user preferences or external signals. The key pathways for executing the smart home appliances and devices strategy include:
  - Promote and install EU EnergyStar heating, ventilation, and air conditioning (HVAC) systems in municipal, commercial, industrial, and residential buildings.
  - Promote and install EU EnergyStar appliances which use a great deal less power than their predecessors.
  - Promote and install smart power strips which sense energy demand and cut off power supply to fully charged or not in use devices.
  - Promote and install smart meters to allow:
    a. Consumers to manage their energy usage based on what they need and afford by having access to live energy prices and adjusting their usage accordingly.
    b. Consumers to remotely control their home appliances and devices by means of such advanced functions as scheduling, programming, as well as reacting to different contextual situations.
    c. Self-optimize and self-control energy consumption through integrating sensing and actuation systems in different kinds of appliances and devices for balancing power generation and usage.
    d. Provide insights into how the energy flows can be influenced by the consumer behaviour thanks to the in-house sensors that can provide data on energy-using appliances.
  - Promote and install easy-to-use home energy monitoring systems (HEMS) which present useful information on energy usage directly to the consumer's devices, allowing them to change their behaviour as well as save money in the long run. HEMS also offer homeowners more options than smart meter-to-smart appliance connections, e.g., a sophisticated level of preprogrammed preferences in terms of turning on some appliances based on the amount of the energy consumed within a day, week, or month.
  - Promote and install energy monitoring software on smartphones in case the smart meter is already installed in the house so as to allow one to read the information collected by the smart meter.
  - Install energy monitoring systems in municipal buildings for obtaining information about energy consumption, such as electricity meter, electricity ambient conditions, internal ambient conditions, and temperature.
- Environmental control and monitoring: The increasing urbanization trend contributes to environmental degradation, but, currently, the new technologies offer real-time tracking of air pollutants and the ability to implement preventive measures, with the aim to achieve healthy, zero-carbon environments by integrating urban planning, the environment, and ICT infrastructures. Environmental monitoring complements smart grid and advanced metering infrastructure strategies to control greenhouse gas emissions. Smart environmental control systems can collect crucial data for policymaking and citizen guidance to reduce emissions. According to Bibri, the key pathways needed for executing the environmental control and monitoring strategy are:

- Develop and implement more effective mechanisms to get consumers and producers to use innovative solutions to reduce GHG emissions to levels that are economically, environmentally, and socially sustainable.

- Develop and implement environmental control systems associated with energy efficiency (e.g., smart meters, smart sensors, automation devices, monitors, etc.).
- Develop and implement environmental control measures for preventing GHG emissions.
- Convert the small-scale tests performed in the areas of air pollution and noise pollution into pilot projects and then transition to large-scale deployments and implementations.
- Devise and implement solutions for control over air pollution which analyze the data collected from sensors on the level of air pollution in the different districts.
- Develop and implement different prevention systems, including monitoring, forecasting, and modelling based on artificial neural networks, i.e., computing systems inspired by biological neural networks and based on a collection of connected nodes called artificial neurons, for enhancing decision-making to remove different types of pollutants detrimental to public health.
- Facilitate the operation of the air quality monitors by regulatory agencies, citizens, as well as researchers to investigate the air quality and the effects of air pollution.
- Devise and implement solutions for noise pollution control which analyze the data collected from sensors on the level of noise pollution for planning of work to reduce it. Such solutions should enable to optimize and centralize the collection, integration, processing, and dissemination of information by the noise sensors of different suppliers and sound level meters distributed throughout the neighbourhood. The fine-grained information of noise can inform people's daily decision-making as well as policymakers on tackling noise pollution.
- Use the data recorded by the various sensors connected to the city's Wi-Fi network and reporting in real time such parameters as air quality, noise levels, temperature, humidity, and gas dust particles concentrated in particular urban environments to analyze the impacts of the measures taken to improve the state of the environment, to make inferences about the quality of the air, to compile further programs for environment protection, and to identify the areas where further actions are to be undertaken.
- Create living labs for environmental monitoring management which provide a variety of services by using sensors to measure a range of physical parameters. The active sensors recording the relative and appropriate information for the services should be spread across the different zones of the city for obtaining the accurate data for these services. Use the collected data to increase the knowledge of the most important city problems that need to be solved.
- Develop and implement an integrated automated environmental protection system in the city. The results of measurements should be published in online platforms to be visited by special software developers on a monthly basis.
- Promote easy to use and set up hardware and software for environmental monitoring systems (sensors and base units) among businesses, organizations, and institutions to:
    a. Measure and log a range of environmental conditions (e.g., relative humidity, temperature, differential pressure, pressure, flow, lux, and carbon dioxide) in real time.
    b. Track and provide early warnings in case of critical events or unfavorable conditions before they turn into disasters.
    c. Provide various solutions for environmental monitoring about server rooms, data centers, storage facilities, and laboratories to organizational and institutional units, as well as to those related to the ICT infrastructure of the city, such as horizontal information platforms, analytical centers, and operations centers.
- Commit to further developing and advancing environmental monitoring technologies and enhancing their applications in the future to guarantee a maximized effect of the use of the information collected about the state of the environment. This is due to the challenges of enacting environmental monitoring, notably the effective integration of multiple environmental data sources originating from different environmental networks and institutions. Such integration requires specialized observation equipment, tools, techniques, and models to establish air pollutant concentrations at different spatial and temporal scales.

Sensor technology is the key enabling technology of the IoT. The sensors serve as main sources for big data analytics as a computational process. In this respect, the automated approach to data generation is the most common and prominent in the context of the IoT. There are several tools associated mainly with sensors that can be employed in the automated approach to generating urban data, including:

Table 1: IoT sensors and uses

Sensor Technology	Application in IoT
GPS in vehicles and on people	Tracing and tracking travel patterns
Smart tickets	Passenger travel tracking
RFID tags (Radio-frequency identification)	Object and people tracking
Sensed data from embedded sensors	Regular communication of measurements
Capture systems	Data capture during task performance
Digital devices	Recording and communicating usage history
Digital traces	Data generation from purchasing and supply situations
Transactions and interactions	Data about digital transactions and interactions
Clickstream data	Tracking website and app navigation
Automatic meter reading (AMR)	Continuous utility usage communication
Automated monitoring of public services	Real-time monitoring of public services
Scanning of machine-readable objects	Registration and tracking of objects and parcels
Machine to machine interactions	Interactions between IoT devices
Uniquely indexical objects and machines	Automatic work and traceability of IoT devices
Transponders	Vehicle and traffic flow monitoring

Source: own elaboration

The automated approach is associated with various automatic functions of the devices and systems that are widely deployed across urban environments. Indeed, there has been increased interest in the IoT and especially its sensor network with respect to monitoring the operation and condition of urban and public infrastructure, such as energy systems, power grid systems, and environmental and green conditions. By its nature, the IoT involves different types of things (Table 2):

Table 2: Things related with IoT technologies

Type of Things	Description and Examples
Tagging Things	Radio Frequency Identification (RFID) tags and Near Field Communication (NFC) tags are attached to everyday objects and people for identification and tracking purposes.
Sensing Things	Sensors act as devices to collect data from the physical world and transmit it to the virtual world. Examples include temperature sensors, motion sensors, and environmental sensors.
Thinking Things	Smart things have the ability to process information, make independent decisions, self-configure, self-regulate, and self-repair. These devices can act autonomously based on the data they collect and analyze.

Miniaturized Things	Sensing and computing devices based on Micro-Electro-Mechanical Systems (MEMS) or Nano-Electro-Mechanical Systems (NEMS). These devices are incredibly small, virtually invisible, and can be embedded in everyday objects to enable interaction and connectivity within smart things. Micro-engineering and nanotechnology enable their miniaturization.

Source: own elaboration

The IoT involves all kinds of objects, including individuals, road traffic, parking, public transit, street lighting, buildings, water systems, energy systems, distribution networks, vehicles, appliances, and air. These objects entail devices with intelligence, communication, sensory, and actuation capabilities related to such applications as machine–to–machine, vehicle–to–vehicle, and people–to–things applications.

3.1 Practices for the analysis of the measurement

There is great potential for smart meter data to deliver public interest benefits and in doing so contribute to equity in energy transitions through promoting the accrual of benefits to collective rather than solely individual or commercial interests.

In this sense, the pursuit of mastering the complexity of the data mining process obtained from Big Data technologies on the basis of the IoT, requires building an entirely new holistic system for big data analytics based on linking the built environment (including, forms, energy system, water system, waste system, etc.) and the infrastructure passing into and out of urban areas (i.e. transportation systems, communication systems, and distribution networks) to its operational functioning, management, and planning. This is necessary for facilitating the implementation of urban intelligence and planning functions directed towards advancing and maintaining the contribution of smart sustainable cities to environmental sustainability through continuously optimizing and enhancing the operations, functions, services, designs, strategies, and policies associated with energy as an urban system and domain. The entire analytical process able to create the needed knowledge services for enhanced decision–making and deep insights should be expressible within systems which support the following:

Table 3: Needed knowledge services for enhanced decision–making

Analytical Process Stage	Description
Data Acquisition	Acquiring data from multiple distributed sources, primarily through automatic and routine sensing of data.
Data Stream Management	Managing data streams to handle continuous and real-time data flow efficiently.
Data Integration	Integrating heterogeneous data from various sources into a coherent database.
Data Transformation and Preparation	Transforming and preparing data for further analysis and processing.
Data Mining and Network Analytics	Distributing data mining and network analytics for pattern and model extraction.
Model and Pattern Organization	Organizing the extracted models and patterns for efficient retrieval and usage.
Model and Pattern Formation	Forming patterns and models based on the analyzed data.
Model and Pattern Quality Evaluation	Evaluating the quality of the extracted models and patterns.
Visualization and Exploration	Visualizing and exploring behavioural patterns and models for better understanding.

Simulation and Prediction Methods	Building simulation and prediction methods based on the mined patterns and models.
Deployment for Intelligent Decision Support	Deploying the obtained results to provide intelligent decision support to users.

Source: own elaboration

The multifaceted potential of the smart city approach as enabled by ICT has been under investigation by the UN through their study on "Big Data and the 2030 Agenda for Sustainable Development" [6]. Currently, urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired world generates and analyzes overwhelming and incredible amounts of data. The datafication of spatiotemporal citywide events has become a salient factor for the practice of smart sustainable urbanism.

At the heart of such urbanism is a computational understanding of city systems and processes that reduces urban life to logical and algorithmic rules and procedures, while also harnessing urban big data to provide a more holistic and integrated view or synoptic intelligence of the city. In this context, big data computing is an emerging paradigm of data science, which is of multidimensional data mining for scientific discovery over large-scale infrastructure. Data mining/knowledge discovery and decision-making from voluminous, varied, real-time, exhaustive, fine-grained, indexical, dynamic, flexible, evolvable, relational data is a daunting challenge/task in terms of storage, management, organization, processing, analysis, interpretation, evaluation, modelling, and simulation, as well as in terms of the visualization and deployment of the obtained results for different purposes. Big data computing amalgamates, as underpinning technologies, large-scale computation, new data-intensive techniques and algorithms, and advanced mathematical models to build and perform data analytics.

The broad availability of urban data is pushing research in the technologies of big data analytics, towards realizing and implementing urban intelligence functions and related simulation models and optimization and prediction methods. In this sense, not all data are equally generated, and their variety is associated with the purpose of their use, among others. There are opportunistic data which are collected for one purpose and then used for another, e.g., data owned by cell phone companies to run their operations but used by transport companies to better understand urban mobility. User-generated data result from the engagement of citizens, e.g., data from social media platforms which provide valuable information to better understand today's cities. Purposely sensed data, e.g., automated data, reflect the power of ubiquitous urban sensors that can be deployed ad hoc in public and private spaces to better understand some aspects of urban life and dynamics.

The range of the emerging big data applications as novel analytical and practical solutions that can be utilized is potentially huge, as many as the case situations where big data analytics may be of relevance to enhance some sort of decision or insight in connection with urban systems and domains. In the sequel, the most common big data applications are identified and enumerated in relation to the key systems and domains of smart sustainable cities, and their sustainability effects are elucidated, which are associated with the underlying functionalities pertaining to urban operations, functions, services, designs, strategies, and policies in the context of such cities, as illustrated in the following Tables (Table 4 - Table 9).

Table 4: Key analytical and practical applications of big data technology for Transport Domain

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Transport	Monitoring and analyzing road conditions and traffic jams to detect accidents early on and then quickly responding to them by providing alerts and road assistance, thereby reducing or avoiding them and ensuring safety to drivers
	Controlling traffic flow and predicting traffic conditions with the aim to reduce roads' congestion by opening new roads and directing vehicles to alternative ones, thereby improving traffic patterns as well as enhancing or re-engineering transport infrastructure on the basis of historical congestion data

	Using open-source frameworks to implement large-scale agent-based simulation models where different scenarios can be supported by these models, such as air pollution from traffic
	Explaining why traffic significantly varies from 1 hour or day to another even if demand profiles are similar, and how and the extent to which this may affect energy consumption patterns and concomitant GHG emissions levels accordingly
	Predicting spatiotemporally the development and propagation of traffic congestion with small errors, and explaining how the severity of these effects can be stronger in case of non-recurrent events (e.g. accidents), as well as how this can affect the productivity and resilience of transportation systems
	Helping to understand whether or the extent to which the real urban traffic can be considered an equilibrium system, equilibrium conditions with small variations, with respect to cost functions as well as how people really make choices in transportation networks for long periods and how these choices affect the development and propagation of traffic congestion in such networks
	Providing effective ways to identify the macroscopic observables and control parameters that are of influence on individual decisions and integrating them in agent-based simulation models, based on the large number and variety of trajectories and disaggregated traffic data in different locations and of different sizes
	Modelling the traffic evolution under strong or significant changes of network topologies
	Calculating and analyzing the costs and environmental impacts of the transportation choices or decisions of people, combining all modes of transit
	Interconnecting various components of transportation systems (vehicles, infrastructure, drivers, roads, networks, parking spaces, etc.) for enhancing the control, management, and optimization of different processes (in relation to, for example, energy efficiency, GHG emissions, land use, etc.)
	Providing location-based services related to on-board navigation systems, which allows effective use of existing transport infrastructure and network and thus cost- and time efficient routes. This in turn minimizes traffic congestion
	Addressing equity and inclusion issues in urban transport using smartphone apps and thus playing a key role in creating and mainstreaming socially sustainable urban transport
	Providing proximity-based services showing information when passengers really need it and thereby enabling them to choose different modes of transport in real time
	Enhancing transportation system efficiency by influencing personal travel behaviour decisions using advanced platforms and smartphone apps.
	Providing visibility into transit system performance based on cloud-based solution, and helping cities make better decisions about transportation by combining big data and spatial analytics
	Advanced parking allows efficient management of multiple parking spaces using and integrating sensors, as well as access to real-time and historical data and making optimal use of parking resources
	Gathering, integrating, and delivering the data on parking spaces by combining Wi-Fi infrastructure with IP cameras, sensors, and smartphone apps, and then providing visibility into parking analytics, including usage and vacancy periods, which can help with long-term city planning

	Enabling an integrated solution to the parking search problems, a location-based smart application which monitors and controls sensors deployed on the curb-side, and communicates the information in real time to the driver

Table 5: Key analytical and practical applications of big data technology for Mobility Domain

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Mobility	Finding answers to many challenging analytical questions about travel or mobility behaviour, such as: What is the spatiotemporal distribution of individual travel following the most popular itineraries? How do individual behave when approaching a key attractor, such as a central station and airport? How can we predict areas of dense traffic in the near future? How can we predict travel behaviour in mixed-land use areas across spatial and over different temporal scales? How can we classify mobility behaviour in high density areas? How can we classify travel behaviour according to some contextual variables (e.g. spatiotemporal setting)? How can we predict areas of frequent cycling and walking mode in the near future? How can we find useful travel behaviour categories or collective mobility patterns? How can we find correlation between mobility modes and environmental and life quality indicators?
	Explaining how travel behaviour or mobility mode is related to the network topology, and small or large perturbations in demand profiles and network characteristics affect the choices of individuals concerning routes, modes, and departure times
	Explaining how urban design features and related planning tools affect the choices of people in terms of travel mode, behaviour, and route, and how this in turn affects social structures and economic networks
	Gathering, integrating, and analyzing real-time mobility data and data from large-scale datasets that can simultaneously record and calibrate dynamical traces of individual and collective mobile movements across various spatial scales and over different temporal scales to understand the dynamic interplay between individual and collective mobility and social interactions
	Using big mobility data to scrutinise different spatiotemporal patterns together with the intensity and frequency of social interactions as well as social structures, thereby coupling mobility patterns and social networks, which can edge towards understanding and studying the evolutionary dynamics of cities as social spheres and their evolving borders
	Analyzing travel behaviour and mobility modes together with transport systems and networks for discovering patterns, making correlations, and then acting upon the results by deploying them across different decision support systems
	Enabling new business models such as Mobility-as-a-Service, such as car sharing, bike sharing, and driver service (as well as premium parking and city parking)
	Enabling local authorities to monitor and respond to mobility in real-time manner
	Improving the different aspects of physical and virtual mobility for effective spatial and non-spatial accessibility to opportunities, services, and facilities

	Enabling complex knowledge discovery processes from the raw data of individual trajectories up to high-level collective mobility knowledge, capable of supporting the decisions of mobility and transportation administrators in relation to different aspects of sustainability
	Advancing the content of social media to extract useful information that might be linked to new schemes for mobility management. Social media data will come on stream that is likely to be more focussed as social media technology becomes widespread
	Allowing seamless, efficient, and flexible travel across various modes, i.e., multi-modal transport system. For example, a multimodal trip planner allows users to schedule transit, travel, and map information, and gives detailed step-by-step directions alongside interactive route maps and also details of public transport services required and transfer information
	Providing hassle-free usage of multiple modes of shared and public transport
	Enabling citizens to spend less time in traffic and more time for important things in life, to have flexibility to use the best-fitting transport mode, to enjoy safer and sustainable transport system, and to benefit from lower costs, as well as allowing cities to reduce or optimize the use of land resources

Table 6: Key analytical and practical applications of big data technology for Energy and Power Grid Domains

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Energy	Finding answers to several analytical questions about energy usage levels and consumption patterns, such as: How can we predict energy consumption increase and decrease in the near future? How can we predict or characterize urban energy usage in dense and/or mixed-land use areas? How can we predict or characterize household energy consumption? How can we predict GHG emissions and their environmental impacts in the near future? How can we predict urban energy usage over different temporal scales?
	Allowing citizens to have access to live energy prices and to adjust their use accordingly
	Enabling the use of pricing plans in accordance with energy demand and supply models
	Reorganizing energy demand and supply using advanced pricing and billing mechanisms, based on the energy market and production
	Providing incentives to the users and consumers that save energy, and creating other incentives to use renewable or carbon-neutral energy at a certain time by offering a better price for electricity on a windy or sunny d
	Self-optimizing and -controlling energy consumption through integrating sensing and actuation systems in relation to different kinds of appliances and devices for balancing power generation and usage
	Enabling distributed energy systems to become self-managing and self-sustaining, as well as services in the energy market to become dynamically reorganized and coordinated
	Enabling new mechanisms for trade on the basis of supply and demand in the energy market

	Allowing consumers to manage their usage based on what they actually need and afford
	Enabling users to remotely control their home appliances and devices based on the IoT, and providing them with advanced functions like scheduling, programming, and reacting to different contextual situations
	Controlling millions of connected distributed energy resources across the Internet using demand response optimization and management systems
	Allowing users and consumers to precisely estimate rooftop solar electric potential (PV panels) for almost every building by a simple click or by inputting an address using an interactive online rooftop solar mapping tool
	Enabling energy systems to gather and act on near real-time data on power demand, generation, and consumption from end-user connections (information about producers and consumers' behaviour)
Power grid	Supporting decision-making pertaining to the generation and supply of power in line with the actual demand of citizens and other city constituents to optimize energy efficiency and thus achieve energy savings
	Optimizing power distribution networks associated with energy demand and supply
	Monitoring and analyzing energy consumption and GHG emissions levels in real time across several spatial scales and over different temporal scales, with the purpose to curb energy usage and thus mitigate environmental impacts, as well as enhancing the performance and effectiveness of the power system
	Managing distribution automation devices to improve the efficiency, reliability, and sustainability of power production and distribution
	Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times
	Avoiding the expensive and carbon-intensive peaks in power grid using new ways of coordination with regard to the overall ensemble of users and consumers and provide dynamic pricing schemes
	Enabling power distribution based on a community or neighbourhood model instead of a broadcasting model
	Improving coordination and planning around power generation from renewable energy plants depending on wind or sun, as good estimations of power generation from wind, solar panels, and photovoltaic plants can be made in advance

Table 7: Key analytical and practical applications of big data technology for Environment, Buildings and Infrastructure Domains

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Environment	Improving the environment through increasing air quality and reducing noise pollution and GHG emissions by deploying and setting up stations across the city as well as mounting sensors on bike wheels and cars for measuring and analyzing air data and acting upon the obtained results
	Providing information about air quality extracted from cities' preexisting environmental monitoring networks using Web applications, a rapid and effective technological answer to the needs of people with special sensitivity to environmental allergies

	Connecting data, citizens, and knowledge to serve as a node for building open indicators and distributed tools, and thereafter the collective construction of the city for its own inhabitants, using an open-source platform for crowd-sourced environmental monitoring
	Predicting future environmental changes based on spatial and temporal geographic maps, and detecting natural disasters to save lives and resources
	Removing many types of pollutants detrimental to the public health through pervasive sensors deployed for detecting pollution in the air and water systems
	Monitoring the urban climate and analyzing related data to discover the origins of GHG emissions, as well as measuring and monetising cities' CO2 emissions by combining satellites and ground sensors' data
Buildings	Monitoring and optimizing the operational energy use within residential, industrial, public, and commercial buildings by means of an integrated system of sensors and actuators associated with the mechanical, electrical, and electronic systems of heating, ventilation, and air-conditioning (HVAC). This can even be more effective if implemented across several spatial scales and over different time spans
	Monitoring and managing the environmental conditions in buildings as well as demand control ventilation and control temperature, in addition to the energy system performance
	Minimizing heat/cooling losses and monitoring CO2 emission levels
	Managing window and door operations and providing lighting based on occupancy schedules
	Allowing the digital and physical objects in buildings to, based on a sensor and actuator system, process data, self-configure, and make independent decisions pertaining to their operations and functions by reacting to the physical environment
	Building energy benchmarking through visualization tools that make it possible to view energy usage for individual buildings using maps, charts, and statistics to home in on a region of interest and view energy usage
Infrastructure	Monitoring and controlling the operations and structural conditions of urban infrastructures, including roads, railway tracks, bridges, tunnels, power grids, and water systems to minimize risk, decrease cost, and ensure safety and service quality, thereby improving incident management, emergency response coordination, service efficiency, and operational costs reduction
	Allowing for scheduling repair and maintenance activities in an efficient manner by coordinating tasks between different service providers and operators of urban infrastructures and facilities
	Monitoring, managing, and enhancing waste and water systems and related distribution networks
	Relating urban infrastructures effectively to their operational functioning through control, automation, optimization, and management enabled by data analytics
	Smart waste systems designed for public spaces, which comprise modular components that enable cities to deploy waste and even compost stations that respond to the needs of each station's locations
	Increasing efficiency and transparency in waste management based on sensor solutions, through tracking container fill-levels and optimizing pickup routes, thereby reducing the environmental footprint of the waste
	Enabling a dynamic routing system for waste management using software tools and sensors to lower costs of services by building, delivering, and analyzing the most efficient routes for a fleet
	Using simulation models to estimate water supply and demand. Users can explore how water sustainability is influenced by different scenarios of regional growth, climate change impacts, drought, and water management policies

	A cloud-based platform for data-driven water demand management intended, which maximises water-use efficiency and improve financial forecasting accuracy through engaging citizens
	Smartening up urban metabolism by collecting, processing, and analyzing a large amount of data pertaining to the use of material and energy resources as well as waste generation, and then identifying and suggesting alternative routes of development that would reduce the ecological footprint of the city while ushering in new relations with the immediate surrounding lands and water

Table 8: Key analytical and practical applications of big data technology for Urban Planning and Urban Design Domains

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Urban planning	Relating the urban infrastructure to its planning through monitoring, analysis, modelling, simulation, prediction, and intelligent decision support associated with engineering, strategy development, and policy design
	Fully integrating urban systems, coordinating urban domains, and coupling urban networks to enhance land use and development, optimize resource utilization, reduce city costs, and streamline processes
	I0ntegrating urban systems in terms of operations, functions, services, strategies, and policies for more effective and efficient functioning, management, and p
	Helping cities quickly identify underperforming domains, evaluating improvement and cost-saving potential, and prioritising domains and actions for energy and performance efficiency interventions using decision-support tools
	Developing intelligence functions for the efficiency of energy systems, the improvement of transport and communication systems, the effectiveness of distribution networks, the optimal use and accessibility of facilities, and the optimization of ecosystem and human service provision
	Using urban simulation models to aid urban planners and strategists in understanding under what conditions urban systems and domains may fail to deliver or underperform at the level of sustainability and what to do about it
	Using advanced modelling and simulation systems to predict changes and forecast potential problems, and accordingly to enhance current designs, mitigate environmental impacts, and avoid public health risks
	Predicting population growth and socio-economic changes and needs and thus devising more effective strategies in terms of seamlessly integrating advanced technologies and sustainable urban design and planning principles
	Grouping, characterising, and profiling citizens in relation to sustainable lifestyles for inducing behavioural changes and improving the quality of life and well-being
	Enabling joined-up and integrated planning which allows system-wide effects to be

	tracked, understood, analysed, and built or integrated into the very designs and responses that characterize urban operations, functions, and services
	Analyzing policies and their impact and effectiveness with the aim to improve or change them according to new social and urban trends and major global shifts
	Enabling space-time convergence in planning (and design) methods based on sophisticated simulation models using computer models of various kinds that operate at various spatial scales and over different time spans as to predicting changes and understanding how cities function in connection with land use, densification, public transport, location of physical activities, and so on
	Enabling short-termism in city planning—what takes place in cities measured, evaluated, modelled, and simulated over days or months instead of years or decades
Urban design	Monitoring, analysing, and evaluating the environmental and social performance of urban sustainability strategies (typologies and design concepts) in terms of the extent to which they contribute to sustainable development goals
	Analyzing and evaluating the relationship between individual and collective mobility and environmental and socio-economic performance assumed to be achieved through urban sustainability strategies, i.e., spatial and urban proximity, contiguity, agglomeration, and/or connectivity
	Enhancing the performance and practicality of urban sustainability strategies through augmenting them with smart applications and services, or improving their integration based on different spatial scales using simulation models
	Optimizing sustainable urban design in terms of the principled set of organized and coordinated spatial patterns and structures and physical arrangements with regard to the contribution to sustainable development goals
	Informing future designs on the basis of predictive insights and forecasting capabilities enabled by the aggregated urban simulation models of different situations of urban life thanks to the recent advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium- and long-term changes
	Facilitating the application of systems thinking and complexity sciences to solve the existing wicked problems associated with sustainable urban design, such as the distribution of sustainable typologies across several spatial scales
	Allowing citizens to view the location and size of their city's trees, submit information to help tag them, and advocate for more trees in their area, based on an interactive Web application that measures cities' green spaces. This relates specifically to greening which is a key concept of sustainable urban design

Table 9: Key analytical and practical applications of big data technology for Academic research and Governance Domains

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Academic research	Overcoming the limitations of 'small data' studies associated with such data collection and analysis methods as surveys, focus groups, case studies, participatory observations, interviews, content analysis, and ethnographies, including high cost, infrequent periodicity, quick obsolescence, inaccuracy, incompleteness, as well as subjectivity and biases
	Overcoming the inherent deficiencies of limited samples of data that are tightly focused, time- and space-specific, restricted in scope and scale, and relatively expensive to generate and analyse, which affects the robustness of research results
	Drastically changing the way, the research data can be collected, processed, analysed, modelled, and simulated within various academic and scientific research domains so as to make decisions easier to judge and more fact-based in relation to urban operations, functions, strategies, plans, policies, and other practices
	Completely redefining urban problems and understanding them in new ways, as well as enabling entirely novel ways to tackle them, thereby doing more than just enhancing existing practices, especially in relation to sustainability
	Transforming and advancing knowledge based on the deluge of urban data that seeks to provide more sophisticated, wider-scale, finer-grained, real-time understanding, and control of various aspects and complexities of urbanity
	Enabling well-informed, knowledge-driven practices based on advanced forms of intelligence with regard to the operational functioning, management, design, planning, and development of urban systems in the context of sustainability
	Promoting and facilitating openness and access to public data and their integration with the private information assets for use in city analytics and big data studies to advance the knowledge about sustainability
	Advancing environmental indicators and objective targets for the purpose of monitoring progress, implementing strategies, allocating resources, and increasing the accountability of stakeholder
	Enabling novel and harmonising urban-level metrics for monitoring the goals of sustainable development through more objective and robust indicators and targets developed and continuously enhanced based on big data analytics
	Exploring and discovering laws and principles of sustainability pertaining to environmental and socio-economic aspects, and allowing an inference of stakeholders' responses to operations, functions, services, strategies, designs, and policies in relevance to sustainability
Governance	Enabling governments to establish, formulate, and implement more effective policies based on the enhanced insights (trends, shifts, lifestyles, environmental concerns, etc.) resulting from the useful knowledge that is extracted from large masses of data on citizens and their behaviour and tendencies in terms of sustainability, education, and healthcare
	Facilitating platforms for shared knowledge for ensuring democratic governance and informed participation by allowing citizens to get more involved and engaged and to blend their knowledge with that of urban experts
	Enabling widespread participation of citizens in relation to several functions of city governance and planning
	Building up e-governance tools and connecting the cooperative participation with the personal knowledge of citizens with respect to promoting environmentally friendly activities, such low-carbon mobility, sustainable travel behaviour, emission-free transport, demand-based utility, incentive-based energy usage, etc.

	Organizing and coordinating various governmental agencies with common interests towards collaboration, integration, optimization, and further development
	Enabling responsive e-government to rich, dynamic, and real-time data for efficient service delivery, enhanced interaction, and empowered citizenry, or more effective government management. This can be enabled through wireless communication networks, data processing platforms, cloud/fog computing, distributed computing, and mobile computing that have the ability to transform relations with citizens and other relevant arms of government
	Reducing corruption, enhancing transparency, providing convenience, decreasing costs, achieving equity and inclusion, and promoting citizen empowerment through advanced e-government

Table 10: Key analytical and practical applications of big data technology for Healthcare, Public safety and Education Domains

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Healthcare	Predicting epidemics, disease outbreaks, and cures, as well as preventing or avoiding preventable death
	Flagging potential health issues frequently or on a demand basis by monitoring and analyzing complex occurrences and events
	Enabling efficient healthcare systems that provide permanent monitoring, traceability of patients and their medical devices, and full accessibility of their data
	Using monitoring devices or specialized sensors to quickly detect anomalies, recognise patients' behaviours, and identify and predict changes in their normal parameters
	Enabling remote health monitoring systems by observing patients outside of conventional medical or clinical settings, thereby reducing healthcare delivery costs
	Integrating clinical devices into living spaces to enable patients to communicate health data to hospitals or medical centers using smartphone apps
	Enabling efficient emergency notification systems by facilitating the dissemination of messages to many groups of people alerting or notifying them of an extant or pending emergency situation
	Connecting medical centers, patients, and doctors with data repositories and health monitoring software tools
	Enabling doctors to detect the warning signs of serious illness during the early stage of treatment
	Facilitating rapid changes in the models of treatment delivery and many decisions behind these changes
	Using consumer devices to encourage healthy living, especially for senior or elderly citizens
	Mining DNA of citizens to discover, model, simulate, and improve health aspects
	Enabling responsive and proactive environments that allow for easy participation of citizens in their own healthcare management, as well as a remote monitoring of physical activity and well-being and e-inclusion for citizens with physical disabilities
	Mainstreaming and tailoring care services, enhancing diagnosis processes, and providing precautionary and proactive care services as well as accurate, appropriate, and history-aware responses to health issues
Public safety	Monitoring urban environments to alert citizens and informs public services of potential risks and vulnerabilities

	Contributing to risk assessment and hazard identification and providing immediate response to perceived threats
	Allowing or denying access to certain individuals to public places as well as preventing potential unrest and thereby protecting public places and citizens
	Predicting natural disasters to save lives and resources
	Enabling a data-driven approach to understanding and addressing transportation-related health issues using an online database and analytical tool to inform public and private efforts to improve transportation system safety and public health
	Tracking and predicting pollution or spread of chemicals in certain urban areas to prevent or mitigate adverse health effects by notifying citizens to evacuate or avoid those areas
Education	Improving education and learning methods in terms of efficiency, effectiveness, and richness through adaptable, personalised, flexible, and pertinent processes and ser
	Optimizing evaluation methods as to finding out whether the allocated resources are producing the right results, or the allocation is being done efficiently, as well as whether there is a need for the integration and coordination of these resources for further effectiveness, efficiency, and cost reduction
	Enhancing learning attitudes and behaviours by analyzing interactions with the different sorts of academic material and reactions to academic curriculums, and the acting upon the obtained results
	Enhancing the existing, or creating new, education and learning practices based on deep insights into emerging social trends and global shifts, extracted as a result of big data analytics
	Allowing citizens to actively engage in, and benefit from, the kind of leaning environments that are conducive to the adaptation to societal development and change in terms of new scientific paradigms, emerging intellectual transitions, discontinuities, disruptive innovations, technological advancements, and so on
	Continuously advancing knowledge production, teaching, and learning methods to deliver and disseminate the most relevant and useful forms of education with regard to current societal needs and market demands
	Reducing private education cost, providing life-long learning and education opportunities, and enabling self-learning and creative education

Source: Bibri, S.E. (2019). The anatomy of the data-driven smart sustainable city: instrumentation, datafication, computerization and related applications. Journal of Big Data, 6, 1-43.

The underlying idea of one data-driven smart sustainable city implies the process of drawing all the kinds of analytics associated with urban life into a single hub, supported by broader public and open data analytics. This involves creating a city-wide instrumented or centralized system that draws together data streams from many agencies (across city domains) for large scale analytics and then direct it to different centers and labs. Urban operating systems as part of cloud computing infrastructure explicitly link together multiple urban technologies to enable greater coordination of urban systems and domains. Urban operations centers attempt to draw together and interlink urban big data to provide integrated and holistic views and synoptic city intelligence through processing, analyzing, visualizing, and monitoring the vast deluge of urban data that is used for real-time decision-making pertaining to sustainability using big data ecosystems. Strategic planning and policy centers serve as a data analytic hub to weave together data from many diverse agencies to control, manage, regulate, and govern urban life more efficiently and effectively in relation to sustainability.

Bearing this in mind, its necessary say that there exist a range of city architectures that essentially aim to provide the appropriate infrastructure for big data systems and applications for steering urban processes and enhancing urban practices, and whose components serve to form, compose, or make up a whole. These architectures typically influence the relationship between their components and urban constituents and entities. As an example, the architecture of the data–driven smart sustainable city illustrated in Figure 1 entails specialized urban, technological, organizational, and institutional elements dedicated for improving, advancing, and maintaining the contribution of such city to the goals of sustainable development.

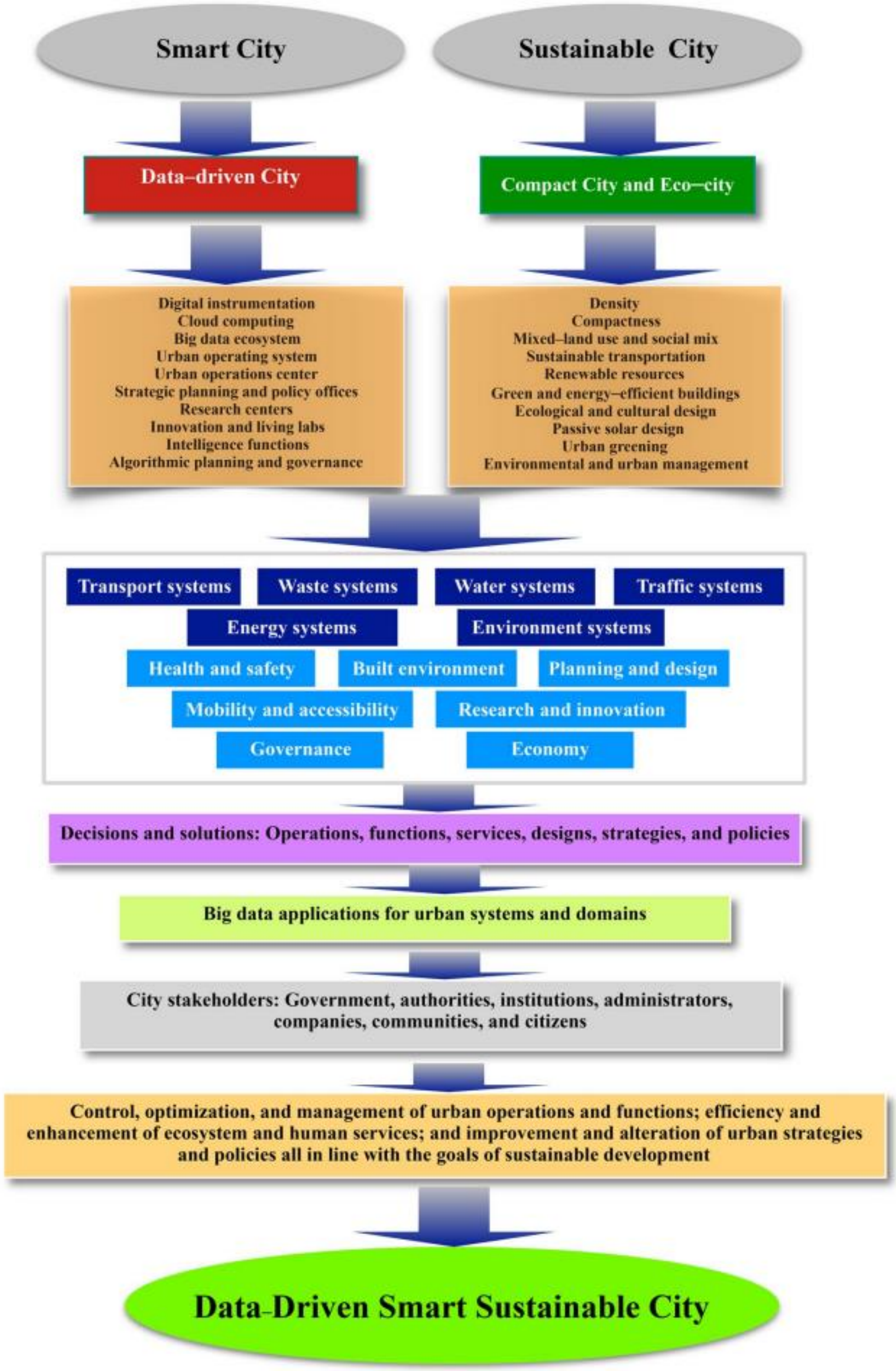


Figure 1: An architecture of Data-driven smart sustainable city

Source: Bibri, S.E. (2019). The anatomy of the data-driven smart sustainable city: instrumentation, datafication, computerization and related applications. Journal of Big Data, 6, 1-43.

The architecture of the data–driven smart sustainable city example is derived based on the outcome of the above thematic analysis and technical literature. This outcome justifies the relationship between the different layers of the architecture. It is worth pointing out that the layered approach to this architecture is motivated by the scientific literature on smart cities, sustainable cities, and smart sustainable cities. However, a layered approach is only one among other approaches to consider in this regard.

4 Digital twin practices at neighbourhood scale

This section presents a discussion aimed at identifying and describing the challenges of operating digital twins in the urban context, which are virtual models of physical assets in the cities that enable data analysis and simulations.

The term Digital Twin (DT) has been attracting significant attention in the last few years, especially in the context of the urban environment. Behind the contemporary term lies mostly what software engineers refer to as plain old data, derived from multiple sources, stitched together in various forms and ready for consumption for different needs of the end-users of the twin. On the city scale, since the DT is required to serve a variety of purposes, including multi-physics simulations [7, 8], what-if scenarios [9, 10] and life-cycle analysis [11, 12], a common groundwork for the different means of the consumption of data is of great importance; even if the digital twin needs to adapt to which data is being analysed, the common denominator is a 3D city model [13].

The initial concern to address is that, despite the increased use of the term Digital Twin, there is no common definition in use and, consequently, the term is used in inconsistent ways: as a digital replica of an asset in a BIM context, as a 3D city model, as a digital representation of the physical environment including its dynamic processes, as geospatial information infrastructure, etc. Even though a single definition of a DT in the geospatial domain is lacking, there is consensus that it should be based on 3D city models, containing objects with geometric and semantic information; it should contain real-time sensor data; and it should integrate a variety of analyses and simulations to be able to make the best design, planning and intervention decisions. To support those decisions, all information should be presented to users (citizens, decision-makers, experts) in a user-friendly visualization of the DT in a one-stop-shop dashboard.

From this perspective, neighbourhoods as an ideal scale for intervention as it provides an interface between individual residents, local authorities, policymakers and the community as a collective. It is also a practical scale to address social problems and challenges as several neighbourhood-oriented sustainability assessment tools work directly at this scale already. Finally, the nature of support is limited to digital tools that provide decision support at the early stages of the design process (See Figure 2)

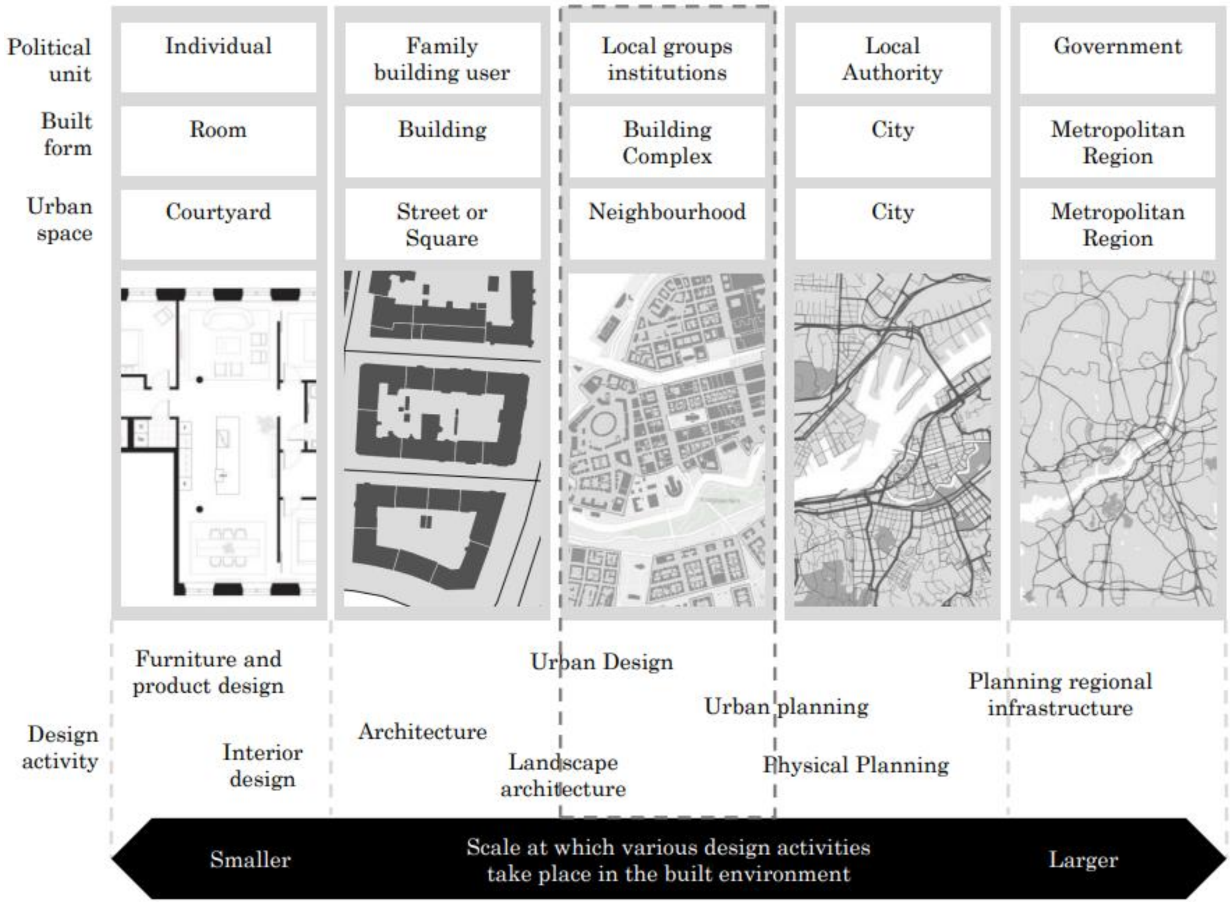


Figure 2: Scale of design activity in the built environment

Source: Somanath, adapted from Erickson and Lloyd-Jones (2001)

Digital Twins give value by supplying relevant data to simulation models. Nevertheless, DTs are extremely reliant on their use cases, leading to an extensive DT catalogue (van der Valk et al., 2021) [14]. However, a conclusive list of use cases for this accumulation of feasible DT application areas does not exist [15, 16, 17]. Simultaneously, determining the appropriate use cases for DTs could be difficult.

Beyond visualization, due to enhanced computation and storage systems, simulations and applications are being developed for both district- and city scale models [18]. Nevertheless, clarification in the classification of district-scale use cases is lacking, as use cases are predominantly considered at the component or city scale. Following a literature review made by Alva 2022 [19], use cases of Digital Twins that provide similar services to their stakeholders have evident patterns of technologies being used for their implementation will be presented.

Finally, it is worth mentioning the term Urban Social Sustainability (USS). It has been a concept with many understandings and definitions [20] and the path towards creating sustainable communities is often paved with a myriad of challenges and contesting conceptualisations [21]. Here, the definition of socially sustainable neighbourhoods of Shirazi and Keivani [22] as localities where social qualities are exercised and practised within the neighbourhood space at an acceptable and satisfactory standard is adopted. The research literature on USS suggests a strong connection between improving social qualities and aspects of the built environment. Kain et al. (2022) and Jenks and Jones (2010) [23, 24] discuss the role of densities and land use typologies of the urban form and their relationship to social qualities. The authors suggest higher densities and mixed-use urban forms lead to a higher quality of life due to an increase in social interaction and community spirit. At the same time, they point out that there are also several claims that compaction could lead to negative impacts on social qualities, such as lower access to green spaces, deteriorating health, a reduction in living space and less affordable housing. Caulfield et al. [25] identify clear connections between social factors and the environment. They state that sustainable cities are formed through the synergies between infrastructure and policies. Social infrastructures (such as schools and hospitals), public services (such as water, public transport and electricity), housing and inclusive public spaces complemented by good governance and socio-cultural policies collectively form the policy areas that lead to sustainable cities.

Given the importance of the built environment in shaping USS there are several stakeholders with varied interests, and designers can often find themselves employed by any one of them; however, they must often address the interests of those who are not necessarily their employers [26]. It is often the designer that intermediates between the intent of the decision-makers and the ones most affected by these decisions, serving the role of the glue in the multidisciplinary teams that are involved in the shaping of the built environment; they are the interpreters and facilitators of changes in the culture who then synthesise new kinds of cultural forms.

Sustainability tools in the built environment primarily focus on the environmental and sometimes economic dimension of Sustainable Development (SD) [27]. At the building scale, there are Green Building Assessment Tools such as Leadership in Energy and Environmental Design (LEED) [28], Building Research Establishment Environmental Assessment Method (BREEAM) [29], German Green Building Council (DGNB) [30] and Global Sustainability Assessment System (GSAS) [31]. Such tools often focus on the social dimension through occupant wellbeing and comfort. The WELL certification programme [32] goes one step further to assess the personal wellbeing of an occupant mentally as well as physically. Extensions of Green Building Assessment Tools such as LEED neighbourhood and BREEAM neighbourhood focus on similar dimensions of SD but at the neighbourhood level.

In some European countries, specifically Sweden and Norway, the neighbourhood scale of USS has seen direct intervention from the city and municipal bodies through the provision of social tools. In Sweden, the city of Gothenburg has developed Sociala konsekvensanalyser (social impact assessment), Barnkonsekvensanalyser (child impact assessment) and Kulturkonsekvensanalys (culture impact assessment) to evaluate the social and cultural consequences of designs. There also exist complimentary planning tools such as PRISMA [33], developed by researchers for use at the neighbourhood scale. General criticisms of these tools are the lack of transparency in the development of the tools, follow up on the results of the tool and the vague approach to dealing with stakeholder value systems[1]. To promote inclusivity and encourage citizen participation in the design process, stakeholders have increasingly used collaborative planning tools [34]. These tools provide a structure to the discourse between stakeholders involved in a design project of the neighbourhood scale.

4.1 Use cases for Digital Twins

An overview of the documented use cases for Digital Twins is summarised next. The use cases are classified into six groups—District-/City-Level Forecasting, Emergency Planning, Operational Optimisation, Participatory Planning, Policy Development, and Scenario Modelling. This classification is largely adopted from Callcut et al. (2021) and further based on the criteria and definition mentioned in the previous sections. DTs for smart cities may have more than one service provided at the same time that addresses citizen engagement or administration. Therefore, the inventory shows instances of Digital Twin projects falling into multiple groups.

- **Use case: District-/City-Level Forecasting**

A city is an intricate arrangement of numerous different actors, with a large number of jobs, connections and communications. In order to document this, the DT of a city can best be built as a biological system of single twin elements [35]. DTs at the district or city-level are sensible computerized portrayals of urban communities (counting their resources, cycles, and frameworks) that help independent direction pointed toward conveying district or city-level results (urban management, planning, and related services) and give informed decision-making capabilities [36]. Johannsen (2021) propose a framework that incorporates Digital twins of the occupants of the city, who can effectively look at and intentionally modify their digital twin through their way of behaving. They suggest that—assuming it is utilized as citizen empowerment—a DT can be used for public participation processes, not just mirroring the activities of every resident in the citywide setting yet envisioning them, permitting the clients to essentially test the impacts of their activities and conduct changes. DTs for forecasting can assist with diminishing unforeseen unfortunate results by assisting actors with better system understanding and their circumstances while the system is as of now in full activity and cannot be halted for test [37].

- **Use case: Emergency Planning**

[1] Eken, Anna, Josefine Magnusson, Anna Hildesson, Stefan Molnar, and Karl De Fine Licht (2017). "Rätt verktyg för jobbet? En översikt över verktyg för social hållbarhetsanalys i städer". In: Mistra Urban Futures Report (cit. on pp. 17, 36).

Digital Twins for Emergency Planning aim to serve towards designing and preparing immediate responses or exit strategies for catastrophic incidents. The incidents that may involve natural disasters, healthcare threats, security hazards, or such dangerous situations for communities. Several attempts have been made to establish smart city DTs through the use of precise BIM and big data [38]. Despite being useful in several domains such as urban planning and built environment, researchers lack emphasis on details of emergencies or disasters, and the current investigations have shown an absence of consideration regarding catastrophe or emergency related viewpoints concerning the components referenced previously [39].

- **Use case: Operational Optimisation**

Digital Twins for Operational Optimisation has advanced towards performance management of operations which is both practical and efficient for various urban systems and resources such as urban mobility, energy, environment, communication, building, and infrastructure. Ni (2021) offer a digitalization framework for historic structures that incorporate IoT, cloud computing, and AI [40]. Their research uses DTs to preserve, anticipate, and optimize specified aspects using real-time and historical data analytics. Sensors or other data sources are used in historic buildings to capture heterogeneous data such as energy usage metering, indoor environment and outside temperature. The data is then periodically uploaded and kept in the cloud platform's database. These data are used to train AI models for monitoring historic buildings, estimating energy usage, and autonomously regulating energy-consuming equipment in order to achieve human comfort, building conservation, and energy efficiency balance.

- **Use case: Participatory Planning**

Increasingly, the physical world and the digital world overlap through various digital platforms such as IoT, VR, AR, machine learning, and natural language processing. This has prompted designers to conceptualise the need to integrate dashboards and platforms from multiple smart city platforms into one system. Only through the creation of a shared ontology of the city can this task be accomplished, making it possible for the different data systems to communicate with each other. Digital Twins, also, need to consider aspects such as inclusivity and citizen participation when extending the concept into complex cultural and social entities like cities [41].

As examples, Matthys (2021) demonstrate the importance of gamification of DTs for public participation with the help of the "3D city game Ghent" project, launched by the city of Ghent (Belgium) in 2016, and Xu (2019) developed a 3D immersive VR driven eco feedback system that allows facility managers and occupants to interact with real-time data about energy consumption [42, 43]. The first model uses the gamification to motivate cooperation creativity, and thinking about spatial development and could also serve Smart Cities as a crowdsourcing strategy to enrich datasets. In second place, a detailed back-end and front-end design and development of the VR-integrated eco-feedback system is presented. Authors claim their research approach, if implemented widely in cities, may promote energy-conscious behaviours among its residents and facilitate timely interventions to achieve energy savings.

- **Use case: Policy Development**

Considering upcoming technological, business model, and spatial-temporal changes that innovations will bring, policymakers should be prepared with tools suitable to execute dependable, timely analyses, and comprehensive scenarios of urban logistics. Marcucci et al. (2020) explain the Digital Twin concept, outlining its potential for urban freight transport policymaking and planning and clarifying how it should be conceptualized [44]. They recommend that DTs in a Living Lab approach could be characterized using both behavioural and simulation models at the same time. This helps to stimulate planning processes that are well-informed, effective, and participatory, and, consequently, to predict behaviour and reaction both to structural changes and policy measures implementations.

Papyshev and Yarime (2021) explore the DT technology potential for simulating policy interventions. In the DT models, simulations of the activities of individuals in urban environments are often based on historical data, which means they cannot predict things based on data that is not available and may present certain privacy concerns [45]. They propose that an expected solution to these difficulties is synthetic data. They widen the concept of data creation towards synthetically human-generated artificial data which imitates the actual data replacing the machine-generated data. Due to the fact that no real individual in society will be represented by the data generated through this method, it will not cause legal or privacy concerns. Accordingly, a synthetic population can be created for the DT to illustrate realistic behavioural responses to hypothetical policy interventions.

In other hand, Jouan and Hallot (2020) advocate the application of DT principles, as a digital replica using Heritage BIM models for preventive conservation of heritage places [46]. They emphasise a value assessment process for conservation based on the identification of tangible features of significance, threats and the corresponding mitigation strategies. An information structure on preventive conservation strategies is the result of the data model. In the context of policy development, this framework demonstrates the need for a DT approach and sets a foundation for future implementation.

- **Use case: Scenario Modelling**

DTs for Scenario Modelling explore design options and analysis through realistic modeling of a real-world problem for virtual testing. For instance, comprehensive datasets and statistical leverage required to analyse scenario space for high-dimensional traffic, particularly safety assessment and "stress testing" of automated driving functions, can be created by virtual trials or scenario modelling. According to Brunner et al. (2019), several facets of a realistic scenarios are (i) stochastic and probabilistic nature of processes, (ii) human factors, (iii) edge cases and outliers, and (iv) technology limitations.

In this state-of-the-art review, the use cases of UDT platforms and applications were documented. This includes the listing and analysis of several UDT use cases which represent the interactions between a system and its stakeholders. The focus is on district-scale UDT applications that model, manage, and analyse buildings, transportation, energy, water, utility, and infrastructures that form a city. The documented UDT use cases are classified into six groups—District-/City-Level Forecasting, Emergency Planning, Operational Optimization, Participatory Planning, Policy Development, and Scenario Modelling. Two groups, Emergency Planning and Policy Development, have the least amount of UDT use cases developed and lead to future research work on UDTs for Emergency Planning and Resilience.

It is important to be pointed out that technology applied in digital twins is a means rather than an end. The building of digital twins aims to solve urban issues and plan a liveable city for people. The initial notion may be blurred by a purely technology-driven approach; however, the identification of the practical value of digital twins is crucial in this context. Therefore, a combination of social and legal perspectives to complement the technical dimension and offer a more complete understanding of digital twins is deemed necessary.
In this sense, a study conducted by Lei in 2023 was taken to delve into the non-technical issues faced by digital twins. The author conducted research based on a literature review and a survey using the Delphi method, in which 52 experts from 23 countries participated, with the majority working in Europe [47]. Of these experts, 14 are from industry, 12 from government, and the remaining 23 experts work in universities or research institutes. Furthermore, 44.2% of the respondents have been working for over 20 years in domains related to digital twins. The Delphi survey had 3 rounds, asking experts to list and rank the challenges for their organizations regarding digital twins in urban and geospatial fields. In the final round, participants were asked to rate the challenges identified by severity. This round tends to reflect to what extent these challenges have hindered the functioning of digital twins. In the pursuit of quantitative evaluation, the Likert scale was adopted to measure the degree of severity with 5 points: 1 - Insignificant, 2 - Minor, 3 - Moderate, 4 - Major, 5 - Severe. Figure 3 shows the results of the Delphi Method

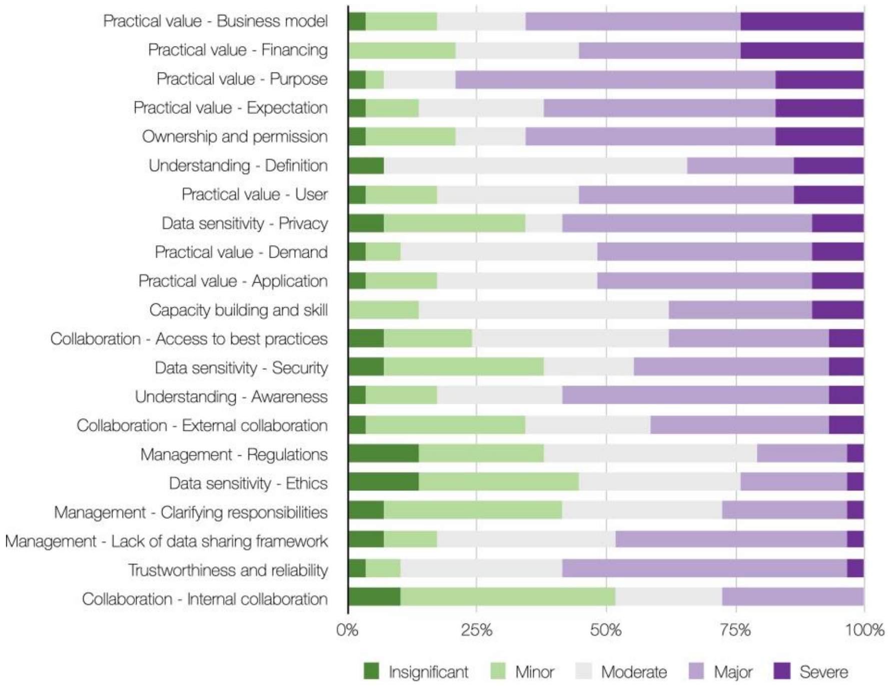


Figure 3: Non-technical issues related with Digital Twins

Source: Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. Automation in Construction, 147, 104716.

The results show that challenges from social and legal perspectives are considered more severely. It is noted that challenges around the category of practical value receive more attention than others. The business model and financing are identified as the most severe barriers with a rating of 7 by participants, indicating the highest degree of severity. A part of 79.3% of the experts suggests that the purpose of digital twins is a more than important problem that requires further clarification. Some issues are concluded with less severity. For example, 13.8% of participants rate the regulations with insignificant severity, while 41.4% consider it a moderate challenge based on their experience. Additionally, the survey reveals that over 59% of participants believe that the definition of digital twins is a moderate barrier. However, compared to our research work review results, the majority identifies the lack of definition as a significant challenge. Such a case reflects a different approach between academia and industry.

Although current research has defined urban digital twins in many ways, widely varied definitions may generate different situation awareness on this topic. Such ambiguity will pose problems when practitioners start a practical project on urban digital twins without a consensus on what a digital twin should be. Similarly, many panellists consider the practical values of urban digital twins as the main issues. e.g., who the end-users are, their demands, and the purposes of urban digital twins. In general, the needs of urban digital twins vary in different cases. For example, in transport studies, urban digital twins can manage nearly real-time traffic information and plan accessible areas for passengers. Urban digital twins can also be applied to simulate e.g., the impact of construction projects on the urban environment in the scope of city planning. Therefore, rather than dive directly into practical applications of urban digital twins, it is important to have a deep discussion with practitioners to define the understanding, the purpose and the demands, tracing back to the origin [48].

5 Operational assessment indicators at neighbourhood level

SmartLiving EPC aims to enhance the assessment of neighbourhood energy performance by introducing an indicator-rich certification scheme. Under this framework, there is a need to develop an enriched set of indicators for EPCs, providing more information to the neighbourhood inhabitants regarding the actual performance of their buildings and open spaces, and enabling to policymakers to take informed decisions to improve their behaviour. This goes beyond mere energy consumption calculations, focusing on the smart-readiness of a district's infrastructure, including assessing buildings' smartness and sustainability through life cycle approaches, as well as defining the thermal and human comfort conditions within the building. Table 5 presents a taxonomy of indicators for operational assessment of neighbourhood energy and non-energy parameters.

Table 11: Preliminary taxonomy of Operational Assess Rating Indicators

Dimension	Cathegory	Indicator	Use	Energy	Social	LCA	LCC
Environmental	Neighbourhood Services	Urban Conditioning (District heating and cooling)	% of population using renewable and efficient urban heating/cooling systems	Annual energy used for heating/cooling (kWh/(km2 · hab))	Days a year with temperatures near to historical maximums and minumus Thermal confort	Annual emissions intensity of heating/cooling (tCO2e/(km2 · hab))	Annual costs of urban heating/cooling (EUR/(km2 · hab))
		Domestic Hot Water	% of population using renewable and efficient DHW systems	Annual energy used for HW (kWh/(km2 · hab))	% of temperature variation between the neighborhood and outskirts Thermal confort	Annual emissions intensity of DHW (tCO2e/(km2 · hab))	Annual costs of urban DHW (EUR/(km2 · hab))
		Illumination	% of population that use street illumination of at least Eh 20 lux	Annual energy used for the street lighting network (kWh/(km2 · hab))	Light Pollution Index Unified Glare Rating (UGR) Visual Confort	Annual emissions produced by the street lighting and lighting urban assets (tCO2e/(km2 · hab))	Annual costs produced by the street lighting (EUR/(km2 · hab))
		Water distribution	% of population using water systems	Annual energy used to provide water (kWh/(km2 · hab))	Water Poverty Index Water Quality Index	Annual emissions produced to provide the water consumption (tCO2e/(km2 · hab))	Annual costs produced to provide the water consumption (EUR/(km2 · hab))
		Sewage	% of population connected to a water treatment plants with energy and material recovery	Annual energy used for the water treatment plants (kWh/(km2 · hab))	% of population connected to a water treatment plant Ecological Risk Index	Annual emissions intensity of the water treatment plants (tCO2e/(km2 · hab))	Annual costs of the water treatment plants (EUR/(km2 · hab))
		Service Station (fuels)	% of population that use service station / EV charging points	Annual energy used to keep service stations/charging points in operation (kWh/(km2 · hab))	Charging Infrastructure Index	Annual emissions produced by the transport needs (tCO2e/(km2 · hab))	Annual costs produced by the transport needs (EUR/(km2 · hab))
		Electricity distribution	% of population using renewable	Annual energy used to supply	Annual percentage of hours of	Annual electricity	Annual electricity (EUR/(km2 · hab))

			and efficient electrical systems	and distribute electricity (kWh/(km2 · hab))	electricity provision Global infrastructure index (GINF)	intensity (tCO2e / (km2 · hab) or (km2 · hab))	
		Telecommunication services	% of population that use 5G network	Annual energy used to keep the telecommunication system (kWh/(km2 · hab))	Annual percentage of hours of service provision Telecommunication Infrastructure Index	Annual emissions produced by the telecommunication system (tCO2e/(km2 · hab))	Annual costs produced by the telecommunication system (EUR/(km2 · hab))
		Solid waste management	% of population using renewable and efficient urban noise insulation systems (green walls)	Annual energy used for the waste collection system (kWh/(km2 · hab))	Ecological Risk Index	Annual emissions produced by the waste collection system (tCO2e/(km2 · hab))	Annual costs produced by the waste collection system (EUR/(km2 · hab))
	Urban Comfort	Heat Island	% of population using extra energy to cooling due the excess of temperature	Annual of excess or defect energy used for heating/cooling due to the process of a heating island (kWh/(km2 · hab))	Days a year with temperatures near to historical maximums Thermal Confort	Annual of excess or defect emissions produced by the heating/cooling due to the heating island (tCO2e/(km2 · hab))	Annual cost for excess or defect energy intensity of heating/cooling due to the process of a heating island (EUR/(km2 · hab))
		Air quality	% of population using extra energy to filtering due low air quality index	Annual energy used for ventilation (kWh/(km2 · hab))	Year Average Common Air Quality Index Moran Index (MI)	Annual emissions intensity produced by purified air blowing (tCO2e/(km2 · hab))	Annual costs produced by purified air blowing (EUR/(km2 · hab))
		Noise	% of population that uses additional energy to noise insulating due to high ambient noise	Annual energy used for noise insulation (kWh/(km2 · hab))	Year averange common City Noise-Air index	Annual emissions intensity of noise insulation systems (tCO2e/(km2 · hab))	Costs of noise insulation systems (EUR/(km2 · hab))
	Energy	Energy Generation	% of population that uses local renewable energy generation services	Annual maximum use of the energy generation (kWh/(km2 · hab))	Self consumption (%) Thail Index Power Quality Index	Annual maximum emissions produced by the generation intensity (tCO2e/(km2 · hab))	Annual maximum costs produced by the generation (EUR/(km2 · hab))
		Energy Storage	% of population that uses energy energy storage / local balancing services	Annual maximum use of the energy cumulative (kWh/(km2 · hab))	Autarky rate (%) Thail Index Power Quality Index	Annual maximum emissions produced by the cumulative intensity (tCO2e/(km2 · hab))	Annual maximum costs produced by the cumulative (EUR/(km2 · hab))
Social	Urban mobility	Public Transport	% of population that uses a public transport stop that is less than 500m away	Annual energy consumption of the public transport use (kWh/(km2 · hab))	% of population with 500 m of a public transport stop Transport	Annual emissions produced by the transport needs of the population	Annual costs produced by the transport needs of the population (EUR/(km2 · hab))

					sustainability index Walkability Index	(tCO2e/(km2 · hab))	
		Private Transport	% of population that uses a public or private car park that is less than 500m away	Annual energy consumption of the public transport use (kWh/(km2 · hab))	Precense of Low Emission Zone in the district	Annual emissions produced by the transport needs of the population (tCO2e/(km2 · hab))	Annual costs produced by the transport needs of the population (EUR/(km2 · hab))
		Accesibility	% of population that frequents different points of interest in the urban area, less than 500m	Average energy consumption (kWh) to reach specific places based on the frequency of visits to those places	15-Minute City Index Walkability index	Average emissions produced (tCO2e) taken by the population to reach to specific places	Average costs produced (EUR) taken by the population to reach to specific places (Recreational and cultural spaces, Educational, Health, Shopping, Public administration, Financial infrastructure)
	Economics	Logistics	% of population that requires loading and unloading of goods transported within a radius of 500 m distance	Annual energy consumption of logistic services in the neighbourhood (kWh/(km2 · hab))	MSCI Circular Economy Index	Annual emissions produced by logistic services in the neighbourhood (tCO2e/(km2 · hab))	Annual costs produced by logistic services in the neighbourhood (EUR/ton)
		Real-life conditions	% of population within the AROPE rate	Energy consumption of buildings and urban areas, associated with behaviors linked to sociodemographic and quality of life variables (kWh/(km2 · inhab))	AROPE indicator (At risk of poverty and/or exclusion)	Emissions produced by buildings and urban areas, associated with socio-demographic and quality of life variables (tCO2e/(km2 · hab))	Costs produced by buildings and urban areas, associated with socio - demographic and quality of life variables (EUR/(km2 · hab))
Institutional	Urban Plannig	Urban Density	% of population that moves in areas of 50,000 inhabitants/km2	Use of solar heat gains/energy savings (kWh/(km2 · hab))	Human density index (HDI) Population density index (PDI)	Annual emissions saved by the use of solar heat gains (tCO2e/(km2 · hab))	Annual costs saved by the use of solar heat gains (EUR/(km2 · hab))
	Green Areas	Urban green spaces / forests	% of population that uses or frequents green spaces and urban forests	Annual energy consumption to manage the urban green space / forest (kWh/(km2 · hab))	Vegetation index Normalized Difference Vegetation Index (NDVI)	Annual water and emissions produced to manage green spaces (tCO2e/(km2 · hab))	Annual water and costs produced to manage green spaces (EUR/(km2 · hab))
		Urban agriculture	% of population that uses or frequents places for urban agriculture	Annual energy consumption to manage the urban green space / forest (kWh/(km2 · hab))	Vegetation index Normalized Difference Vegetation Index (NDVI)	Annual water and emissions produced to manage green spaces (tCO2e/(km2 · hab))	Annual water and costs produced to manage green spaces (EUR/(km2 · hab))

Source: own elaboration

The table comprises a total of eight columns. This taxonomy is organized across three distinct scales: dimension, category, and indicator, providing a coherent framework for categorizing and comprehending the diverse elements depicted in the table. The subsequent columns show the conceptual definitions of each indicator, taking into account five unique analytical perspectives: Use, Energy, Social, Life Cycle Analisys (LCA) and Life Cycle Costing (LCC). These perspectives offer a multi-dimensional interpretation of how each indicator can be understood and evaluated within the given context. The Use perspective provide a conceptual definition of each indicator in terms of its operational use. This perspective underscores the functional of the assessed indicator. Transitioning to the Energy perspective, we explore how each indicator relates to the energy aspects of the context it addresses. This analysis aids in comprehending the indicator's energy implications. Next, the social perspective factors in the indicator's consequences on social dynamics and relationships within the context. It delves into how the indicator may influence or be influenced by social factors, offering a broader understanding of its social relevance. Finally, The LCA and LCC columns propose to analyze urban assets from the perspective of Life Cycle Analysis and Cost Cycle Analysis respectively.

The characterization of eight indicators from the table in Chapter 5 is presented below as an example. To facilitate comprehension, a standardized template was developed. This template includes the Indicator Name, Definition, and Calculation Procedure for five different aspects: Proximity, Energy, Social, Life Cycle Analysis (LCA), and Life Cycle Costing (LCC). The selected indicators are aligned with specific assets at the neighborhood scale.

Table 12: Characterization of "Burden of Poverty" Indicator

Category	**Economics: This category focuses on evaluating the overall urban services aspects of a neighborhood, which includes Logistics, Burden of Poverty and Real-life conditions**
Indicator name:	**Burden of Poverty**
Proximity (%)	Measures the percentage of the population with an overload of domestic tasks due to not being able to carry out the recommendations marked in the SmartLivingEPC.
	Calculation Procedure: Identify the buildings whose annual salary if the inhabitants is X% of the total investment cost reflected in the individual SmartLivingEPC recomendations. Divide this by the total amount of inhabitants of the neighbourhood and multiply by 100.
Energy (kWh/(km2 · hab))	This measures the amount of extra energy that is used due to not carrying out the recommendations marked in the SmartLivingEPC.
	Calculation Procedure: Identify households that cannot benefit (do not have savings, do not have access to financing) from the cost reflected in the individual SmartLivingEPC recommendations. Add the energy consumption derived from the overload of household tasks caused by the lack of access to the implementation of SLEPC recommendations. Calculate the energy savings possible to achieve by implementing the individual SmartLivingEPC recommendations for those buildings. Subtract both values and normalize the result by the neighborhood area and the total number of inhabitants.
Social (Score)	This measures the impact on the health of the population due to the overload of domestic tasks due to not being able to carry out the recommendations of SLEPC (DALYs).
	Calculation Procedure: Identify households that cannot benefit (do not have savings, do not have access to financing) from the cost reflected in the individual SmartLivingEPC recommendations. Identify the housekeeping tasks related to IAQ improvement and summer excess temperature and winter defect temperatures indicated in the individual SmartLivingEPC recommendations for those buildings and then follow the methodology indicated in [2,3 and 4] to estimate the number of DALYs lost.
Life Cycle Analysis	This indicator evaluates the environmental impacts associated with the domestic tasks carried out by households that cannot carry out the recommendations set in the

[2] https://www.sciencedirect.com/science/article/pii/S0033350623003359
[3] https://www.tandfonline.com/doi/full/10.1080/14733315.2023.2198800
[4] https://academic.oup.com/ije/article/52/3/783/6893949

(tCO2e/(km2 · hab))	SmartLivingEPC throughout their life cycle, both by area and by population, within the urban area.
	Calculation procedure: Make an inventory of households that cannot afford the cost reflected in the individual SmartLivingEPC recommendations (that do not have savings or access to financing). Evaluate the total emissions in tCO2 from extra domestic tasks during the life cycle of the homes (Te). Calculate what the amount of emissions in tCO2 from the life cycle of the homes would be if they could implement the recommendations (Ter). Obtain the value of the Cost of Inaction using Te - Ter. Finally, divide them by the product of the urban area (in square kilometers) and the population (inhabitants).
Life Cycle Costing (EUR/(km2 · hab))	This indicator evaluates the cost associated with the domestic tasks carried out by households that cannot carry out the recommendations set in the SmartLivingEPC throughout their life cycle, both by area and by population, within the urban area.
	Calculation procedure: Make an inventory of households that cannot afford the cost reflected in the individual SmartLivingEPC recommendations (that do not have savings or access to financing). Evaluate the total costs in EUR from extra domestic tasks during the life cycle of the homes (Tc). Calculate what the life cycle cost of the homes would be in EUR if they could implement the recommendations (Tcr). Obtain the value of the Cost of Inaction using Tc - Tcr. Finally, divide them by the product of the urban area (in square kilometers) and the population (inhabitants).

Table 13: Characterization of "Heat Island" Indicator

Category	**Urban Comfort: This category focuses on evaluating the overall urban services aspects of a neighborhood, which includes Heat Island, Air quality and Noise**
Indicator name:	Heat Island
Proximity (%)	This indicator measures the percentage of the population affected by the excess of temperature due to the urban heat island effect.
	Calculation Procedure: Count all the inhabitants of the neighborhood. Identify the population affected by the urban heat island effect within the analyzed area. Calculate the percentage of affected neighbors with respect to the total number of residents in the neighborhood.
Energy (kWh/(km2 · hab))	Evaluates the excess or savings in annual energy consumption due to the use of heating/cooling systems, due to the urban heat island process, measured in kWh per unit area and per capita within the urban area.
	Calculation procedure: Determine the annual energy intensity of the buildings in the neighborhood based on consumption data in kWh. Calculate, through simulation, the use of systems to maintain the interior temperature of buildings in a range of 21ºC to 24ºC and a relative humidity between 30% and 50%. Finally, calculate the difference of Energy used with mitigation measures - Energy used without mitigation measures, and divide this result by the product of the total area of the neighborhood in square kilometers (Km2) and the total number of residents of the neighborhood.
Social (Score)	Measures the impact of actions applied to maintain or improve the quality of life and health of residents living in areas affected by high temperatures caused by the urban heat island effect.
	Calculation Procedure: Identify values of frequency and severity of extreme heat episodes, incidence of respiratory, cardiovascular and cerebrovascular diseases and mortality from heat-related diseases. Assign scores or values to each parameter based on established criteria or standards. Combine these values to get an overall score. A higher score generally indicates greater negative social impact within the neighborhood.
Life Cycle Analysis (tCO2e/(km2 · hab))	This considers the annual excess or defect emissions produced by the actions for heating/cooling due to the urban heat island effect, measured in tCO2e per unit area and per capita within the urban area.

	Calculation procedure: Determine the intensity of CO2 emissions of the buildings in the neighborhood based on the life cycle analysis, in tCO2e. Simulate the manage actions to maintain the interior temperature of buildings in a range of 21ºC to 24ºC and a relative humidity between 30% and 50% and calculate emissions during the life cycle of the buildings. Finally, calculate the difference between emissions with mitigation measures - emissions without mitigation measures, and divide this result by the product of the total area of the neighborhood in square kilometers (Km2) and the total number of residents of the neighborhood.
Life Cycle Costing (EUR/(km2 · hab))	This considers the annual excess or defect costs produced by the actions for heating/cooling due to the urban heat island effect, measured in EUR per unit area and per capita within the urban area.
	Calculation procedure: Determine thecost of the buildings in the neighborhood based on the life cycle analysis, in EUR. Simulate the manage actions to maintain the interior temperature of buildings in a range of 21ºC to 24ºC and a relative humidity between 30% and 50% and calculate emissions during the life cycle costing of the buildings. Finally, calculate the difference between costs with mitigation measures - costs without mitigation measures, and divide this result by the product of the total area of the neighborhood in square kilometers (Km2) and the total number of residents of the neighborhood.

Table 14: Characterization of "Service Station (Fuels)" Indicator

Category	**Neighbourhood Services: This category focuses on evaluating the overall urban services aspects of a neighborhood, which includes Urban Conditioning, Illumination, Water distribution, Sewage, Electricity distribution, Solid waste management and others service-related systems.**
Indicator name:	Service Station (Fuels)
Proximity (%)	This indicator measures the percentage of the population that moves to a service station (of the different fuel types, including standard fuels an EV charging point) within a short distance.
	Calculation Procedure: Calculate the area of influence of a service station considering it as the maximum distance at which a vehicle can reach the service station without using more than 1% of the fuel standar tank. Next, identify the inhabitans of the buildings that have fuel loading needs and lives inside the area of influence of the service station. Finally, sum all the inhabitants of those buildings and and normilize by neighbourhood area and total number of inhabitants.
Energy (kWh/(km2 · hab))	This evaluates the annual energy consumption (excluding the energy serviced to the vehicles) of the service station or EV charging point, considering both per-unit area and per-capita energy consumption.
	Calculation Procedure: Determine the total energy consumed by the service station or EV charging point within the urban area in kWh (excluding the energy provided to the vehicles). Then divide it by the product of the urban area (in square kilometers) and the population (inhabitants).
Social (Score)	Measures the impact on the quality of life of residents who lives in the radius of influence of a service station or charging point.
	Calculation Procedure: Identify IAQ values, environmental noise, intrusive light, road safety. Assign scores or values to each parameter based on established criteria or standards. Combine these values to get an overall score. A higher score generally indicates a higher negative social impact within the neighborhood.
Life Cycle Analysis (tCO2e/(km2 · hab))	This considers the annual emissions for the use of service station or EV charging point (excluding emissions from the energy serviced to vehicles) within the urban area, accounting for both per-unit area and per-capita emissions.
	Calculation procedure: Identify the assets related to service station and EV charging point and their impact to be evaluated. Collect data on all operational inputs and outputs of the

	system throughout its life cycle. Evaluate the life cycle emissions of each service station or EV charging point in tCO2e and add them. Divide the result by the product of the urban area (in square kilometers) and the population (inhabitants).
Life Cycle Costing (EUR/(km2 · hab))	It evaluates the annual costs (excluding the cost of the energy vector serviced to the vehicles) for the use of the service station or EV charging point, considering both area and population factors, within the urban area.
	Calculation procedure: Identify the assets related to service station and EV charging point and the costs to be evaluated. Collect data on all operational inputs and outputs of the system throughout its life cycle costing. Evaluate the life cycle costing of each service station or EV charging point in EUR and add them. Divide the result by the product of the urban area (in square kilometers) and the population (inhabitants).

Table 15: Characterization of "Urban Conditioning (District Heating and Cooling)" Indicator

Category	**Neighbourhood Services: This category focuses on evaluating the overall urban services aspects of a neighborhood, which includes Urban Conditioning, Illumination, Water distribution, Sewage, Electricity distribution, Solid waste management and others service-related systems.**
Indicator name:	**Urban Conditioning (District Heating and Cooling)**
Proximity (%)	Urban conditioning measures the percentage of the population within the urban area that uses urban heating and cooling systems. Evaluate the accessibility of these systems for residents.
	Calculation Procedure: Measure the total land area of the neighborhood in square kilometers (Km2). Next, identify and calculate the land area on which urban condition services are used (including streets, equipped public transport stops, among others). Divide the total land area of urban thermal condition services by the total land area of the neighborhood and multiply the result by 100 to obtain the percentage.
Energy (kWh/(km2 · hab))	This indicator measures the annual use of heating and cooling within the neighborhood, expressed in kilowatt-hours per square kilometer per resident (kWh/(km2 · inhab)). Provides information on the efficiency of the neighborhood's urban environmental conditioning system.
	Calculation procedure: Determine the total hours of use in a year, in kilowatt-hours (kWh). Then, divide this value by the product of the total neighborhood area in square kilometers (Km2) and the total number of neighborhood residents. The result is the annual energy intensity for urban environmental conditioning in kWh per square kilometer per inhabitant.
Social (Score)	Evaluates the number of days of the year in which temperatures approach historical maximums and minimums. It indicates the need for environmental conditioning of the neighborhood to achieve recommended values of thermal comfort for residents.
	Calculation Procedure: Calculate parameters related to thermal comfort, such as air temperature, wind speed, solar radiation or thermal sensation, among others. Assign scores or values to each parameter based on established criteria or standards. Combine these scores or values to obtain an overall environmental comfort index. A higher index score generally indicates a more comfortable environment within the neighborhood.
Life Cycle Analysis (tCO2e/(km2 · hab))	This indicator evaluates the environmental impacts associated with the use of urban conditionig services in all stages of the life cycle of the district, factored by both area and population, within the urban area.
	Calculation procedure: Identify the assets related to the urban thermal conditioning service and their impact to be evaluated. Collect data on all operational inputs and outputs of the system throughout its life cycle. Evaluate the life cycle emissions of the heating and cooling system within the urban area and divide them by the product of the urban area (in square kilometers) and the population (inhabitants).

Life Cycle Costing (EUR/(km2 · hab))	This indicator evaluates the costs associated with the use of urban conditionig services in all stages of the cost cycle of the district, factored by both area and population, within the urban area.
	Calculation procedure: Identify the assets related to the urban thermal conditioning service and their costs to be evaluated. Collect data on all operational inputs and outputs of the system throughout its cost cycle. Evaluate the life cycle costing of the heating and cooling system within the urban area and divide them by the product of the urban area (in square kilometers) and the population (inhabitants).

Table 16: Characterization of "Sewage" Indicator

Category	**Neighbourhood Services: This category focuses on evaluating the overall urban services aspects of a neighborhood, which includes Urban Conditioning, Illumination, Water distribution, Sewage, Electricity distribution, Solid waste management and others service-related systems.**
Indicator name:	Sewage
Proximity (%)	This measures the percentage of the population that use the services of water treatment plants or sewage.
	Calculation Procedure: Measure the total land area of the neighborhood in square kilometers (Km2). Next, identify and calculate the area of land where the services of a water treatment or sewage plant are used. Divide the total area of sewer services by the total area of the neighborhood and multiply the result by 100 to obtain the percentage.
Energy (kWh/(km2 · hab))	This indicator evaluates the annual use of water treatment plants within the neighborhood, considering both energy consumption per unit area and per inhabitant. Provides information on the efficiency of the neighborhood's segawe system.
	Calculation Procedure: Determine the total energy consumed by the use of water treatment plants within the urban area in kilowatt-hours (kWh). Then, divide it by the product of the urban area (in square kilometers) and the population (inhabitants). The result is the annual energy intensity of the sewer network.
Social (Score)	Measures the impact on the quality of life of residents who use a water treatment plant, or who are deprived of sewage service.
	Calculation Procedure: Identify the presence or absence of a water treatment plant (WWTP) within the neighborhood. Calculate the use of each building. Defines an area of influence of 500m around the water treatment plant. Identify the buildings that are within the radius of influence. Identify the incidence of gastrointestinal, respiratory and dermatological diseases among the inhabitants of the buildings in the area of influence. Assign scores or values to each parameter based on established criteria or standards. Combine these values to get an overall score. A higher score generally indicates greater negative social impact within the neighborhood. Calculation Procedure: Identify the presence or absence of a sewer network. Identify the incidence of gastrointestinal, respiratory and dermatological diseases among inhabitants of buildings that do not have access to a sewage network. Assign scores or values to each parameter based on established criteria or standards. Combine these values to get an overall score. A higher score generally indicates greater negative social impact within the neighborhood.
Life Cycle Analysis (tCO2e/(km2 · hab))	This considers the emissions intensity for the use of water treatment plants and the sewage network, at all stages of the life cycle, accounting for both emissions per unit area and per capita, within the urban area.
	Calculation procedure: Take an inventory of the assets related to the water treatment plants and sewage network within the area of the neighbourhood and identify the impacts to be evaluated. Collect data on all operational inputs and outputs of the system throughout its life cycle. Evaluate the life cycle emissions of the water treatment plants and sewages in

	tCO2, and divide them by the product of the urban area (in square kilometers) and the population (inhabitants).
Life Cycle Costing (EUR/(km2 · hab))	It evaluates the total costs associated with the use of water treatment plants and sewages system, considering both area and population factors, within the urban area.
	Calculation procedure: Identify the assets related to the water treatment plants and sewage network within the urban area and the impacts to be evaluated. Collect data on all operational inputs and outputs of the system throughout its life cycle. Evaluate the life cycle costing of the water treatment plants and sewage net in EUR, and divide them by the product of the urban area (in square kilometers) and the population (inhabitants).

Table 17: Characterization of "Illumination" Indicator

Category	**Neighbourhood Services: This category focuses on evaluating the overall urban services aspects of a neighborhood, which includes Urban Conditioning, Illumination, Water distribution, Sewage, Electricity distribution, Solid waste management and others service-related systems.**
Indicator name:	Illumination
Proximity (%)	This indicator measures the percentage of the population that use street lighting providing more than 20 lux of illumination. It assesses the availability of adequate street lighting for the residents.
	Calculation Procedure: Measure the total land area of the neighborhood in square kilometers (Km2). Next, identify and calculate the rete of use of the urban street lighting services (including lighting of the roads, traffic lights, luminous ads, among others). Divide the total land area of street lighting services by the total land area of the neighborhood and multiply the result by 100 to get the percentage.
Energy (kWh/(km2 · hab))	This indicator evaluates the annual energy intensity related with the use of street lighting and lighting urban assets within the neighborhood, expressed in kWh/(km2 · inhab). Provides information on the efficiency of the neighborhood's street lighting network.
	Calculation Procedure: Determine the total energy intensity per year of use of the neighborhood's urban lighting service in kilowatt-hours (kWh). Then, divide this energy intensity by the product of the total neighborhood area in square kilometers (Km2) and the total number of neighborhood residents. The result is the annual energy intensity for urban environmental conditioning in kWh per square kilometer per inhabitant.
Social (Score)	This indicator assesses various factors related with the use of street lighting such as Security, Accesibility, Visual Comfort and Stetic. These aspects focus on the overall lighting environment's impact on the residents' quality of life.
	Calculation Procedure: Calculate parameters of public lighting use related to Safety (driving), Accessibility (people with visual disabilities), Visual Comfort (related to specific tasks or activities) and Aesthetics (integration of public lighting in the urban landscape). Assign scores or values to each parameter based on established criteria or standards. Combine these scores or values to obtain an overall street lighting index. A higher index score generally indicates an environment with greater lighting and visual comfort within the neighborhood.
Life Cycle Analysis (tCO2e/(km2 · hab))	This indicator considers the environmental impacts produced in all stages of the life cycle related to the use of public lighting and urban lighting, both by surface and by population, within the urban area.
	Calculation procedure: Identify the assets related to the street lighting and lighting urban assets within the urban area and the impacts to be evaluated. Collect data on all operational inputs and outputs of the system throughout its life cycle. Evaluate the life cycle emissions of the street lighting and lighting urban assets in tCO2, and divide them by the product of the urban area (in square kilometers) and the population (inhabitants).
Life Cycle Costing (EUR/(km2 · hab))	Evaluates the costs associated with the use of street lighting and urban lighting assets, factored by both area and population, within the urban area.

	Calculation Procedure: Calculate the costs of using urban lighting throughout its life cycle within the urban area in EUR, and divide it by the product of the urban area (in square kilometers) and the population (inhabitants).

Conclusions

The foundation for the development of an operational methodology for scaling complex buildings was laid out in this deliverable. The consideration of neighbourhood-scale operational energy aspects played a crucial role in achieving this objective. It was proposed that the integration of digitization and new technologies would facilitate environmentally respectful behaviors among citizens and companies, thereby reducing energy consumption and carbon footprint. The four strategies outlined in the resource efficiency and climate responsibility approach, focusing on smart energy and smart environment, included the establishment of a Smart grid and advanced metering framework, the design of Smart buildings, the promotion of Smart home appliances and devices, and the implementation of Environmental control and monitoring.

Detailed descriptions of the necessary infrastructure and smart sensors for measuring real performance at the neighbourhood scale were provided, raising questions about the practices for analyzing operational data in urban areas. This work served as a foundational support for initiating the methodological development of an evaluation and qualification scheme for building complexes. As a result, a preliminary taxonomy of urban indicators for evaluating energy performance was obtained.

Through an extensive bibliographical review, the discussion of digital twin practices at the neighbourhood scale was explored, along with the integration of measurement results from smart sensors for building complexes. Finally, standardized procedures for the measurement, processing, and reporting of energy consumption data at the complex scale were emphasized, as well as the evaluation of this data to define the operational qualification of building complexes.

It is worth emphasizing that the next stages of this work involve defining how these indicators will be evaluated. This will cover key aspects such as the design of specific algorithm, the determination of data sources and the integration of the component tools proposed by SmartLivingEPC. The current taxonomy is a dynamic work in progress, the primary focus of which is the conceptualization and categorization of these indicators, a critical step in the process. Looking ahead, the next phase will involve refining assessment methodologies, which will include the development of precise mathematical procedures. These methodologies will take into account data sources and the seamless integration of relevant components, adapted to the unique characteristics of each indicator.

References

[1]. EU Energy Star Programme, European Energy Efficiency Platform E3P, Joint Reserch Center, https://e3p.jrc.ec.europa.eu/node/189#:~:text=The%20European%20Energy%20Star%20Programme,the%20environment%20by%20saving%20energy.

[2]. Bibri, S. E., & Krogstie, J. (2020). The emerging data–driven Smart City and its innovative applied solutions for sustainability: The cases of London and Barcelona. Energy Informatics, 3, 1-42.

[3]. Odendaal, N. (2003). Information and communication technology and local governance: Understanding the difference between cities in developed and emerging economies. Computers, environment and urban systems, 27(6), 585-607.

[4]. Lee, J. H., Phaal, R., & Lee, S. H. (2013). An integrated service-device-technology roadmap for smart city development. Technological Forecasting and Social Change, 80(2), 286-306.

[5]. Nathali Silva, B., Khan, M., & Han, K. (2017). Big data analytics embedded smart city architecture for performance enhancement through real-time data processing and decision-making. Wireless communications and mobile computing, 2017.

[6]. United Nations. Big Data and the 2030 agenda for sustainable development. Prepared by A. Maaroof. 2015. http://www.unescap.org/events/call-participants-big-data-and-2030-agendasustainable-development-achieving-development.

[7]. Hamid Reza Ranjbar, Ali Reza Gharagozlou, and Ali Reza Vafaei Nejad. 3D Analysis and Investigation of Traffic Noise Impact from Hemmat Highway Located in Tehran on Buildings and Surrounding Areas. Journal of Geographic Information System, 04(04):322–334, 2012

[8]. Esther Rivas, Jose Luis Santiago, Yolanda Lechón, Fernando Martín, Arturo Ariño, Juan José Pons, and Jesús Miguel Santamaría. CFD modelling of air quality in Pamplona City (Spain): Assessment, stations spatial representativeness and health impacts valuation. Science of The Total Environment, 649:1362–1380, February 2019

[9]. Jean-Marie Bahu, Andreas Koch, Enrique Kremers, and Syed Monjur Murshed. Towards a 3D spatial urban energy modelling approach. International Journal of 3-D Information Modeling (IJ3DIM), 3(3):1–16, 2014

[10]. Alina Galimshina, Maliki Moustapha, Alexander Hollberg, Pierryves Padey, Sébastien Lasvaux, Bruno Sudret, and Guillaume Habert. What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one. Energy and Buildings, 251:111329, 2021

[11]. Aneta Strzalka, Jürgen Bogdahn, Volker Coors, and Ursula Eicker. 3D City modelling for urban scale heating energy demand forecasting. HVAC and R Research, 17(4):526– 539, 2011.

[12]. Felix Heisel, Joseph McGranahan, Joseph Ferdinando, and Timur Dogan. Highresolution combined building stock and building energy modelling to evaluate whole-life carbon emissions and saving potentials at the building and urban scale. Resources, Conservation and Recycling, 177:106000, 2022

[13]. Pettit, I. Widjaja, P. Russoa, R. Sinnott, R. Stimson, and M. Tomko. VisualiSation Support for Exploring Urban Space and Place. Technical report

[14]. van der Valk, H., Haße, H., Moller, F., Otto, B., 2021. Archetypes of ¨ Digital Twins. Business & Information Systems Engineering, 1–17

[15]. Gerlach, B., Zarnitz, S., Nitsche, B., Straube, F., 2021. Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits. Logistics, 5(4), 8

[16]. Kugler, S., Kern, A., Anderl, R., 2021. Method for the generation of use case related views for Digital Twins. Procedia CIRP, 104, 1896–1900

[17]. Jones, D., Snider, C., Nassehi, A., Yon, J., Hicks, B., 2020. Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36-52.

[18]. Hietaharju, P., Ruusunen, M., Leiviska, K., 2019. Enabling Demand Side ¨ Management: Heat Demand Forecasting at City Level. Materials, 12(2), 202

[19]. Alva, P., Biljecki, F., & Stouffs, R. (2022). Use cases for district-scale urban digital twins. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48, 5-12.

[20]. Chiu, R L (2003). "12 Social sustainability, sustainable development and housing development". In: Housing and social change: East-west perspectives. Vol. 221. Routledge (cit. on pp. 10, 38).

[21]. Kohon, J. (2018). "Social inclusion in the sustainable neighbourhood? Idealism of urban social sustainability theory complicated by realities of community planning practice". In: City, Culture and Society 15, pp. 14–22. issn: 18779166. doi: 10.1016/j.ccs.2018.08.005 (cit. on pp. 9, 10).

[22]. Shirazi, M. Reza and Ramin Keivani (2019b). Urban Social Sustainability: Theory, Policy and Practice. Routledge studies in sustainability. Routledge, pp. 42–58. isbn: 9781138069381. doi: 10.4324/9781315115740-3 (cit. on pp. 1, 2, 12, 13, 50).

[23]. Kain, Jaan-Henrik, Marco Adelfio, Jenny Stenberg, and Liane Thuvander (2022). "Towards a systemic understanding of compact city qualities". In: Journal of Urban Design 27.1, pp. 130–147 (cit. on p. 12).

[24]. Jenks, Mike and Colin Jones (2010). Dimensions of the Sustainable City. London: Springer, p. 288. isbn: 9781402086465. doi: 10.1007/978- 1- 4020- 8647- 2 (cit. on p. 12).

[25]. Caulfield, Jon, Mario Polèse, Richard Stren, and Mario Polese (2001). The Social Sustainability of Cities: Diversity and the Management of Change. Vol. 27. 3, p. 381. isbn: 9780802047670. doi: 10.2307/3552480 (cit. on pp. 12, 13).

[26]. Erickson, Bill and Tony Lloyd-Jones (2001). "Design problems". In: Approaching Urban Design: the design process, Harlow: Pearson Education Ltd (cit. on pp. 5, 13, 15, 16, 19, 20).

[27]. Somanath, S., Hollberg, A., & Thuvander, L. (2021). Towards digitalisation of socially sustainable neighbourhood design. Local Environment, 26(6), 770-789.

[28]. Olakitan Atanda, Jubril (2019). "Developing a social sustainability assessment framework". In: Sustainable Cities and Society 44. May 2018, pp. 237–252. issn: 22106707. doi: 10.1016/j.scs.2018.09.023 (cit. on pp. 3, 16).

[29]. Ali, Hikmat H. and Saba F. Al Nsairat (2009). "Developing a green building assessment tool for developing countries - Case of Jordan". In: Building and Environment 44.5, pp. 1053–1064. issn: 03601323. doi: 10.1016/j.buildenv.2008.07.015 (cit. on pp. 3, 16).

[30]. Stender, Marie and Annette Walter (2019). "The role of social sustainability in building assessment". In: Building Research and Information 47.5, pp. 598–610. issn: 14664321. doi: 10.1080/09613218.2018.1468057 (cit. on pp. 17, 38).

[31]. Phondani, Prakash C, Arvind Bhatt, Esam Elsarrag, Yousef M Alhorr, and Ali El-Keblawy (Oct. 2016). "Criteria and indicator approach of global sustainability assessment system for sustainable landscaping using native plants in Qatar". In: ECOLOGICAL INDICATORS 69, pp. 381–389. issn: 1470-160X. doi: 10.1016/ j.ecolind.2016.05.003 (cit. on p. 17).

[32]. Danivska, V., C. Heywood, M. Christersson, E. Zhang, and S. Nenonen (2019). "Environmental and social sustainability–emergence of well-being in the built environment, assessment tools and real estate market implications". In: Intelligent Buildings International 11.3-4, pp. 212–226. issn: 17508975. doi: 10 . 1080 / 17508975.2019.1678005 (cit. on p. 17).

[33]. De Fine Licht, K. and Anna Folland (2019). "Defining "Social Sustainability": Towards a Sustainable Solution to the Conceptual Confusion". In: ETIKK I PRAKSIS 13.2, pp. 21–39. issn: 1890-3991. doi: 10.5324/eip.v13i2.2913 (cit. on p. 37).

[34]. Haklay, Muki and Piotr Jankowski (2018). "Selected modern methods and tools for public participation in urban planning – a review". In: Quaestiones Geographicae 37.3, pp. 127–149 (cit. on p. 17).

[35]. Johannsen, C., Senger, D., Kluss, T., 2021. A digital twin of the socialecological system urban beekeeping. A. Kamilaris, V. Wohlgemuth, K. Karatzas, I. N. Athanasiadis (eds), Advances and New Trends in Environmental Informatics, Springer International Publishing, Cham, 193– 207.

[36]. Nochta, T., Wan, L., Schooling, J. M., Parlikad, A. K., 2021. A SocioTechnical Perspective on Urban Analytics: The Case of City-Scale Digital Twins. The Journal of urban technology, 28(1-2), 263-287.

[37]. Grieves, M., Vickers, J., 2017. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. Springer International Publishing, Cham, 85–11.

[38]. Dembski, F., Woessner, U., Letzgus, M., Ruddat, M., Yamu, C., 2020. Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. Sustainability (Basel, Switzerland), 12(6), 2307.

[39]. Shaharuddin, S., Maulud, K. N. A., Rahman, S. A. F. S. A., Ani, A. I. C., 2022. Digital twin for indoor disaster in smart city: a systematic review. International archives of the photogrammetry, remote sensing and spatial information sciences., XLVI-4/W3-2021, 315- 322.

[40]. Ni, Z., Eriksson, P., Liu, Y., Karlsson, M., Gong, S., 2021. Improving energy efficiency while preserving historic buildings with digital twins and artificial intelligence. IOP conference series. Earth and environmental science, 863(1), 12041

[41]. Turillazzi, B., Leoni, G., Gaspari, J., Massari, M., Boulanger, S. O. M., 2021. Cultural Heritage and Digital Tools: the Rock Interoperable Platform. International journal of environmental impacts (Print), 4(3), 276- 288.

[42]. Matthys, M., De Cock, L., Vermaut, J., Van de Weghe, N., De Maeyer, P., 2021. An “animated spatial time machine” in co-creation: Reconstructing history using gamification integrated into 3d city modelling, 4d web and transmedia storytelling. ISPRS International Journal of Geo-Information, 10(7)

[43]. Xu, L., Francisco, A., Mohammadi, N., Taylor, J. E., 2019. Development of a virtual reality integrated community-scale eco-feedback system. Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation, American Society of Civil Engineers Reston, VA, 87–94.

[44]. Marcucci, E., Gatta, V., Pira, M. L., Hansson, L., Brathen, S., 2020. ˚ Digital Twins: A Critical Discussion on Their Potential for Supporting Policy-Making and Planning in Urban Logistics. Sustainability (Basel, Switzerland), 12(24), 10623.

[45]. Papyshev, G., Yarime, M., 2021. Exploring city digital twins as policy tools: A task-based approach to generating synthetic data on urban mobility. Data and Policy, 3.

[46]. Jouan, P., Hallot, P., 2020. Digital Twin: Research Framework to Support Preventive Conservation Policies. ISPRS international journal of geoinformation, 9(4), 228-25.

[47]. Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. Automation in Construction, 147, 104716.

[48]. Pawson, R., & Tilley, N. (1997). Realistic evaluation. sage.

Advanced Energy Performance Assessment towards Smart Living in Building and District Level

https://www.smartlivingepc.eu/en/

https://www.linkedin.com/company/smartlivingepc/

https://twitter.com/SmartLivingEPC

https://www.youtube.com/channel/UC0SKa-20tiSabuwjtYDqRrQ

This project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement number 101069639. The European Union is not liable for any use that may be made of the information contained in this document, which is merely representing the authors' view.