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Τεχνητής Νοημοσύνης στις Έξυπνες Πόλεις



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Περίληψη

Η παρούσα διπλωματική εργασία πραγματοποιήθηκε με ανάλυση συστηματικής βιβλιογραφίας και δικτύου παραπομπών (Systematic Literature Network Analysis – SLNA) και έχει σαν κύριο στόχο τη διερεύνηση της σχέσης μεταξύ Τεχνητής Νοημοσύνης (Artificial Intelligence - AI) και των έξυπνων πόλεων. Η μελέτη επικεντρώθηκε σε τρεις κύριες ερευνητικές περιοχές, καθεμία από τις οποίες διατυπώθηκε ως ξεχωριστό ερευνητικό ερώτημα. Το πρώτο ερευνητικό ερώτημα είχε τίτλο " Ποιός είναι ο ρολος και οι εφαρμογές του AI στις έξυπνες πόλεις;". Σε αυτό το σημείο, εξετάσαμε το συγκεκριμένο ερώτημα και εντοπίσαμε κρίσιμους τομείς όπως η έξυπνη διακυβέρνηση, η ευφυής κινητικότητα, η περιβαλλοντική βιωσιμότητα, η δημόσια ασφάλεια, η υγεία και η οικονομική ανάπτυξη, μέσω των οποίων αναδείχθηκε η δυνατότητα του AI να υποστηρίζει διαδικασίες λήψης αποφάσεων σε πραγματικό χρόνο, με προγνωστική και αυτόνομη λειτουργία. Το δεύτερο ερευνητικό ερώτημα που απαντήθηκε στην παρούσα διπλωματική εργασία είχε τίτλο " Πώς οι περιφερειακές και πολιτισμικές διαφορές επηρεάζουν την υιοθέτηση και την αποτελεσματικότητα του AI στις έξυπνες πόλεις; ". Για να απαντήσουμε σε αυτό το ερευνητικό ερώτημα, πραγματοποιήσαμε μελέτη περιπτώσεων από πόλεις της Ευρώπης, της Ασίας, της Βόρειας Αμερικής, της Μέσης Ανατολής, της Αφρικής και της Ωκεανίας και αναδείξαμε πως η τοπική διακυβέρνηση, οι κοινωνικοοικονομικές συνθήκες και οι πολιτισμικές αξίες είναι αυτά που καθορίζουν την πορεία ενσωμάτωσης του AI στα αστικά συστήματα. Από αυτήν την ανάλυση, προέκυψαν επίσης σημαντικά συμπεράσματα που αφορούν την ανάγκη για ανάπτυξη στρατηγικών έξυπνων πόλεων που να ευθυγραμμίζονται με τις ιδιαιτερότητες της κάθε περιοχής και να προάγουν την ισότιμη καινοτομία. Το τελευταίο ερευνητικό ερώτημα της διπλωματικής μας εργασίας είχε τίτλο " Ποιες είναι οι κρίσιμες απαιτήσεις που πρέπει να εκπληρώσουν οι έξυπνες πόλεις για να είναι βιώσιμες; ". Σε αυτό το ερευνητικό ερώτημα, μετά από εις βάθος ανάλυση της βιβλιογραφίας, κατηγοριοποιήσαμε τη βιωσιμότητα σε τρεις βασικές διαστάσεις - περιβαλλοντική, οικονομική και κοινωνική - και στη συνέχεια εξετάσαμε το πώς τεχνολογίες όπως το AI, το Διαδίκτυο των Πραγμάτων (Internet of Things - IoT), το υπολογιστικό νέφος (cloud computing) και η τεχνολογία blockchain συμβάλλουν στην επίτευξη της μακροπρόθεσμης ανθεκτικότητας και αποδοτικότητας. Παράλληλα αναλύσαμε και τις προκλήσεις που προκύπτουν από την υιοθέτηση αυτών των τεχνολογιών όπως για παράδειγμα την ηθική χρήση, την προστασία των προσωπικών δεδομένων και την ενεργειακή κατανάλωση. Η εργασία αυτή παρουσιάζει μια δομημένη αποτύπωση της διασύνδεσης μεταξύ του AI και της βιώσιμης αστικής ανάπτυξης προσφέροντας με αυτόν τον τρόπο πολύτιμο υλικό σε ερευνητές, πολιτικούς και επαγγελματίες του χώρου που ασχολούνται με τον σχεδιασμό έξυπνων, δίκαιων και βιώσιμων πόλεων του μέλλοντος.

Λέξεις Κλειδιά

Έξυπνη Πόλη, Τεχνητή Νοημοσύνη (AI), βιωσιμότητα, πολιτικές διαφορές, αστική καινοτομία, ψηφιακή διακυβέρνηση

Bibliometric study on the use of Artificial Intelligence in Smart Cities

Alexandros Roditis

Abstract

This thesis was conducted using Systematic Literature Network Analysis (SLNA) and had as its main objective the investigation of the relationship between Artificial Intelligence (AI) and smart cities. The study focused on three main research areas, each of which was formulated as a separate research question. The first research question was titled ‘What is the role and applications of AI in smart cities?’ At this point, we examined this specific question and identified critical areas such as smart governance, intelligent mobility, environmental sustainability, public safety, health and economic development, through which AI's ability to support real-time decision-making processes with predictive and autonomous functionality was highlighted. The second research question answered in this thesis was titled ‘How regional and cultural differences influence the adoption and effectiveness of AI in smart cities?’. To answer this research question, we conducted case studies of leading smart cities in Europe, Asia, North America, the Middle East, Africa and Oceania and showed that local governance, socio-economic conditions and cultural values are what determine the course of AI integration into urban systems. This analysis also yielded important conclusions regarding the need to develop smart city strategies that are aligned with the specific characteristics of each region and promote equitable innovation. The final research question of our thesis was entitled ‘What are the critical requirements that smart cities must fulfil in order to be sustainable?’. In this research question, after an in-depth analysis of the literature, we categorised sustainability into three basic dimensions - environmental, economic and social - and then examined how technologies such as AI, the Internet of Things (IoT), cloud computing and blockchain technology contribute to achieving long-term resilience and efficiency. At the same time, we analysed the challenges arising from the adoption of these technologies such as ethical use, personal data protection and energy consumption. This paper presents a structured overview of the interconnection between AI and sustainable urban development, thus providing valuable material for researchers, politicians and professionals involved in the design of smart, fair and sustainable cities of the future.

Keywords

Smart city, Artificial Intelligence, sustainability, regional differences, urban innovation, digital governance

Ευχαριστίες

“This thesis is dedicated to my beloved family for their continual moral, spiritual and emotional support and to my esteemed advisor, Prof. Periklis Chatzimisios for their invaluable guidance and mentorship through this journey.”

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Συντομογραφίες

AI	Artificial Intelligence
ICT	Information and Communication Technologies
IoT	Internet of Things
SLNA	Systematic Literature Network Analysis
SLR	Systematic Literature Review
CNA	Citation Network Analysis
SDG	Sustainable Development Goals
ITS	Intelligent Transport Systems
XAI	Explainable AI
EV	Electric Vehicle
UHI	Urban Heat Island
ISO	International Organization for Standardization
ITU	International Telecommunication Union
IEEE	Institute of Electrical and Electronics Engineers
SSC	Smart Sustainable Cities

Chapter 1: Introduction

The concept of "smart city" was initiated in 1993 when the city of Singapore presented itself as an "intelligent city". Since then, the concept of smart city has been at the forefront of the international research community and has been the primary topic of discussion in all political debates on regional development initiatives at the national and international levels. In general, "smart cities" are those that make considerable use of Information and Communication Technologies (ICT) to achieve benefits across a variety of domains and initiatives [1]. The fact that practically every city in the world, regardless of size, is incorporating the transition from traditional to smart cities into their medium- and long-term budget proposals is not an exaggeration.

There are many reasons why the smart city concept is in the forefront of the research and academic communities. The first and probably most significant reason is the rapid urban population growth. According to [2] and [3], by 2050, the global urban population is expected to reach 66% or 70% respectively. Bearing in mind that the world population is also expected to increase by 10% by then, the national governments will have to deal with overpopulated cities. This amount of surge in urbanization will have drastic impacts on cities' environment, management, security and society.

What makes smart cities smart is the use of cutting edge technologies in order to improve the quality of life of their residents. Among the various technologies that enable smart cities, the one which stands out the most is Artificial Intelligence (AI). AI has emerged as a critical technological driver within the evolution of smart cities, acting as the cognitive engine that processes vast datasets and transforms raw urban information into actionable intelligence. Unlike previous digital infrastructure technologies such as the Internet of Things (IoT) and cloud computing, which are primarily concerned with connectivity and data accumulation, AI is characterized by the fact that it allows for predictive, autonomous and adaptive decision-making systems [4]. These features empower urban governance frameworks to become more responsive, efficient, and citizen-oriented [5], [6]. Originally developed to be used in automation and robotics, AI has found expansive application in urban areas, facilitating use cases across smart governance and mobility, environmental management and public safety. AI-driven systems such as machine learning algorithms and federated learning frameworks allow city administrators to model urban growth and manage and optimize traffic and energy supply, personalize public services, and enhance disaster preparedness [6], [7], [8]. The utilisation of AI technology in combination with the use of real-time urban data collected through IoT devices, will allow cities to create intelligent systems with the capability to anticipate challenges and react to evolving conditions, all while supporting goals of sustainability, inclusivity and operational efficiency [5], [9]. So the usage of AI not only enables smart cities but actually is crucial in shaping their structure, responsiveness and innovative capacity [7], [10].

Another important technology that helps us define the term smart cities is the IoT. The IoT refers to a network of smart devices which process unique ids and communicate with one another using standard communication protocols. This digital infrastructure enables devices to monitor their environment using embedded sensors and to actively interact with it through actuation mechanisms [11]. The IoT vision was initially conceived and implemented within industrial areas which significantly contributed to the emergence and evolution of the Industry 4.0 framework. Over time, the distinctive capabilities of IoT technologies have proven instrumental in addressing wider societal challenges [12], [13].

Alongside the technological evolution that supports the creation of smart cities, there has been a growing academic interest in understanding the wider implications of these urban innovations. Smart

cities, in contrast to their strict technological interpretation, have acquired a broader meaning, transcending the strict technological meaning and adopting a complex social-ethical ecosystem where innovation, modern governance and sustainability coexist and help each other improve. The integration of AI, IoT, cloud computing and other technologies helps us collect data that shows us how a city can improve people's living standards and even set new standards for them. However, as cities become more and more reliant on digital infrastructure and intelligent systems, a new set of challenges emerges, ranging from ethical and privacy concerns to issues of interoperability, the digital divide and long-term sustainability. These multifactorial dynamics create the requirement for a deeper understanding of how technological capabilities intersect with urban governance, regional realities, sustainability imperatives and real-life applicable decisions.

For these purposes, we will further examine the three main areas of research concerning the multidimensional relationship between AI and smart cities. At first, there is a need to examine various applications of AI in a variety of urban points of interest such as governance, traffic, public safety, the natural environment and health care, among the more imminent areas. Secondly, we will further examine the influence of regional and cultural factors on the adoption and effectiveness of AI in smart cities, highlighting the differentiated paths of urban innovation as applied around the world. Furthermore, there is great importance in the requirements that smart cities must meet in order to be fully sustainable. Regarding these concerns, we will discuss how AI and other contemporary technologies may contribute environmentally, economically, and socially to multiple urban demographics. Through these three research questions, our study aims to deliver a comprehensive and detailed analysis based on real data on the matter of how smart cities can evolve responsibly and sustainably upon the age of AI.

In order to achieve the aforementioned objectives, our approach adopts a structured research methodology based on Systematic Literature Network Analysis (SLNA). SLNA combines the rigor of Systematic Literature Review (SLR) with the network mapping capabilities of Citation Network Analysis (CNA). This approach allows us to present a comprehensive picture of detailed academic findings on the subject and to identify learning gaps that have not yet been thoroughly researched and might need further investigation. The core of the analysis of the thesis is based on a collection of academic studies and publications from the world's leading digital libraries and well-renowned databases, filtered through tailored criteria for both the selection and rejection of relevant material. The outcome of this research offers theoretical insight and practical recommendations that can advise policymakers, urban planners and technology developers in their efforts to build a smarter, fairer, and more sustainable urban future for all.

The structure of our thesis is organized as follows: Chapter 2 introduces and critically analyzes the concept, evolution, and foundational principles of smart cities, drawing from both academic literature and policy frameworks. Chapter 3 outlines the research methodology employed in this study, presenting the SLNA approach and detailing the processes of data collection, filtering, and analysis. Chapter 4 focuses on the role and diverse applications of AI in smart city environments, mapping how AI technologies are transforming key urban sectors. Chapter 5 examines how regional and cultural differences shape the adoption and effectiveness of AI in smart cities, supported by global case studies and comparative analysis. Chapter 6 explores the critical requirements that smart cities must fulfill in order to be sustainable, discussing the alignment of smart initiatives with the Sustainable Development Goals (SDGs), and addressing environmental, economic, and social dimensions of sustainability. Finally, Chapter 7 concludes the thesis with a synthesis of key findings, a reflection on current

challenges and opportunities, and future directions for research and policy in the domain of AI-driven sustainable urban development.

Chapter 2: Smart Cities: Concept, Evolution and Core Principles

2.1 Introduction

The rapid urbanization of the past decades, combined with the relentless advancement of technology, has led to a profound transformation of cities worldwide. In this context, the concept of the "smart city" has emerged as a dynamic response to the complex challenges posed by modern urban life. While the term has been widely popularized, its conceptualization remains multifaceted, with definitions and frameworks evolving over time to reflect new priorities, technological capabilities, and societal needs. In this chapter we aim to systematically analyze the concept of smart cities, trace their evolution, and highlight their core principles, based on a critical synthesis of the most relevant scholarly and policy literature.

2.2 Defining the smart city

As we mentioned earlier, the term "smart city" has been the subject of intense academic, policy, and industry debate. Early interpretations of the concept largely focused on the integration of ICT into urban infrastructure and services, aiming at enhancing operational efficiency and quality of life [1]. However, as the concept matured, it incorporated broader dimensions such as human capital, governance models, environmental sustainability, and social inclusion.

One widely accepted and comprehensive definition suggests that a smart city is "a city where investments in human and social capital and traditional (transport) and modern communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance" [1]. This definition captures the multi-dimensional nature of smart cities, emphasizing the interplay between technology, society, economy, governance, and the environment.

In line with this, the European Parliament (2014) highlighted that smart cities must integrate technologies with governance innovation and social capital development [12]. Other studies propose frameworks such as the "SMELTS" model (Social, Management, Economic, Legal, Technology, and Sustainability), stressing that smart cities are not just technologically equipped urban areas, but dynamic socio-technical systems that require holistic management approaches [13]. Figure Smart Cities: Concept, Evolution and Core Principles.1 below visualizes the "SMELTS" model, where the inner level consists of the factors which have greater impact on the smart city initiatives and the outer level factors are the ones which might get influenced by the inner level before impacting the smart city initiatives.

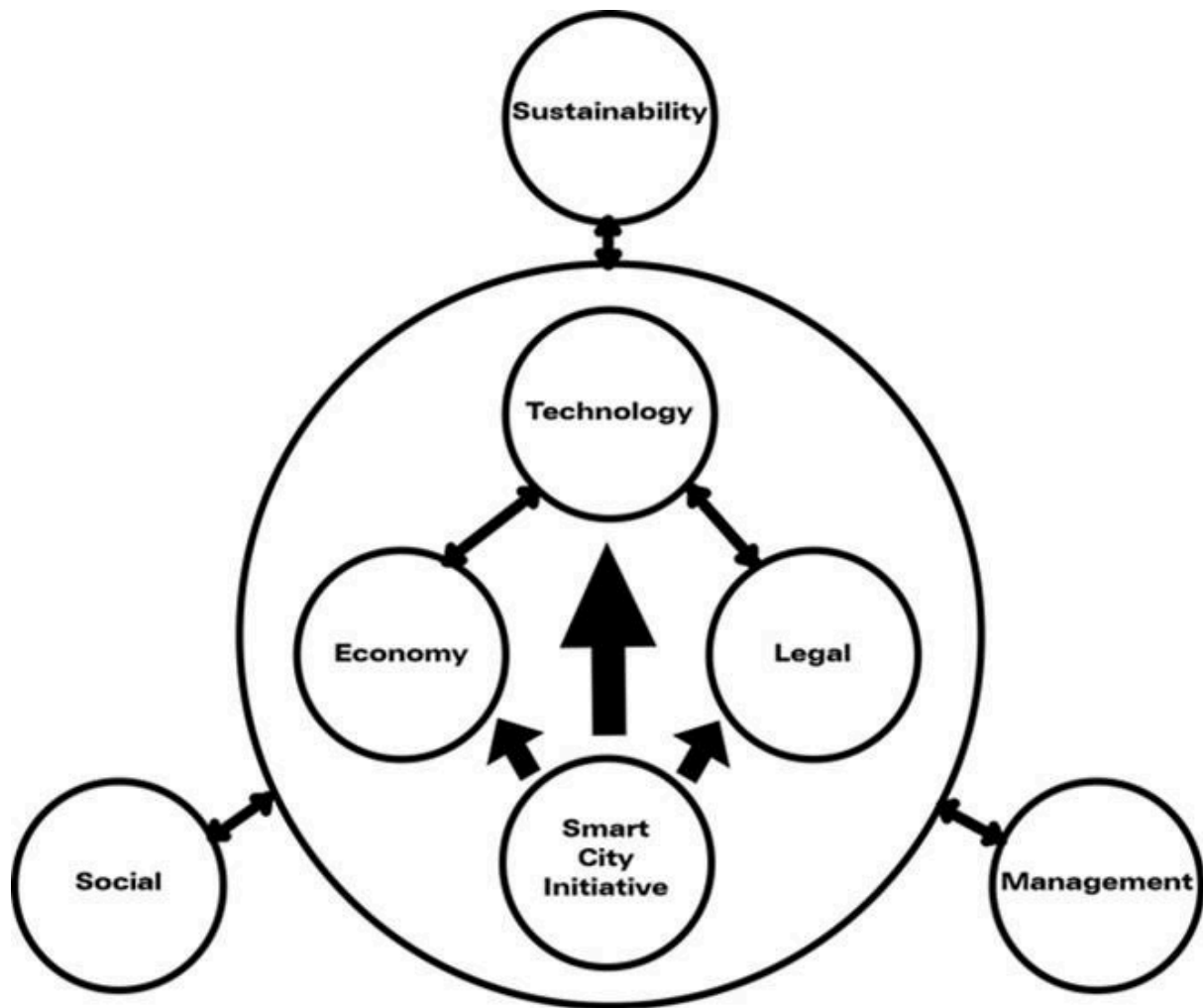


Figure 2.1: SMELTS framework diagram [13]

2.3 Evolution of smart city concept

The smart city concept has undergone significant evolution, influenced by technological advancements and shifting socio-economic priorities:

- First phase (1990s-early 2000s): The initial conceptualizations, such as the "wired city" and "digital city," focused mainly on telecommunications infrastructure and the provision of online services [13]. These early projects were technology-centric and lacked a strong emphasis on citizen engagement or sustainability.
- Second phase (mid-2000s-early 2010s): The concept expanded to include governance and citizen-centric dimensions. The integration of ICT with urban management led to the idea of "e-governance" and "smart governance," aiming to enhance transparency, efficiency, and participation [12].

- Third phase (2010s-present): The smart city concept has matured into a broader urban development model, incorporating sustainability, resilience, inclusivity, and innovation ecosystems. Recent frameworks link smartness to urban resilience, emphasizing that technological solutions must support cities' abilities to adapt to shocks such as climate change or pandemics [14].

We observe that the way smart cities are developed is changing, and from an approach that strictly concerns technological development, it is now based on a socio-technical model that has a more human-centered development.

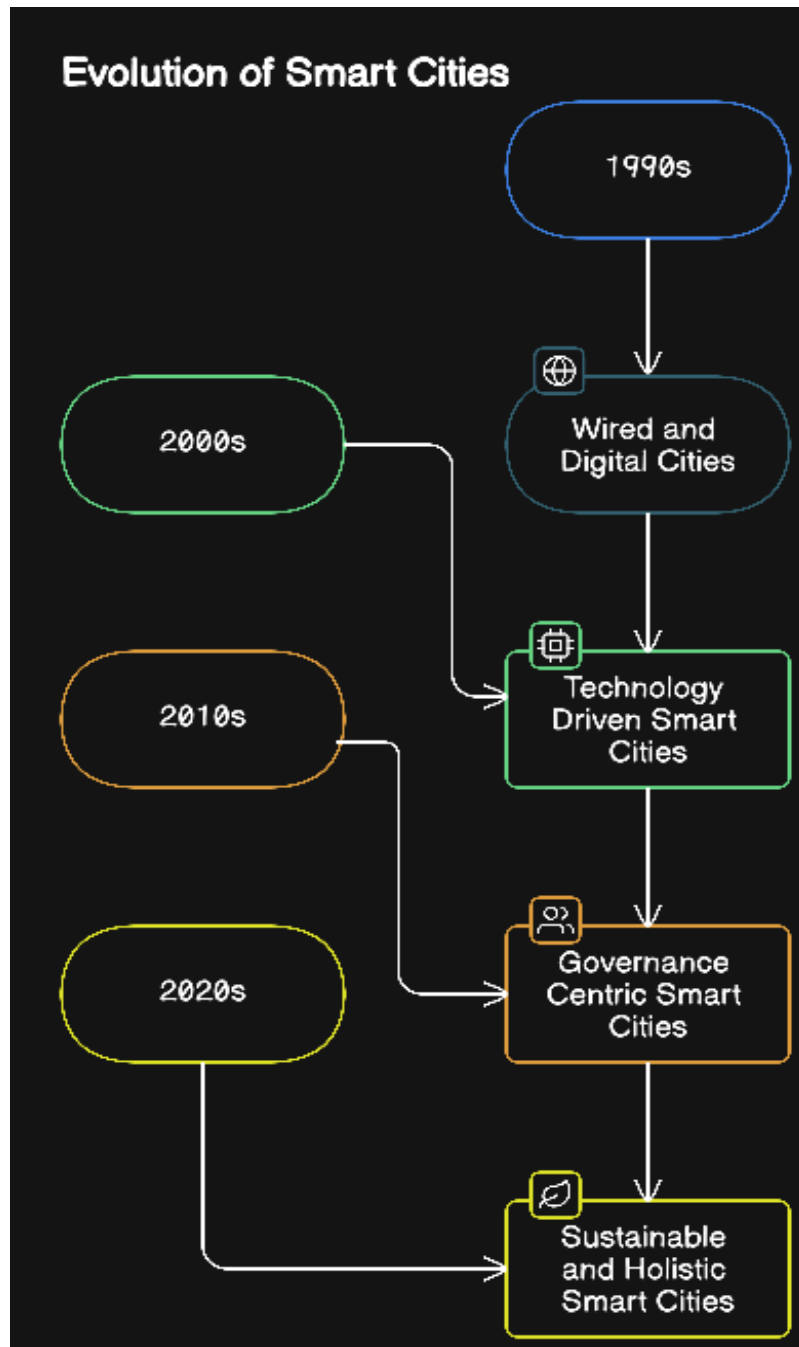


Figure 2.2: Evolution timeline of smart cities [1], [12], [13]

2.4 Core principles of smart cities

Through bibliographic research, we identified the main principles of smart cities, which are as follows:

2.4.1 Integration of technologies

The combination of different technologies is an important part of smart cities. Firstly ICT enables real-time data collection, resource optimisation and new forms of service delivery [15]. Technologies such as the IoT, Big Data, AI, and cloud computing form the backbone of smart city infrastructure [12], [13].

However, technology is not an end in itself; it serves as an enabler of higher-order goals like sustainability, resilience, and quality of life improvement [15].

2.4.2 Citizen-centric approach

The shift towards a citizen-centric model is evident in the emphasis on participatory governance, social innovation, and community engagement [12], [13]. Smart cities are increasingly conceptualized as "smart communities," where citizens actively co-design, co-produce, and co-evaluate urban services [12].

This approach recognizes that technology must empower, not displace, human agency in shaping urban futures [15].

2.4.3 Sustainability and resilience

Sustainability is a non-negotiable component of the smart city agenda. Cities are expected to balance economic growth with environmental stewardship and social equity [14], [16]. Resilience — the capacity to absorb shocks and maintain essential functions — has become equally critical, especially after global crises like COVID-19 [14].

The integration of smart technologies into resilience planning (e.g., smart grids, flood monitoring sensors) demonstrates how digital infrastructure can support sustainable urban futures [14].

2.4.4 Holistic governance

Smart governance extends beyond digitizing public services; it requires rethinking urban management structures to foster cross-sectoral collaboration, transparency, accountability, and agility [12]. Studies emphasize that cities need to develop governance models that are adaptive to local contexts, avoiding "one-size-fits-all" solutions [12], [16].

In this context, public value creation — not just technological efficiency — becomes the ultimate metric of success [12].

2.4.5 Economic vitality and innovation

Smart cities also serve as platforms for economic innovation, fostering entrepreneurship, supporting smart industries, and attracting talent [13], [16]. Building innovation ecosystems — including universities, startups, and knowledge-intensive businesses — is seen as crucial for maintaining economic competitiveness in the digital age [13].

Notably, smart cities are associated with the "knowledge economy," where value is increasingly generated through ideas, data, and collaboration rather than traditional manufacturing [15].

2.5 Typologies and models of smart cities

As the concept of the smart city matured, scholars and practitioners have proposed various typologies to better understand the different models that cities adopt based on their specific contexts, goals, and capacities. Although there is no universal classification, several dominant models can be identified:

2.5.1 Technology-driven smart cities

In the early stages of smart city development, many initiatives were heavily technology-driven, emphasizing the deployment of ICT infrastructure to optimize city operations and services [13]. These cities often focused on technical solutions such as smart grids, intelligent transport systems (ITS), and data-driven governance platforms.

However, this approach has been criticized for sometimes sidelining social and governance dimensions, resulting in technocratic models with limited citizen engagement [1], [12].

2.5.2 Human-centric and socially inclusive smart cities

In response to the technocentric approach, a human-centric model has emerged, emphasizing the empowerment of citizens with a focus on the community [13]. Thus, cities aim to integrate mechanisms of participatory governance.

Cities adopting this model recognize that the success of smart city initiatives depends not only on technology but also on the active involvement and satisfaction of the citizens they serve [16].

2.5.3 Sustainable smart cities

Another important model we encountered presents smart cities as platforms for achieving environmental sustainability [14]. These cities integrate smart technologies with green infrastructure, sustainable mobility solutions, resource-efficient urban planning, and climate adaptation strategies.

Examples include initiatives that use IoT-based monitoring systems for pollution control, or AI-powered predictive models for disaster resilience [14], [17]. We will analyse the importance of sustainability in smart cities more in depth in another chapter.

2.5.4 Economic innovation and smart industry

Some smart cities are primarily designed as innovation ecosystems that stimulate entrepreneurship, attract talent, and foster knowledge-based industries [16]. These cities focus on building smart economies by leveraging startups, universities, and research centers, combined with supportive digital infrastructure.

This model emphasizes the role of smart cities as engines of economic competitiveness in the globalized knowledge economy [15].

2.5.5 Integrated and holistic smart cities

More recently, the most advanced visions for smart cities advocate for an integrated model that simultaneously addresses technology, governance, environment, economy, and social inclusion in a

coherent and systemic manner [14]. These cities aim for balanced development across multiple domains, understanding that true "smartness" is holistic rather than fragmented.

2.6 Dimensions of smart cities

Building on the previous typologies, researchers have also identified key dimensions or "pillars" that characterize smart cities. A SLR reveals that the following dimensions are most commonly emphasized:

2.6.1 Smart economy

Smart cities promote entrepreneurship, innovation, productivity, and competitiveness [13], [16]. A strong focus is placed on creating favorable conditions for new business development, supporting creative industries, and fostering public-private partnerships that stimulate economic growth [1].

2.6.2 Smart governance

Good governance in smart cities includes participatory decision-making, transparency, responsiveness and effective public administration enhanced by digital tools [12], [16]. Some key examples are e-government platforms, open data initiatives, and collaborative urban planning processes [1].

In addition, cities are encouraged to adapt governance structures to their local contexts, recognising the diversity of political systems and citizens' expectations [12].

2.6.3 Smart environment

Environmental sustainability is a critical dimension, including initiatives on energy efficiency, carbon footprint reduction, waste management and biodiversity protection [14], [16]. Technologies such as smart meters, renewable energy grids and green building standards are used to achieve these goals.

Resilience to climate change and other environmental shocks is increasingly integrated into the smart environment agenda [14]. The concept of environmental sustainability will be thoroughly analysed in chapter 6.

2.6.4 Smart mobility

Smart mobility basically refers to the use of ICT to create efficient and sustainable transport systems [13], [15]. This includes smart traffic management, better use of public transport, the creation of electric vehicle (EV) support infrastructure and the promotion of alternative modes of transport, such as cycling and walking.

Cities such as Columbus (Ohio, USA) have received positive feedback on the use of sensors to enhance urban mobility [16].

2.6.5 Smart people

Another key aspect of smart cities is the development of the human factor. Smart cities invest in education, lifelong learning, digital literacy and citizen engagement [12], [18]. Empowering people with skills for the digital age and promoting a culture of innovation are considered vital for maintaining smart urban ecosystems.

2.6.6 Smart living

Finally, smart living emphasizes the enhancement of citizens' quality of life which includes health, safety, cultural vitality, and social cohesion [16]. Digital health services, smart homes, online cultural offerings and security monitoring systems are some examples of smart living implementations.

In summary, a truly smart city should perform well in all of the above dimensions, rather than excelling in just one. A visual representation of the dimensions of a smart city is presented in the table 2.1 below.

Table 2.1: Smart city dimensions framework [1], [12], [15], [16]

Dimensions	Description
Smart Economy	Focuses on innovation, entrepreneurship, productivity, and global competitiveness.
Smart Governance	Promotes transparency, participation, responsiveness, and efficient public administration.
Smart Environment	Emphasizes environmental sustainability, resilience to climate change, and green infrastructure.
Smart Mobility	Enhances sustainable, efficient transport systems through ICT and intelligent infrastructures.
Smart People	Develops human and social capital through education, digital skills, creativity, and social inclusion.
Smart Living	Improves quality of life, health services, safety, culture, and housing conditions.

2.6.7 Criticisms and challenges of smart cities

Despite their high potential and many benefits, smart cities also face several criticisms and many challenges. Some of them are:

- Technocentrism and corporate domination: Early models of smart cities were often criticised for being influenced by technology companies' motives and not focused on public interests and citizens' needs [12].
- Privacy and surveillance risks: The widespread use of cameras and sensors for data collection raises significant concerns about citizens' privacy and the possibility of surveillance [12], [14].
- Social exclusion and digital divides: If smart cities are not carefully planned, they might make things worse for people who are not already struggling and leave some groups even more excluded and cut off from digital access [12], [13].

- **Fragmented implementation:** Many projects suffer from a lack of integration, resulting in isolated "smart" initiatives that fail to achieve systemic impacts [12].
- **Governance and accountability issues:** Data-driven management of complex urban systems requires new forms of governance that are not yet fully developed in many cities [12], [16].

Many researchers emphasize the need to incorporate critical and participatory approaches to ensure that smart cities serve the social goals they have set [12], [14]. A visual presentation of the challenges of smart cities can be found in the table 2.2 below.

Table 2.2: Challenges in smart city implementation [1], [12], [14].

Challenges	Description
Technocentrism	Overemphasis on technology, risking neglect of societal needs and equity.
Privacy and Surveillance	Data collection systems can threaten personal privacy and increase surveillance risks.
Digital Divide	Risk of excluding marginalized populations from the benefits of smart services.
Fragmented Implementation	Isolated smart initiatives without systemic integration weaken long-term impact.
Weak Governance Structures	Lack of adaptive, participatory, and transparent governance models for complex urban systems.

2.7 Conclusions

The concept of the smart city has evolved significantly over the past two decades, from technology-centric visions to holistic frameworks integrating human, social, environmental, and economic dimensions. While smart technologies play a vital enabling role, the true essence of a smart city lies in its ability to foster sustainable development, resilience, citizen empowerment, and inclusive prosperity.

As cities continue to navigate the complex challenges of the 21st century, the smart city model offers valuable tools — but only when grounded in strong principles of equity, democracy, and sustainability. Future research and policy efforts must therefore focus on developing critical, contextualized, and citizen-centered smart city strategies that can truly transform urban life for the better.

Chapter 3: Research Methodology and Execution

3.1 Introduction

This chapter describes the methodology used to investigate the impact of artificial intelligence on smart cities. To achieve a comprehensive understanding of this matter, the study employs the SLNA methodology, which integrates the SLR and CNA methods. This dual approach allows for a structured exploration of the existing literature, while revealing the evolution of the research field over time [9].

3.2 SLNA methodology

As mentioned earlier, a dual methodology was used to compile this literature review. This methodology is called SLNA and was proposed in document [19]. This methodology combines SLR in order to initially select the most relevant studies, along with CNA which is utilized to refine a second selection based on a set of references. As the relevant literature which is available is quite extensive, CNA can be enlisted to assist in better understanding the evolution of the subject.

3.2.1 Systematic Literature Review (SLR)

SLR is a known, structured and methodical approach which is widely used to identify, evaluate and reconstruct existing research into comprehensible documentation. This methodology is particularly valuable in fields such as information systems, where there is a variety of methodologies available in a vast amount of literature. The SLR process is designed and audited to minimize bias and enhance the reliability of relevant findings. As a result it is rendered a critical tool for any current-day researcher [20], [21].

According to Kitchenham [22], SLR is defined as “means of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest”. It was primarily chosen as a main systematic approach because of its ability to offer high-quality reviews which are transparent with results which can be replicated as needed [20]. The primary purposes of the SLR method include:

- Summarizing existing research: SLRs help in classifying large quantities of research studies to provide a clear overview of the current state of knowledge [20],
- Identifying gaps: They highlight areas where research is lacking, thus guiding future research directions [21],
- Informing Policy and Practice: SLRs can influence decision-making processes by providing evidence-based insights. [21].

It is also worth mentioning some of the benefits conducting an SLR offers, that are:

- Rigorous methodology: The structured approach of SLRs enhances the reliability and validity of the findings [21],
- High citation potential: Well-executed SLRs often receive more citations than primary studies, as they provide a valuable resource for other researchers [20], [21],
- Guidance for Future Research: By identifying gaps in the literature, SLRs can direct future research efforts towards underexplored areas [21].

In conclusion, a SLR is an essential methodology for researchers seeking to synthesize existing knowledge in a rigorous and unbiased manner. By following a structured process, researchers can

produce high-quality reviews that not only contribute to the academic community but also inform practice and policy. The SLR methodology is particularly relevant in the diverse field of information systems, where it can help bridge gaps in knowledge and guide future research endeavors.

3.2.2 Citation Network Analysis (CNA)

CNA is a method used to examine a set of citations to identify new studies for further analysis. This process contributes to expanding the knowledge base of an ongoing study. As defined in [19], "a citation network is a system of channels which transform scientific knowledge or information [...] to position the work in the field based on previous knowledge" [[19], p. 404]. CNA enables the visualization of citation networks, highlights the frequency of articles cited, and identifies the most cited works, which form the foundational backbone of a research tradition and can be structured into distinct pathways [19].

CNA functions as a tool leveraging reference lists to trace prior contributions that influence the progression of research. Reference lists for CNA can be generated through various methods: (1) using citation software (such as HistCite [19], which creates citation lists from ISI Citation Databases), (2) applying a research algorithm, or (3) manually. However, since many citation tools are limited to specific databases, this study adopts a manual approach. We will examine the references of articles identified in the SLR and include additional references that meet the inclusion and exclusion criteria defined for this research.

3.3 Research objectives and questions

The very first task is to state our study objectives. The research methodology was designed to address three primary objectives:

- a) To systematically identify and critically evaluate existing literature on the role and application of AI in smart cities,
- b) To analyze the citation relationships between significant works to map the intellectual structure of the field.
- c) To provide evidence-based answers to the research questions guiding the study.

Having established the main objectives of our study, we now need to determine the Research Questions (RQs) that our study is going to answer. The derived research questions and explanations are as follows:

3.3.1 Research Question 1

(RQ1) What is the role and applications of AI in smart cities?

The aim of this research question is to identify all the major applications, technologies, services, use cases, scenarios, domains that AI is used within the context of smart city. The answer to that question will be extremely helpful as the basis for the next research question.

3.3.2 Research Question 2

(RQ2) How regional and cultural differences influence the adoption and effectiveness of AI in smart cities?

The aim of this question is to explore the impact of regional and cultural variations on the integration and performance of AI technologies within Smart Cities. These differences play a critical role in shaping how AI systems are adopted, customized, and utilized to address local challenges and priorities. This research is of great importance to researchers and practitioners as it provides insights into the socio-cultural and regional factors that influence the success and adaptability of AI-based solutions. The findings will contribute to a better understanding of how AI can be leveraged in smart cities based on regional diversity. Furthermore, this question will lay the foundation for classifying AI strategies so that they align with specific cultural and regional contexts and needs, thereby enhancing global scalability.

3.3.3 Research Question 3

(RQ3) What are the critical requirements that Smart Cities must fulfill in order to be Sustainable?

The aim of this question is to identify and analyze the basic requirements that enable smart cities to achieve and maintain sustainability. The value of this question is particularly high for researchers and practitioners in the field, as these sustainability-focused requirements define the framework and operational priorities of smart cities that seek long-term resilience and efficiency. The categorization and classification of Smart City applications will be grounded in these sustainability-oriented demands. Additionally, this question will provide a foundational classification that integrates sustainability principles into the broader architectural and functional design of Smart Cities, serving as a cornerstone for subsequent research and practical implementations.

These questions are central to understanding the transformative potential of AI in urban environments while identifying critical areas for further inquiry.

3.4 Search terms and literature criteria

Now that we have established the RQs that our study is going to answer, the next important step is to identify the most relevant literature and the source that we are going to extract them from. The foundation of any research study lies in identifying the most relevant source material to gather the necessary insights. In this context, our aim is to locate domain-specific research papers that focus on topics related to Smart Cities, AI, and Sustainability. To begin, we must undertake the initial step of preparing for our database search, which involves selecting the most suitable databases for our research needs.

While numerous research databases are available, it is essential to narrow down the list and choose those most appropriate for our objectives. The selection process is guided by several key criteria. The chosen databases must offer extensive coverage of the targeted subject areas, include a variety of material types (such as books, conference proceedings, journals, and magazines), provide advanced tools and options for refining search results, and enable citation tracking for deeper exploration of references. For that reason, we selected Google Scholar (<https://scholar.google.com>) in order to conduct our first selection of the most relevant research. The most important features that Google Scholar provides are its user-friendly search interface as it follows the functionality of the Google search engine, the ability to use advanced search options (Boolean operators AND, OR, NOT) and its extensive coverage of academic content encompassing a broad range of disciplines and material types from various scholarly databases.

Our initial search at Google Scholar showed that most of the articles were extracted from IEEE Xplore (<https://ieeexplore.ieee.org/>), SpringerLink (<https://link.springer.com/>), ScienceDirect / Elsevier (<https://www.sciencedirect.com/>) and the ACM Digital Library (<https://dl.acm.org/>). Other similar sources were available but were excluded as they mainly indexed data from the previously mentioned sources. Additionally, Google Scholar was not utilized for further articles searches due to its tendency to return results from various unrelated fields. In summary, the selected databases were designated as the primary sources for research articles in order to narrow the search specifically to the AI domain.

With the selection of the databases completed, we move to another task, that of the search term definition. We formed our search terms using Boolean strings (the known operators (AND) and (OR)) because of their ability to include multiple search terms simultaneously. The search terms are the following:

- **(AI OR Artificial Intelligence) AND “(smart OR digital OR intelligent) (cities OR city OR communities OR community) applications” AND (survey OR review OR overview)**
- **“(AI OR Artificial Intelligence) technologies” AND “(smart OR digital OR intelligent) (cities OR city OR communities OR community) applications”**
- **(AI OR Artificial Intelligence) AND “(smart OR digital OR intelligent) (cities OR city OR communities OR community) applications”**
- **(AI OR Artificial Intelligence) AND “(smart OR digital OR intelligent) (cities OR city OR communities OR community)” AND sustainability AND (survey OR review OR overview)**
- **(AI OR Artificial Intelligence) AND “(smart OR digital OR intelligent) (cities OR city OR communities OR community)” AND adoption AND (survey OR review OR overview)**

The logic behind these search terms is to identify all research studies relevant to AI applications in smart cities. More specifically, the first three search terms are used to identify the most relevant studies about the AI technologies that are used in the context of smart cities and their applications and thus answer the RQ1. Correspondingly, the fourth search term is used in order to identify relevant studies about sustainability of AI in smart cities which answer RQ2 and lastly, the fifth search term targets studies relevant to adoption of AI in smart cities which answer RQ3.

We now move on to the final step of our research study search preparation: defining the criteria for selecting literature material. These criteria consist of inclusion and exclusion rules that will guide us in determining which papers from the search results are suitable for inclusion in our source material pool.

The inclusion criteria are the follows:

- Papers that concern the use of AI related technologies in Smart Cities applications,
- Papers that are relevant with the latest developments of AI technologies in relation with the Smart Cities,
- Papers that concern Sustainability as a main factor of Smart City architectures,
- Papers that concern the adoption and effectiveness of AI technologies in specific regions.

The exclusion criteria correspondingly are the follows:

- Papers that are not peer reviewed,
- Papers that are still in progress,
- Papers originated from predatory open-access publishers,
- Papers not written in English language,
- Papers not available in full text,
- Papers that do not provide detailed content about our research questions.

3.5 Search results and execution process

In this section, we outline and analyze the literature search execution process, which consists of six distinct phases.



Figure 3.1: Execution process

Phase 1, focusing on database search preparation, was thoroughly detailed in the previous section. With the databases and search terms defined, we now proceed to Phase 2. In that phase we perform the database search using our already defined search terms, in order to identify the most relevant papers to our research and add them to Phase 3, which is the initial research paper pool, from where we will select some key papers to perform the SLNA. Phase 2 was one of the most important tasks to our effort. We needed to refine the available source material and find the most relevant to our research questions. We methodically search the titles, abstracts and full text of each and every paper. Applying the literature selection criteria outlined in the previous section, we refine our source material pools to achieve a significantly improved quality. The results from Phase 2 and 3 initially extracted 77 papers from Google Scholar and after further review, 19 were selected to be added to Phase 3. Because the articles found were not as many as we expected, we decided to repeat this process at IEEE Xplore in order to find more relevant research. Therefore, 82 papers were extracted and 50 of them were added to Phase 3.

Now that Phase 2 and 3 are complete, we continue with the next phase, Phase 4, which is the research papers selection. From the initial research paper pool, we selected the following papers to begin applying the SLNA in order to find more related research to our thesis and therefore, expand our material pool: [23], [5], [6]. The rest of the papers that remain in the Phase 3 were also used to extract more information in specific topics where it was needed. In general, the papers that were chosen to be thoroughly investigated and analyzed for the development of our thesis can be found in the table below.

Table 3.1: Research paper selection

Research Paper Title	Year
Future Trends and Current State of Smart City Concepts: A Survey	2020
Applications of Artificial Intelligence and Machine learning in smart cities	2020
Bibliometric Mapping of Trends, Applications and Challenges of Artificial Intelligence in Smart Cities	2022
On big data artificial intelligence and smart cities	2019
Federated learning for smart cities: A comprehensive survey	2023
Integration of IoT-Enabled Technologies and Artificial Intelligence (AI) for Smart City Scenario	2023
A review on deep learning for future smart cities	2020
Future smart cities requirements emerging technologies applications challenges and future aspects	2022
Applications of federated learning in smart cities recent advances taxonomy and open challenges	2022

Artificial Intelligence in Smart City Applications: An overview	2022
Artificial Intelligence in Smart Cities Systematic Literature Network Analysis	2019
A Review of AI for Urban Planning Towards Building Sustainable Smart Cities	2021
A Systematic Review of Explainable Artificial Intelligence in Terms of Different Application Domains and Tasks	2022
Artificial Intelligence and Machine Learning for Ensuring Security in Smart Cities	2021
Explainable Artificial Intelligence for Developing Smart Cities Solutions	2020
Smart Cities in the Era of Artificial Intelligence and Internet of Things	2018
Use of Artificial Intelligence in Smart Cities for Smart Decision Making A Social Innovation Perspective	2022
Comprehensive systematic review of information fusion methods in smart cities and urban environment	2024
Proceedings of the 18th International Conference on Computing in Civil and Building Engineering	2020
Artificial intelligence and the future of smart cities	2018
A Survey of Explainable Artificial Intelligence for Smart Cities	2023
Applications of artificial intelligence technology in the development of smart cities	2023
From Artificial Intelligence to Explainable Artificial Intelligence in Industry 4.0 A Survey on What How and Where	2022
Edge Computing Enabled Smart Cities: A Comprehensive Survey	2020
Fog Computing Applications in Smart Cities: A Systematic Survey	2020
Smart Cities: A Structured Literature Review	2023
Artificial Intelligence (AI): Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy	2019
Artificial Intelligence Techniques for Smart City Applications	2020
The rise of AI urbanism in post-smart cities A critical commentary on urban artificial intelligence	2023

Artificial Intelligence and Smart Cities: A Bibliometric Analysis	2022
Barriers to artificial intelligence adoption in smart cities: A systematic literature review and research agenda	2023
Special issue on “Applications of Artificial Intelligence in Evolution of Smart Cities and Societies”	2021
Research trends, themes, and insights on artificial neural networks for smart cities towards SDG-11	2023
The Dual Role of Artificial Intelligence in Developing Smart Cities	2022
Artificial Intelligence in the Urban Environment: Smart Cities as Models for Developing Innovation and Sustainability	2020
Green Artificial Intelligence: Towards an Efficient, Sustainable and Equitable Technology for Smart Cities and Future	2021

In Phase 5, we aim to broaden our search to include additional sources of potentially relevant material that may not have been incorporated into the previous phase for various reasons. One possible explanation is that our initial search did not encompass all suitable databases, as not every research paper is indexed across multiple platforms. Another reason could be that the search terms used did not fully capture all material within the relevant domain. This will give a much bigger material pool of relevant research to develop our thesis more in-depth and use most of the material available to us.

With the finalization of our research paper list, we proceeded finally to the last phase. Phase 6 is dealing with the knowledge extraction task, the subsequent analysis of the extracted knowledge. Finally, Figure 3.1 depicts the whole literature execution process in a graphical way.

Phase 6 of the execution process deals with the data extraction. With our source material pool formed, we now extract the appropriate knowledge from the selected research papers (Table 3.1) in order to answer the RQs of our study. Specifically, we studied carefully each of the research papers and recorded the needed information and then applied the SLNA, in order to enrich our material pool and find more relevant literature which will help answer our RQs and broaden our knowledge. During the data analysis process, the collected data is organized into a more structured format, allowing us to develop concepts, categories, and mappings that provide clear and comprehensible answers to the research questions that motivated this study.

3.6 Threats to validity

In this section, we conduct a thorough risk assessment of the entire literature search execution process. Our objective is to identify any potential factors that could compromise the optimal outcomes of our research effort. While some of these risk factors have been briefly mentioned earlier in the thesis, we provide a more detailed analysis here for the convenience of our readers.

The first threat to the validity of our work is the potential omission of a significant number of relevant research papers from our source material pools. Several factors could contribute to this issue. First, we may not have accessed all relevant databases, meaning we lack visibility to database-exclusive

research papers. Second, the search terms we used may not have been optimal, which could result in missing papers that fall within our research scope but were not captured by our queries. Lastly, we might have overlooked research papers published immediately after we concluded our search process. Whether one of these reasons applies, or in the worst case all of them do, this poses a substantial risk to the validity of our findings. The best way to minimize this threat that we have at our disposal is the extension of the search effort by taking advantage of the research papers' references. That was the main reason why we chose the SLNA methodology over the other methodologies available to us. In this manner, we establish a chain of resource material, linking references together to build the most comprehensive source material pool possible, ultimately enhancing the quality of our research outcomes. By applying the SLNA methodology, we significantly mitigate the impact of this threat and improve the reliability of our findings.

A second possible threat we may encounter is the risk of personal judgement errors. These errors could result in the unintentional exclusion of valuable resource material during the paper selection phase. The human element, along with its inherent subjective characteristics, presents challenges that can adversely impact any endeavor. To mitigate these issues, we implement strategies that include a thorough examination of each research paper and ensuring redundancy during the paper selection process. Specifically, we thoroughly analyze every potential research paper, considering the title, abstract, and full text, while evaluating it against our established selection criteria and research questions. For each paper that is excluded during the selection phase, we revisit it at a later date to verify the accuracy of its initial exclusion. Only after this reexamination will we definitively remove the paper from our source material pools.

Chapter 4: The Role and Applications of AI in Smart Cities

4.1 Introduction

AI has become a transformative force in the ongoing evolution of smart cities. While the integration of ICT and IoT provided the initial digital infrastructure for smart urban environments, AI now serves as the "brain" of the city, enabling adaptive, predictive, and autonomous systems that enhance urban governance, sustainability, and quality of life [5], [6], [9]. In this chapter, we systematically explore the role and diverse applications of AI in smart cities, focusing on critical urban domains such as governance, mobility, sustainability, public safety, healthcare, and economic development. Furthermore, we analyze key challenges, including ethical considerations, privacy concerns, and technological barriers that accompany AI integration into urban ecosystems [24], [7].

4.2 AI applications in smart cities

AI technologies are applied across a broad range of urban domains. Table The Role and Applications of AI in Smart Cities.1 below summarizes the main sectors where AI applications are implemented in smart cities.

This distribution illustrates the areas where AI technologies are making the greatest impact, with healthcare and transportation sectors leading the way.

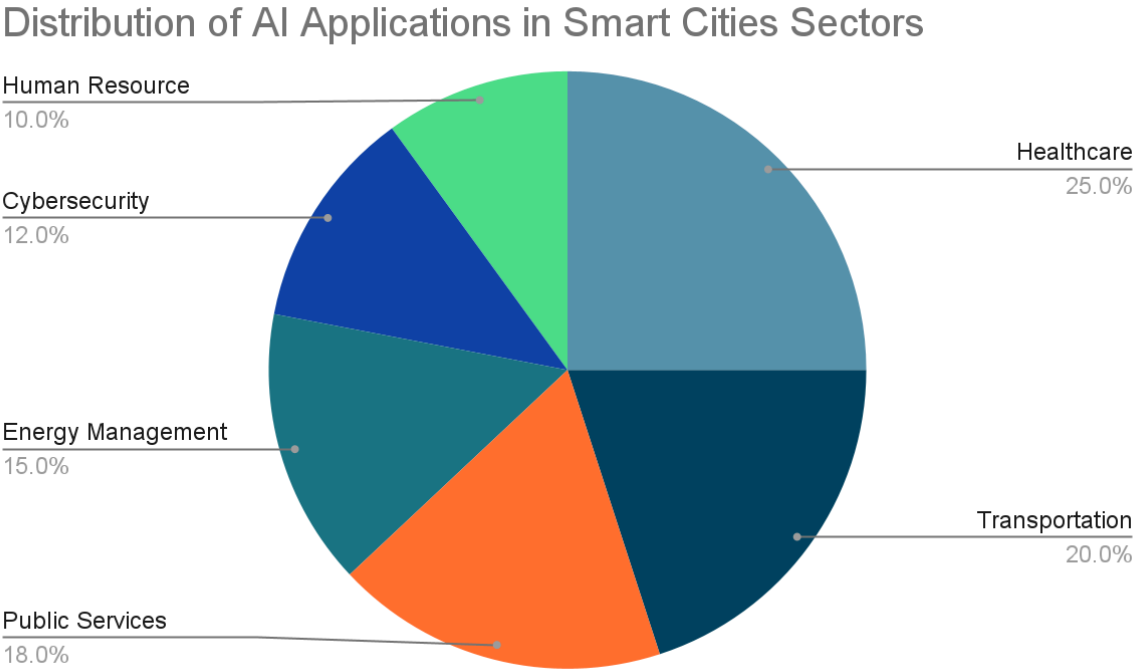


Figure 4.1: Distribution of AI applications in smart cities sectors [9]

4.2.1 AI for urban planning and smart governance

Urban planning has traditionally been a complex, data-intensive process requiring the analysis of diverse socio-economic and environmental variables. AI enhances this process through predictive modeling, scenario analysis, and optimization techniques [25]. Tools like machine learning algorithms can predict urban growth patterns, optimize zoning regulations, and facilitate evidence-based decision-making, ultimately leading to more resilient and sustainable cities [6].

Agent-based simulations and AI-supported digital twins are now widely used to model urban dynamics, allowing policymakers to test the outcomes of different planning strategies in a virtual environment before implementation [7], [26]. AI thus supports not only efficiency but also transparency and participatory governance by enabling open data platforms and citizen engagement tools [6], [7].

4.2.2 AI in transportation and mobility

Transportation remains a cornerstone of smart city initiatives, and AI-driven solutions are redefining urban mobility. Machine learning and deep learning models are deployed to optimize traffic flow, predict congestion patterns, and enhance public transportation efficiency [5], [27], [28]. AI-powered traffic management systems can adapt traffic signals in real time to reduce congestion and emissions [27] [29].

Moreover, AI facilitates the development of autonomous vehicles and ITS, which promise safer, greener, and more efficient urban mobility [5], [8], [30]. Federated learning approaches are also emerging, enabling decentralized training of AI models for traffic prediction and route optimization while preserving data privacy [8], [31].

4.2.3 AI for sustainability and environmental management

AI plays a key role in achieving environmental sustainability goals in smart cities. Applications include smart energy grids that use AI to optimize energy distribution in real time, AI-enhanced waste management systems that predict waste generation and water management platforms that monitor consumption patterns and detect leaks [6], [5], [9].

In addition, predictive analytics are used to predict environmental risks, such as floods and air pollution, allowing preventive measures to be taken [9]. Integrating AI with IoT networks creates "urban nervous systems" capable of sensing and responding to environmental challenges autonomously [6].

4.2.4 AI and public safety

Public safety is another critical aspect where AI has made significant impacts. AI systems assist in crime prediction, emergency response optimization, and surveillance [27], [31]. Predictive policing models analyze historical crime data to allocate law enforcement resources more efficiently, while AI-enhanced video analytics can detect unusual activities in real time [31].

However, these applications raise serious ethical and privacy concerns, especially regarding bias in predictive models and mass surveillance practices [24], [32]. Addressing these challenges requires implementing XAI techniques and adhering to strict governance frameworks [32], [33].

4.2.5 AI in healthcare

Healthcare services in smart cities benefit substantially from AI. AI is used for predictive health analytics, personalized medicine, and public health monitoring [27], [9]. During pandemics, AI-based tools have been employed for early outbreak detection, contact tracing, and healthcare resource allocation [5].

Smart healthcare platforms integrate AI with wearable devices to continuously monitor patients, enabling early detection of anomalies and reducing the burden on hospitals [5], [29], [34]. Federated learning models have also been applied to enable collaborative healthcare research without compromising patient data privacy [35].

4.2.6 AI for economic and business development

AI is a catalyst for economic growth and innovation in smart cities. It enhances business intelligence, automates service delivery, and fosters new business models such as platform economies and AI-as-a-service [27], [10], [36].

AI applications in financial services, real estate, tourism, and retail optimize resource use, predict market trends, and personalize consumer experiences, thereby strengthening urban economies [5], [10], [37]. Smart city platforms supported by AI also promote entrepreneurship and support small businesses by providing them access to big data analytics and digital marketplaces [10].

4.3 Challenges and ethical considerations

4.3.1 Privacy and surveillance concerns

The pervasive deployment of AI and sensor networks in urban spaces raises profound concerns about citizen privacy and potential misuse of surveillance technologies [24], [32]. Cases of facial recognition misuse and opaque data practices have demonstrated the urgent need for transparent data governance policies [24], [32].

4.3.2 Bias and fairness in AI algorithms

AI systems trained on historical data may unintentionally reinforce existing social biases, particularly in sensitive areas such as policing, hiring, or service delivery [24], [32], [31]. The development of explainable AI (XAI) methodologies aims to address these challenges by making AI decision-making processes more transparent and reliable [32], [38], [39].

4.3.3 Implementation barriers

Despite the promising potential of AI, there are obstacles to large-scale implementation in smart cities. Some of these are technological fragmentation, lack of interoperability standards, high economic costs,

and resistance from stakeholders [6], [7], [5]. In addition, the lack of governance structures and AI ethics guidelines further complicates development [7], [32].

4.4 Conclusions

AI has become a critical factor for smart cities, offering many innovative opportunities for city improvement in areas such as planning, mobility, sustainability, public safety, healthcare and economic development. Nevertheless, the integration of AI into city management must be approached critically, with careful consideration of ethical, legal, and societal implications [6], [9].

Future research and policy efforts should focus on promoting transparent, inclusive, and human-centered AI systems, fostering trust among citizens, and ensuring that the deployment of AI in smart cities contributes to equitable, sustainable, and resilient urban futures [24], [32], [7].

As we mentioned earlier, in the following chapters, we will further explore how sustainability principles can be embedded within smart city frameworks, building upon the transformative capabilities of AI outlined in this chapter.

Chapter 5: The Influence of Regional and Cultural Differences on the Adoption and Effectiveness of AI in Smart Cities

5.1 Introduction

The integration of AI in smart cities is not a one-size-fits-all approach; rather, it is significantly influenced by regional and cultural differences. The rapid urbanization of the 21st century has been a driving factor for cities worldwide to embrace new, bold strategies in order to radically enhance livability, sustainability, and efficiency. As mentioned in previous chapters, the concept of smart cities has evolved into an emerging powerful framework which creates the requirement to utilise advanced technologies such as AI, IoT and big data analytics to address ever-evolving, complex, urban challenges. However, the success of smart city initiatives is not the same across all regions and cultures due to mitigating factors such as local governance, economic conditions, and technological infrastructure, which play a decisive role in the effectiveness of any AI-based solutions in effect.

This chapter investigates the interconnected interaction between regional and cultural differences in the effectiveness of the adoption and impact of AI in smart cities. By process of observation of the evolution of smart cities, the examination of key factors and the in-depth analysis of cases from around the world, we can highlight how various different environments may influence urban innovation. The conclusion of the chapter is focused on how these findings can provide knowledge to further promote equitable and sustainable smart city initiatives.

5.2 Evolution of smart cities from 2011 to 2021

The concept of smart cities has evolved significantly during the decade between 2011 and 2021. In the course of this decade, it has been characterized by rapid technological developments, the evolution of models of governance and radical changes in urban priorities, thus providing us with a fascinating narrative of why some cities embraced smart city initiatives while others still have not. If we analyze the list of smart cities from 2011 [40] and 2021 [41], one can easily observe notable changes in composition, geographic diversity combined with multiple underlying factors of smart city development. This section aims to compare these lists, delve into the reasons behind the successes and failures as well as explore the impact of regional and cultural dynamics around this evolution.

5.2.1 Comparative analysis of smart cities: 2011 vs. 2021

Primarily, the smart city landscape began to take shape in 2011 with a few cities located in North America and Europe. Cities such as Amsterdam, Singapore, and San Francisco stood out for their pioneering initiatives in integrating ICT to enhance urban living. Their main area of focus was largely targeted to fundamental technologies such as high-speed internet, basic urban data collection and pilot projects in areas such as transportation and energy management [40].

By 2021, the list of smart cities had expanded significantly, which indicated a steady increase in representation from Asia, the Middle East, and even Africa. Cities such as Dubai, Shenzhen, and Nairobi emerged as notable players in the smart city arena, driven by tailored strategies that addressed local challenges and leveraged regional strengths [41]. This geographic diversification reflects the

global diffusion of smart city principles and highlights the growing recognition of technology's potential to tackle urban challenges worldwide.

Table 5.1: Top ranked smart cities in 2011 and 2021 [42], [43].

LIST OF TOP SMART CITIES IN 2011 AND 2024		
RANKING	2011	2021
1	Songdo, South Korea	Singapore, Indonesia
2	Lavasa, India	Zurich, Switzerland
3	PlanIT Valley, Portugal	Oslo, Norway
4	Skolkovo, Russia	Taipei, Taiwan
5	Masdar, United Arab Emirates	Lausanne, Switzerland
6	Wuxi, China	Helsinki, Finland
7	King Abdullah Economic City, Saudi Arabia	Copenhagen, Denmark
8	Dubuque, Iowa	Geneva, Switzerland
9	Ho Chi Minh City, Vietnam	Auckland, New Zealand
10	Nano City, India	Bilbao, Spain

Key differences between 2011 and 2021 include:

1. Technological advancements:
 - In 2011, cities relied heavily on foundational ICT infrastructure, such as broadband and e-government services, to drive their smart initiatives.
 - By 2021, the integration of AI, IoT, and big data analytics became pivotal, enabling real-time decision-making in areas like transportation, energy management, and healthcare [44].
2. Domain of focus:
 - In 2011, efforts were concentrated on infrastructure and service improvements, such as traffic management and e-governance.
 - By 2021, the focus had expanded to include sustainability (e.g., smart energy grids and waste management), resilience (e.g., disaster response), and inclusivity (e.g., digital inclusion initiatives) [45].
3. Leadership and Governance:
 - Early smart cities emphasized public-private partnerships, often led by local governments [46].
 - In 2021, smart city governance evolved to involve broader stakeholder engagement, including citizens and international collaborations.

5.2.2 Why some cities became smart while others stagnated

The development trajectory of smart cities in the decade under review highlights contradictory results shaped by their unique approaches and challenges. The cities which were marked as more successful, were often characterized by visionary leadership, as leaders prioritized innovation and long-term planning. A great example is the Singaporean government, which played a strategic role in the integration of smart technologies into urban planning and services. Furthermore, cities that quickly adapted to emerging technologies, such as AI and IoT, showed improved efficiency and sustainability in their activities [44]. Another factor that also proved to be vital was the continuous investment in ICT and urban infrastructure which enabled cities to scale up their smart initiatives in a more effective manner. When stronger emphasis on citizen-centric solutions, participatory governance, and personalized services was given, faster adaptation and further public support was ensuredly observed in these cities [46].

Contradictory to this image, the cities that stagnated may have often faced significant resource constraints, especially in developing regions. Their ability to implement ambitious smart city projects was repressed largely because of financial and technical limitations. Partial implementation, characterized by not well-planned strategies, also played a pivotal role in the failure of some cities to achieve smart city status. Additional obstacles were usually created by institutional inaction and stakeholder resistance which further delayed the progress. Weak governance structures and corruption further undermined the potential of many promising projects causing them to stagnate [47], [48].

5.2.3 Lessons from the decade

The integration of AI into city management has emerged as a transformative factor which enabled the automation of processes and the capability of predictive decision-making. The use of big data highlights the vast importance of robust data governance frameworks. The shift towards participatory governance models was a notable trend which emphasized citizen participation in the co-creation of smart city solutions. The span of the decade was also marked by a growing focus on sustainability while climate resilience and environmental goals were becoming central pillars of smart city initiatives. The alignment of these efforts with further global sustainability goals has proven essential to ensure long-term success [25] - [29].

In conclusion, the evolution of smart cities from 2011 to 2021 reflects broader technological, social, and new governance trends. Cities that harnessed emerging technologies, adopted citizen-centric approaches, and prioritized sustainability rose to prominent positions. Conversely, those that were unable to address all the above fell behind. The conclusions we draw from this decade are that cities that want to look to the future must pay close attention to adaptability, inclusion, and resilience in building truly smart urban areas [45].

5.3 What makes some cities smarter than others

As we have already mentioned, not all cities are progressing at the same pace towards becoming smart cities. Some are ahead of the curve and setting global benchmarks, while others are lagging behind despite having the same resources. This inequality is mainly due to differences in governance, innovation ecosystems, citizen participation, and technological infrastructure. Drawing on key insights

from case studies, this section explores in more depth what makes some cities consistently smarter than others [29], [31].

5.3.1 Core factors driving smart city excellence

A critical review reveals several interrelated factors that contribute to the success of smarter cities which include visionary leadership, a robust data ecosystem, proactive citizen engagement and adaptive governance frameworks.

5.3.1.1 Visionary leadership and governance

Smart cities thrive under the type of leadership that envisions long-term urban development combined with technological innovation and sustainability. Cities such as Singapore and Helsinki are a sterling example of this approach, where their municipal leaders have actively prioritized the integration of digital infrastructure into urban planning. Effective governance also plays a critical role because it enables the collaboration between public institutions and private enterprises. This way it is ensured that the smart city initiatives will be in alignment with the goals of the society. In addition, this form of adaptive governance plays a critical role because of its capability to revise policies as a response to changing circumstances [45], [46], [49].

5.3.1.2 Data ecosystems and technological integration

Another key component for a successful smart city is a strong and well developed data ecosystem. When cities make their data open and available and make sure that different systems can work together, it becomes much easier to share and analyse information efficiently. This kind of setup not only helps city operations to run more smoothly but also creates space for new ideas and smarter decision making. Cities such as Zurich and Amsterdam use real-time data for urban management, from traffic optimization to energy consumption as well as monitoring the ability to leverage IoT devices. AI analytics and big data has proven indispensable in delivering smarter services [47], [46].

5.3.1.3 Citizen-centric approach

Citizen engagement also plays a pivotal role in the success of smart city initiatives. Participatory governance models—involving citizens in decision-making through platforms like hackathons and feedback systems—ensure that technological solutions align with local needs. For instance, Barcelona’s adoption of citizen-centric planning tools illustrates how inclusive approaches enhance public trust and utility [46], [45].

5.3.1.4 Innovation ecosystems

Cities fostering vibrant innovation ecosystems—comprising research institutions, startups, and industry partnerships—are often ahead in the smart city race. Cities like Stockholm and Seoul actively foster innovation through incubators, funding programs, and collaboration between academia and industry. These ecosystems enable rapid prototyping and deployment of smart solutions [49], [45].

5.3.1.5 Barriers to smart city progress

Despite these drivers to excellence, some cities face obstacles that hinder their ambitions. Budget limitations, resistance to change and fragmented infrastructure are often some of the main inhibiting factors. For example, the overall progress might stall if some city departments start to operate alone, without unified systems. In a similar manner, some issues like unequal digital access between residents and data privacy concerns can make some residents more concerned and skeptic, which as a result will make it harder to build trust and maintain progress [47], [46].

5.3.1.6 Conclusion

The journey of transforming a city to smart city is not simple and involves a combination of technologies, governance and active citizen participation. Cities that stand out among the others demonstrate a strong commitment to innovation, inclusion and sustainability as they also invest in strong data ecosystems and their citizens' engagement. These cities provide the blueprint for other cities seeking to achieve smart city excellence [49], [46], [45].

5.4 Cases of AI applications in smart cities around the world

5.4.1 Introduction

As we have already established in previous sections, AI has become a key element in smart city development around the world mainly because it offers alternative and creative ways to tackle pressing urban challenges. In the following section, we attempt to explore real-world examples of how smart cities apply AI in order to make their services more efficient, support sustainable growth and enhance their residents' daily lives. With the examination of these case studies, our goal is to understand how different cities in different places are turning AI into practical solutions for complex challenges [44], [49], [50].

5.4.2 AI-driven innovations in urban services

- **Traffic management and mobility:** AI-based traffic management systems have revolutionized traffic management systems in cities such as Barcelona and Los Angeles [44], [50]. By analysing real-time traffic data, these AI systems play a crucial role in the optimization of traffic flow, the reduction of congestion and the improvement of the efficiency of public transport. For example, Los Angeles has implemented an AI-based traffic signal synchronization system which results in significant reductions in travel time and vehicle emissions [44]. Another great example is Singapore, where AI is integrated into autonomous vehicle operations which resulted in enhanced public transportation networks and reduced reliance on private vehicles [44]. These approaches not only address congestion and other motility challenges but also promote sustainability goals.
- **Energy optimization:** Some cities like Copenhagen and Amsterdam have adopted AI-driven energy management systems to improve efficiency and sustainability. In these cases, AI algorithms analyze energy consumption patterns, predict demand and optimize the use of renewable energy sources in order to improve their efficiency. Copenhagen's smart grid system is an example of this, where AI is integrated to balance energy supply and demand

with minimal waste [50]. On the other side of the world, Tokyo is harnessing AI in its disaster-resilient energy systems to ensure reliable power supply in case of emergencies. In general, these systems use predictive analytics to prepare for potential outages and maintain urban resilience [50].

- **Public safety and surveillance:** In cities like London and Dubai we see applications of AI in order to improve their public safety. In the case of Dubai, AI-powered surveillance systems use facial recognition patterns and behavioural analysis to prevent crime and thus ensure public safety. Similarly, London uses AI in various applications regarding the authorities, which aids police with law enforcement and resource allocation in order to counter potential threats. Apart from all the benefits however, these applications also raise ethical concerns about data privacy and security which marks the rising need for stronger regulatory frameworks.
- **Waste management:** AI has also drastically contributed to efficient waste management. A great example of this is Seoul's case study where the operating waste collection systems use sensors and data analytics to optimize collection routes and therefore are able to reduce the operational costs and their environmental impact. These systems are also really helpful to recycling because they monitor waste composition and they can provide feedback to the residents.
- **Healthcare services:** Another area where AI has played a very important role is healthcare and we can see this at Helsinki's and Toronto's cases. Helsinki's AI-based health monitoring systems provide real-time insights into public health trends which enable proactive interventions. In Toronto's case, AI-driven telemedicine platforms have expanded access to healthcare, especially during the COVID-19 pandemic.
- **Education and citizen engagement:** Education and citizen engagement are also areas that AI utilization is reshaping. In Shanghai, AI is being used to personalise education by adopting to the learning process of each student. Meanwhile, in Barcelona AI chatbots are adopted to strengthen their citizen engagement in order to provide their residents with real-time updates on public services and respond effectively to their questions and needs. Together, these applications highlight the potential of AI to create more inclusive and responsive urban environments.

5.4.3 Lessons from AI applications

These examples show how AI can tackle a wide range of urban problems, but making these systems work as intended often depends on factors like having the right technology knowledge, strong government support and whether the public is open to change [47], [51]. At the same time though, ethical issues like privacy, fairness and transparency must be taken into account.

5.4.4 Conclusion

AI applications in smart cities show us the potential of technology to address a wide range of urban challenges. By balancing innovation with ethical considerations the cities can ensure equal benefits for all their citizens.

5.5 Case Studies Around the World

5.5.1 Introduction

Smart cities around the world have shown a wide range of innovative approaches, technologies and values which are reflected in their unique regional and cultural backgrounds. In the section, we will focus on the leading smart city examples of each continent and will attempt to highlight their strategies in order to finally reach a conclusion by analysing how local factors can shape the adoption and the impact of AI solutions.

5.5.2 Europe: Copenhagen, Barcelona, and Amsterdam

Copenhagen's smart city framework's primary focus is on sustainability and utilization of AI to manage energy consumption and reduce carbon emissions [47], [50]. The city's smart grid and AI driven waste management systems are great examples of the cities' commitment to its environmental goals. Furthermore, the high level of community participation is a great illustration of Denmark's known democratic and cultural ethos.

Barcelona has integrated AI technologies in order to enhance urban living through citizen-centric solutions. AI-powered chatbots improve public service delivery, while smart sensors optimize urban mobility and resource management. The city's innovative approach reflects a culture of collaboration and creativity which drives its success as a smart city.

Amsterdam has prioritized sustainability and connectivity in its smart city initiatives. By integrating AI in water management and urban planning, the city addresses environmental challenges while promoting economic growth. Amsterdam's emphasis on open data and innovation fosters a collaborative environment for public and private sector partnerships.

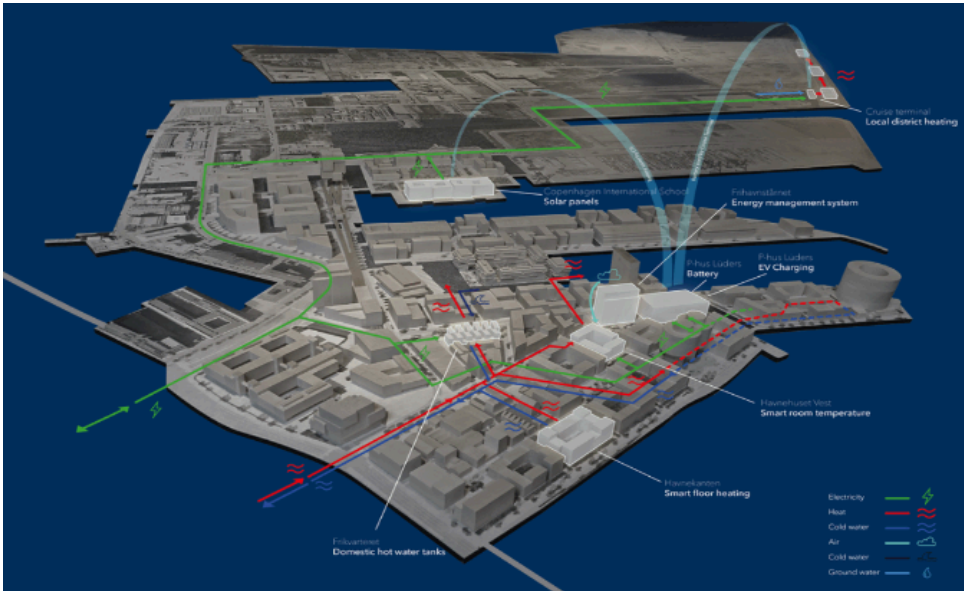


Figure 5.1: A visual representation of Copenhagen's strategies to achieve carbon neutrality by 2025 [52].



Figure 5.2: An overview of Barcelona's smart city features and innovations [53].



Figure 5.3: A visual representation of Amsterdam as a hub of smart city innovation [54].

5.5.3 Asia: Singapore, Tokyo, and Seoul

Singapore stands out as a global leader in smart city innovation due to its comprehensive Smart Nation initiative. Emphasizing efficient governance, digital inclusion, and public trust, the city-state integrates AI into urban planning, healthcare, and mobility systems. Notable implementations include AI-powered predictive healthcare systems and real-time traffic management solutions, ensuring efficiency and sustainability. Culturally, Singapore's focus on societal harmony and trust enhances the acceptance and efficacy of AI applications.

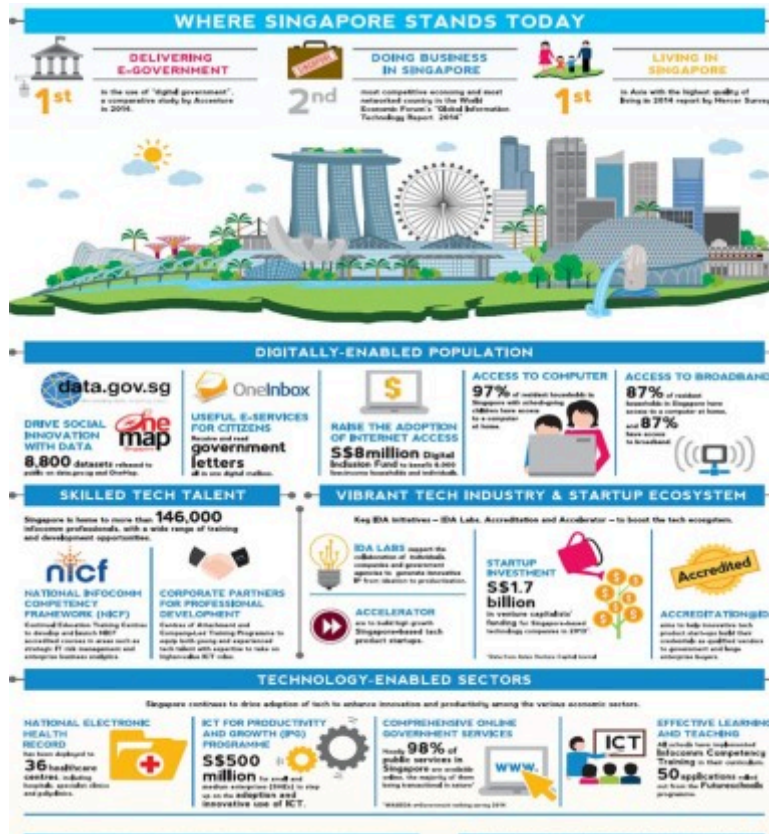


Figure 5.4: An infographic detailing Singapore's Smart Nation initiatives [55].

Tokyo exemplifies how cultural precision and safety are embedded into smart city projects. The city utilizes AI for disaster management, ensuring robust infrastructure resilience against earthquakes and other emergencies. Smart transportation systems like AI-driven metro scheduling reflect Tokyo's emphasis on punctuality and efficiency.



Figure 5.5: A depiction of Tokyo's advancements in smart city technologies [56].

Seoul leverages its strong technology sector to deploy AI in waste management, public transportation, and energy optimization. Its focus on citizen-centric solutions, such as smart housing and digital services, ensures inclusivity and widespread adoption.



Figure 5.6: An overview of Seoul's smart city comprehensive plan [57].

5.5.4 North America: Toronto, Los Angeles, and New York City

Toronto's smart city initiatives emphasize digital innovation and inclusivity. The city leverages AI for healthcare, telemedicine, and urban planning, ensuring equitable access to services. Toronto's diverse population and open governance foster an inclusive approach to AI adoption.

Los Angeles utilizes AI to address urban mobility challenges, implementing systems that optimize traffic flow and reduce emissions. The city's entertainment-driven culture also influences its adoption of AI in creative industries, showcasing the versatility of smart city technologies.



Figure 5.7: Toronto's smart city [58].

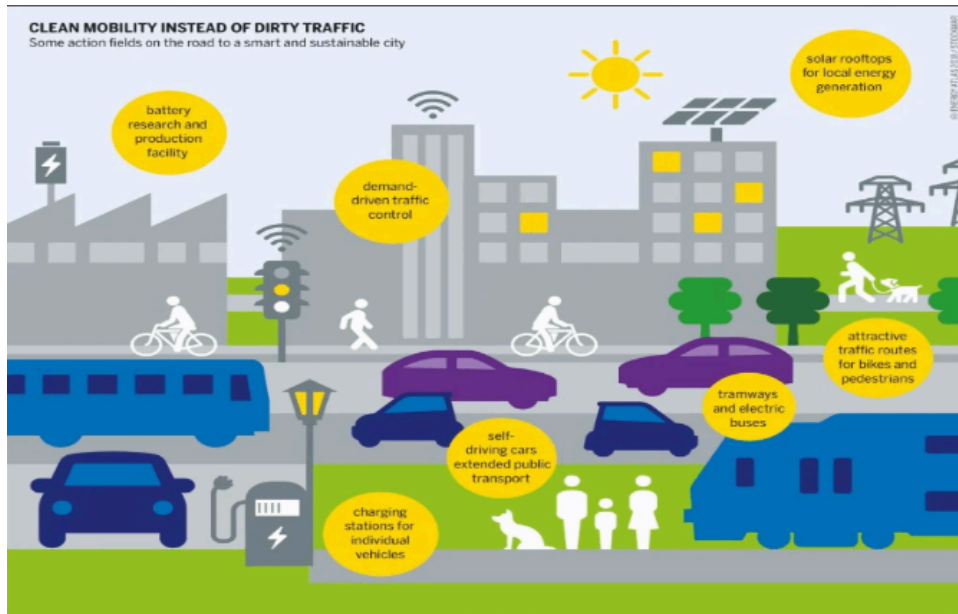


Figure 5.8: An illustration of Los Angeles' plans to become a smarter city by the 2028 Olympics [59].

New York City combines AI with big data analytics to enhance public safety, transportation, and waste management. The city's investments in smart infrastructure and its focus on economic inclusivity ensure that technological advancements benefit all residents. Programs such as LinkNYC demonstrate a commitment to providing free public Wi-Fi and digital services to bridge the digital divide.



Figure 5.9: A LinkNYC kiosk providing free public Wi-Fi in New York City [60].

5.5.5 Middle East: Dubai and Tel Aviv

Dubai's ambitious smart city vision focuses on AI-driven governance, mobility, and public safety. Its initiatives include AI-powered policing and autonomous transportation systems. Cultural factors such as a forward-looking leadership and a strong emphasis on technological excellence drive Dubai's rapid advancements. Additionally, Dubai's Expo 2020 showcased several smart city innovations, further cementing its status as a global leader in urban technology.



Figure 5.10: The launch of Dubai's new center for AI aimed at transforming government services [61].

Tel Aviv has emerged as a tech innovation hub, with a focus on digital services and AI applications in urban planning [51]. Its Smart City Platform provides residents with personalized digital services, enhancing citizen engagement and satisfaction.



Figure 5.11: A rendering of the Atidim Park [62].

5.5.6 Africa: Nairobi, Cape Town, and Kigali

Nairobi represents emerging smart city innovation in Africa, leveraging AI for urban challenges like traffic management and financial inclusion. The city's adoption of mobile money platforms, powered by AI, reflects its unique regional needs and entrepreneurial spirit. Nairobi also focuses on e-governance solutions to enhance service delivery.

Kigali’s smart city initiatives emphasize sustainability and innovation [41]. By deploying AI in infrastructure planning and public services, the city aims to position itself as a leader in Africa’s digital transformation. Kigali’s partnerships with international tech firms and NGOs have been instrumental in accelerating its smart city goals.



Figure 5.14: A depiction of the Kigali Innovation City (KIC) Smart City Project [65].

5.5.7 Oceania: Sydney and Wellington

Oceania’s smart city initiatives focus on sustainability, livability, and resilience to climate change. Sydney leverages AI to enhance urban mobility, improve energy efficiency, and manage natural resources. The city’s smart transportation networks and commitment to renewable energy underscore its emphasis on creating a sustainable urban future.



Figure 5.15: Sydney smart eco-city [66].

Wellington, New Zealand, integrates AI to address seismic risks, utilizing predictive analytics to bolster infrastructure resilience against earthquakes. The city also values inclusivity, with initiatives to ensure smart solutions are accessible to all residents, aligning with its community-driven governance model.

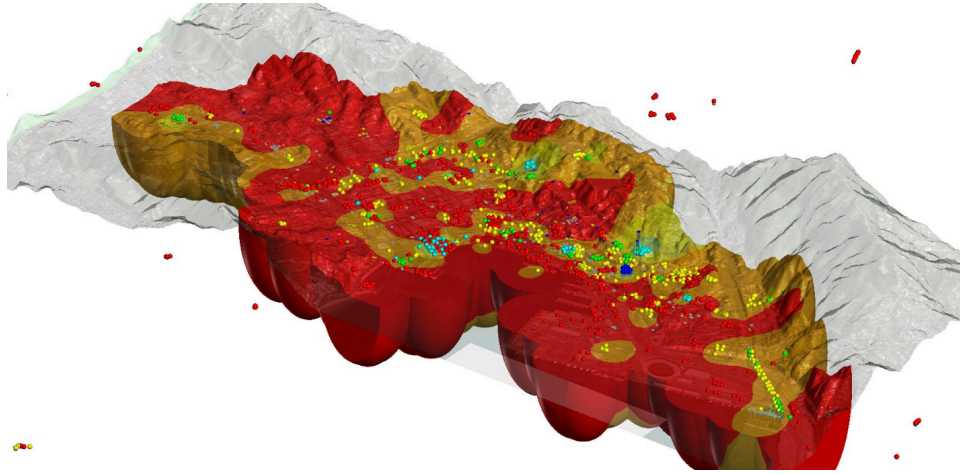


Figure 5.16: A 3D model illustrating Wellington's subsurface, aiding in understanding seismic risks [67].

5.5.8 What each continent values the most

The priorities and values that shape smart cities and the effectiveness of AI vary significantly between continents, influenced by local challenges, cultural attitudes and development goals. These values are crucial for defining strategies and determining the success of smart city initiatives.

- Europe: Sustainability and community engagement are at the heart of the approach to Europe's smart cities initiatives. Cities such as Copenhagen and Amsterdam are focusing on reducing their carbon footprint through the use of energy efficient systems and smart grids. An important element is the attitude of the European Union on data privacy issues as it is constantly changing the framework for data protection and in many cases has been quick to react.
- Asia: Cities in Asia prioritise efficiency, resilience and, most importantly, economic growth. Singapore's Smart Nation initiative reflects the strong emphasis on efficiency and trust in governance, while Tokyo and Seoul focus on infrastructure resilience and technological innovation. Large urban centres in Asia are placing a strong emphasis on integrating technology into everyday life and we see this in the existence of innovative applications for the transportation of people and daily transactions.
- North America: Innovation and inclusion are key to the culture in North America and could not be absent from their smart city applications. From Toronto citizens' equal access to healthcare services through AI to Los Angeles' innovative traffic management solutions, North America continues to show global innovation across all sectors.
- Middle East: In the Middle East we also find a more futuristic approach. Dubai is an example of this with its ambitious and innovative autonomous transport and AI governance projects. Cities in the region are often focused on demonstrating global leadership in innovation and

creating smart solutions, and they become even more valuable when we see them implemented in dry climates and high temperatures.

- Africa: In Africa, the focus is on addressing key urban challenges and improving economic growth. Nairobi’s use of AI to enhance economic management and Kigali’s focus on sustainability reflect the continent's entrepreneurial spirit and resilience. Technology adoption is often driven by practical needs and resource optimization as many countries exhibit vast wealth distribution and proper management of public wealth in many regions is a critical issue.
- Oceania: Oceania values sustainability and resilience, with cities such as Sydney and Wellington leading the way in modern responses to environmental challenges and disaster prevention. Importantly, the huge involvement of communities is important to mention as without them this outcome would be impossible.

Table 5.2: Continent’s primary values

CONTINENT’S PRIMARY VALUES		
Continent	Primary Values	Notable Examples
Europe	Sustainability Resilience Economic Growth	Copenhagen Amsterdam Barcelona
Asia	Sustainability Community Engagement	Singapore Tokyo Seoul
North America	Innovation Inclusivity	Toronto Los Angeles New York City
Middle East	Technological Excellence Futuristic Vision	Dubai Tel Aviv
Africa	Addressing Urban Challenges Economic Development	Nairobi Cape Town Kigali
Oceania	Sustainability Resilience Community Engagement	Sydney Wellington

These regional priorities highlight the diverse approaches to adopting AI in smart cities shaped by the unique contexts and ambitions of each continent. Understanding these values is essential for shaping effective and cultural aligned urban strategies.

5.5.9 Lessons from global case studies

The case studies that we examined show us the importance of adapting smart city strategies into local contexts [41]. We saw that successful smart cities balance innovation with inclusion. This way they

ensure that technological developments align with societal needs and ambitions. Furthermore, we saw that cultural values, governance structures and regional priorities are important factors in the adoption and the impact of AI in urban environments. All these findings can be very useful for policymakers and researchers who will tackle this area of research in the future.

5.6 Conclusion

In this chapter we explored the impact of regional and cultural differences on the adoption and effectiveness of AI in smart cities. A comparative analysis of smart cities from 2011 to 2021 revealed significant transformation of smart cities and it was driven mainly by factors such as technological developments, focus areas, leadership and governance. In addition, through case studies of leading smart cities across continents, this chapter demonstrated how unique regional and cultural contexts can transform the implementation of AI applications and smart city strategies.

Key findings from this chapter are the importance of adapting smart city initiatives to address local challenges and taking advantage of cultural assets to enhance public acceptance and participation. Successful smart cities balance innovation, sustainability and inclusivity, ensuring that technological developments align with societal priorities.

In conclusion, the adoption of AI in smart cities is not a one-size-fits-all endeavor. Regional and cultural diversity offers a rich tapestry of approaches that other cities can learn from [47], [41]. As urban areas continue to evolve, integrating AI responsibly and equitably will be essential to building sustainable and resilient cities of the future. This chapter lays the groundwork for the broader synthesis of these findings in the subsequent chapter, where implications and strategies for fostering equitable urban innovation will be further explored.

Chapter 6: What are the critical requirements that Smart Cities must fulfill in order to be Sustainable

6.1 Introduction

As cities continue to grow in population and complexity, the need for sustainability-driven urban transformation has become more pressing than ever. Rapid urbanization, technological advances and climate change have led to a shift in urban development, where the focus is no longer solely on economic expansion but also on the creation of sustainable and environmentally responsible smart cities. The transition towards Smart Sustainable Cities (SSC) requires a strategy between technological innovations, governance frameworks and environmental policies, thereby ensuring that cities become more efficient and more adaptive to climate change.

This chapter highlights the requirements that smart cities must strive to in order to be sustainable, by examining the integration of sustainability principles with emerging technologies and innovative urban planning strategies. Initially we start with the analysis of the role of the Sustainable Development Goals (SDGs) in smart cities and then we'll delve into different dimensions of sustainability - environmental, economic and social - and examine how they impact the design and governance of smart cities.

Technological developments play a significant role in achieving sustainability, and this chapter will explore in detail how AI, IoT, blockchain and cloud computing can support sustainable smart city initiatives. The issue is though, that alongside these developments, the implementation of sustainable technologies also presents many risks and challenges, which we will also be examining. Addressing these barriers is essential to make sure that technological innovation remains aligned with equitable and environmentally responsible urban development.

In this chapter, we further explore environmental sustainability in the context of smart cities by highlighting the importance of integrated clean energy, efficient waste management, water conservation as well as climate resilience. We will also be exploring ways to support sustainable urban development and mobility solutions by thoroughly examining how smart cities can reduce traffic congestion, improve public transport and promote pedestrian-friendly infrastructure. Consequently, the discussion will move to the frameworks and standards that guide smart sustainable development for cities, which will utilise key international benchmarks such as ISO 37120, the ITU SCC framework and the European Smart Cities Model.

Finally, the chapter will conclude with outlining the key future directions, emphasizing the need for strong policy integration, ethical applications of AI and community-driven urban planning.

6.2 SDGs in the context of smart cities

The SDGs were introduced by the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development, aiming to address global challenges such as climate change, urbanization, environmental degradation, and inequality. Among these, SDG 11: Sustainable Cities and Communities is particularly relevant, emphasizing the need for urban areas to be inclusive, safe, resilient, and sustainable [68].

Simultaneously, smart cities have emerged as a technology-driven approach to urbanization, utilizing big data, AI, IoT, and digital governance to enhance urban life while promoting sustainability [69]. The integration of smart city initiatives with SDGs presents an opportunity to leverage technological solutions for sustainable urban transformation, ensuring that cities become climate-resilient, resource-efficient, and socially inclusive [70].

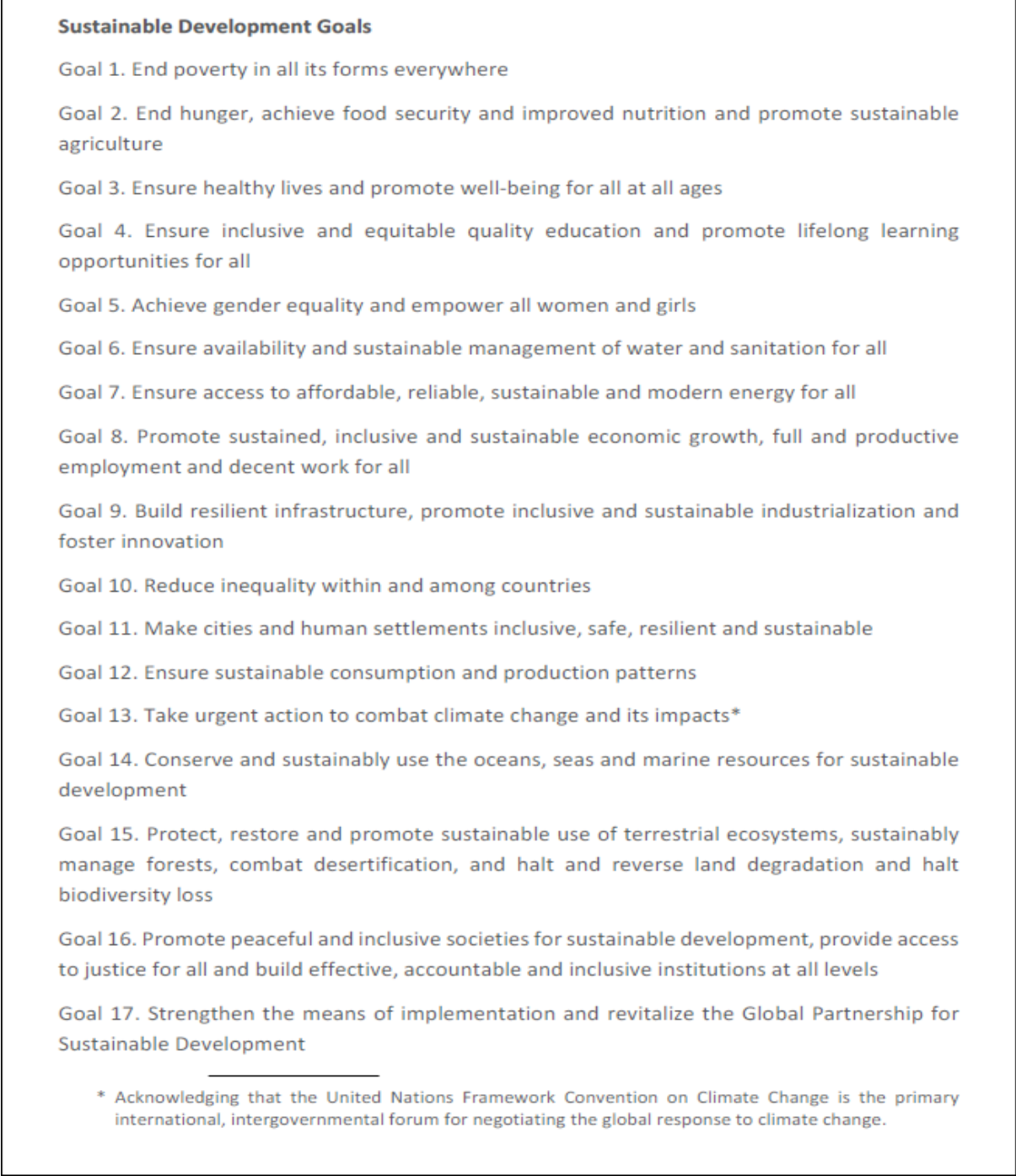


Figure 6.1: SDGs [68]

6.2.1 The role of smart cities in achieving SDGs

With more than 55% of the global population currently living in urban areas, and this figure projected to rise to 68% by 2050, cities play a pivotal role in achieving SDGs [70]. Cities contribute to over 70%

of global CO₂ emissions and account for 60-80% of global energy consumption, making them key drivers of both sustainability and environmental degradation [69].

Smart cities align with multiple SDGs by integrating technological innovation, policy frameworks, and community-driven sustainability initiatives. Key SDGs directly impacted by smart city initiatives include:

- SDG 11 (Sustainable cities and communities): Smart city projects foster resilient infrastructure, intelligent mobility solutions, and urban digitalization [70].
- SDG 6 (Clean water and sanitation): AI-driven smart water management enables real-time monitoring, leak detection, and water quality optimization [69].
- SDG 7 (Affordable and clean energy): The integration of smart grids, renewable energy sources, and energy-efficient infrastructure reduces dependence on fossil fuels [69].
- SDG 9 (Industry, innovation, and infrastructure): IoT-enabled urban planning enhances city resilience, reducing inefficiencies in transportation, housing, and energy consumption [70].
- SDG 13 (Climate action): AI-powered environmental monitoring and real-time climate impact assessments help cities reduce emissions and enhance climate resilience [68].

6.2.2 Key areas where smart cities align with SDGs

The integration of smart city solutions with SDGs is evident across urban planning, mobility, resource management, and governance.

6.2.2.1 Smart urban mobility and sustainable transportation

The rapid urbanization of modern cities has led to traffic congestion, air pollution, and inefficient public transport systems. Smart cities integrate AI-driven traffic control, EV networks, and IoT-enabled transit monitoring to promote sustainable mobility solutions. AI-powered predictive analytics optimize public transit schedules, improving accessibility and reducing carbon footprints, in alignment with SDG 11.2 (sustainable transport systems) [70].

6.2.2.2 Digital governance and smart public services

Governance in smart cities is increasingly shifting toward e-governance platforms, AI-driven decision-making, and blockchain-based transparency mechanisms. These digital governance models enhance citizen participation, improve public service delivery, and strengthen institutional accountability, contributing to SDG 16 (Peace, Justice, and Strong Institutions) [69].

6.2.2.3 Waste and circular economy management

Urban waste generation is a critical challenge, with millions of tons of waste generated daily. Smart cities employ AI-enabled waste sorting, IoT-connected smart bins, and blockchain-based recycling incentives to optimize waste collection and promote circular economy practices. These initiatives directly support SDG 12 (Responsible Consumption and Production) [69].

6.2.2.4 Climate resilience and energy efficiency

Smart cities employ climate-responsive infrastructure, smart building technologies, and AI-driven energy analytics to enhance urban resilience. These technologies contribute to SDG 13 (Climate Action) and SDG 7 (Affordable and Clean Energy) by reducing emissions, improving energy efficiency, and promoting low-carbon urban planning [68].

6.2.2.5 Smart economy and digital innovation

The smart city model fosters economic innovation by integrating AI-driven industries, blockchain-enabled financial systems, and IoT-driven economic models. Through digital entrepreneurship, automated supply chains, and smart financial management, cities can enhance economic sustainability and job creation, aligning with SDG 8 (Decent Work and Economic Growth) [69].

6.2.3 Challenges in aligning smart cities with SDGs

Despite the significant potential of smart cities in advancing SDGs, several challenges hinder their large-scale implementation:

- Fragmented urban development strategies: Many smart city projects prioritize technological advancement over sustainability, leading to uncoordinated urban growth [69].
- Governance and policy integration issues: A lack of regulatory alignment between smart city initiatives and national sustainability policies creates gaps in SDG implementation [70].
- Digital divide and social exclusion: While smart technologies improve urban efficiency, unequal access to digital infrastructure contributes to economic and social disparities [68].
- Financial constraints: Large-scale investments are required to implement SDG-aligned smart city solutions, yet many urban areas face funding shortages and infrastructural deficits [70].

6.2.4 Conclusion

Smart cities play a transformative role in achieving SDGs by integrating technology-driven solutions with sustainability frameworks. By aligning digital governance, smart mobility, resource optimization, and climate resilience, cities can enhance urban sustainability and economic inclusivity [69].

However, achieving holistic smart city sustainability requires:

1. Strong regulatory frameworks to integrate smart city policies with SDG objectives.
2. Equitable access to smart city technologies to bridge the digital divide.
3. Sustained investment in green urban infrastructure to enhance climate resilience and environmental sustainability.

By leveraging AI, IoT, big data, and digital governance, smart cities can become catalysts for global sustainability efforts, transforming rapid urbanization challenges into opportunities for resilient, inclusive, and sustainable urban development [70].

6.3 Types and dimensions of sustainability in Smart Cities

6.3.1 Introduction

The concept of sustainability in smart cities extends beyond environmental concerns and includes economic, social, and technological dimensions [71]. A truly sustainable smart city must balance economic growth, social inclusion, and environmental preservation [72].

The smart city model aligns with sustainability by leveraging technology-driven solutions to optimize resource use, improve urban resilience, and enhance the quality of life. Sustainability in smart cities is therefore structured into three core dimensions: environmental, economic, and social sustainability, each of which plays a critical role in ensuring that cities remain efficient, resilient, and livable in the long term [73].

6.3.2 Key dimensions of sustainability in smart cities

Sustainability in smart cities can be categorized into 3 primary dimensions:

6.3.2.1 Environmental sustainability

Environmental sustainability in smart cities focuses on minimizing ecological footprints, optimizing resource efficiency, and integrating renewable energy solutions. Given the growing urban populations and increasing environmental challenges, smart cities employ AI, IoT, and data analytics to improve energy efficiency, water management, and waste disposal systems [71].

Smart cities prioritize green urban planning, integrating green roofs, vertical forests, and urban green spaces to mitigate heat island effects and enhance air quality [73]. Additionally, smart grids and AI-based energy management systems enable cities to transition to low-carbon with the goal of reducing their dependence on fossil fuels [72]. Smart water management systems using IoT sensors and AI-based predictive analytics also ensure that water resources are efficiently utilized while preventing leaks and reducing waste [73].

6.3.2.2 Economic sustainability

By using the term economic sustainability in smart cities we refer to the creation of resilient, technology-based economies which create employment opportunities while simultaneously ensuring long-term economic stability. Digital transformation, automation and economic policies based on AI contribute to the continuous support of urban development. This way they drive the enhancement of innovation, entrepreneurship and the efficient allocation of public resources [71].

The emergence of digital economies, fintech solutions, and smart manufacturing has significantly improved economic sustainability in urban centers. AI and big data facilitate predictive urban planning, allowing cities to anticipate economic trends, optimize public spending, and attract investment in sustainable industries [73]. Smart cities also prioritize the development of circular economies, where recycling, sustainable production, and waste-to-energy conversion drive resource efficiency [72].

Moreover, blockchain-based smart contracts ensure transparency in urban financial transactions, property management, and sustainable investment projects, further strengthening economic resilience [71].

6.3.2.3 Social sustainability

Social sustainability in smart cities focuses on inclusivity, digital equity, and improved quality of life. While technological advancements have significantly enhanced urban efficiency, they have also introduced challenges such as the digital divide, data privacy concerns, and unequal access to smart infrastructure [71].

To ensure equitable smart city development, governments implement e-governance platforms, AI-powered public services, and participatory urban planning initiatives. These strategies enhance transparency, improve citizen engagement, and strengthen public trust in governance [73].

Smart healthcare systems are also revolutionizing urban healthcare accessibility. AI-driven diagnostics, telemedicine, and predictive healthcare analytics ensure that medical services are more proactive and accessible, aligning with social sustainability goals [72], [74]. Additionally, smart cities promote inclusive education models, integrating AI-powered learning platforms, digital literacy programs, and skill development initiatives to bridge the knowledge gap and create a future-ready workforce [73].

6.3.3 The role of technology in sustainability dimensions

Technology serves as a critical enabler across all three dimensions of sustainability. AI, IoT, cloud computing, and blockchain technologies facilitate real-time monitoring, predictive analytics, and data-driven governance, ensuring that smart cities remain efficient, adaptable, and sustainable [71], [75].

For instance, IoT-based smart grids help reduce energy waste and integrate renewable energy sources into urban electricity networks. AI-driven traffic management systems optimize public transport routes, reducing congestion and emissions [73], [76]. Additionally, blockchain technology enhances transparency in sustainable financing and resource management, ensuring fair and efficient distribution of public assets [71].

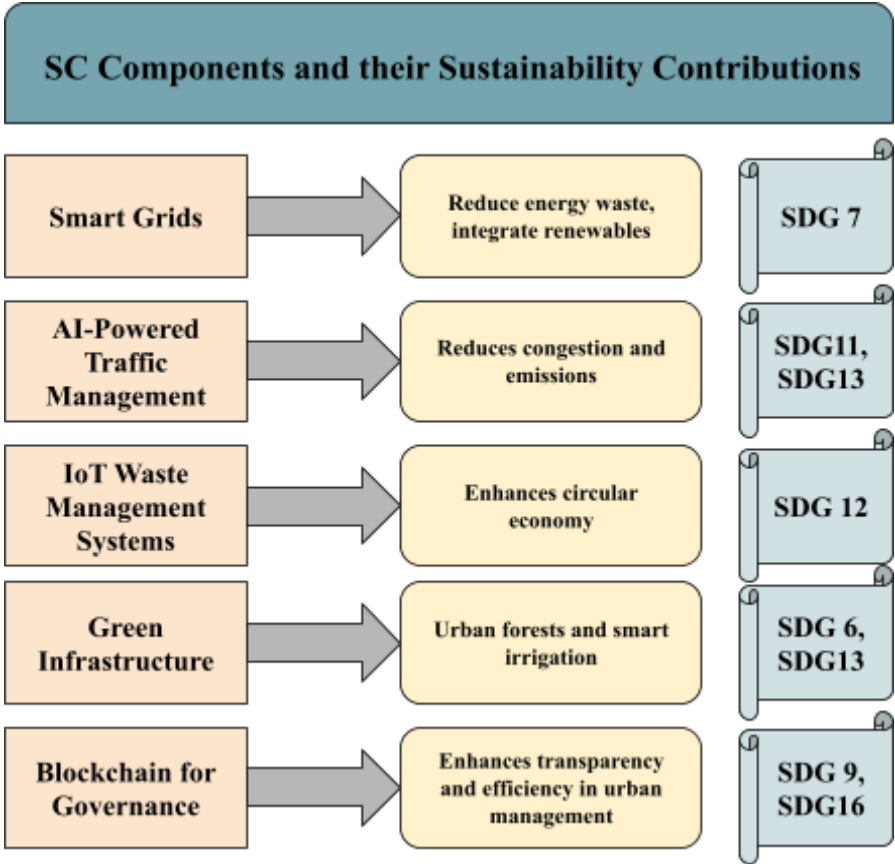


Figure 6.2 How different components of a SC ecosystem contribute to sustainability

6.3.4 Challenges in achieving multi-dimensional sustainability

Despite the benefits of smart cities, several challenges hinder the full realization of environmental, economic, and social sustainability goals:

- High energy demand of smart technologies: While AI, IoT, and blockchain optimize urban efficiency, they also consume substantial energy resources, requiring cities to develop green data centers and energy-efficient computing models [73].
- Regulatory and policy misalignment: Many smart city initiatives lack integrated sustainability policies, leading to fragmented urban development and inefficient resource allocation [72].
- Digital divide and socioeconomic exclusion: Smart technologies benefit urban populations, but unequal access to digital infrastructure can widen social disparities if inclusivity is not prioritized [71].
- Financial barriers to sustainable development: The transition to smart, sustainable infrastructure requires substantial investment, which remains a challenge for cities with limited financial resources [73].

6.3.5 Conclusion

A multi-dimensional approach to sustainability is essential for long-term urban resilience, efficiency, and inclusivity. By balancing environmental, economic, and social sustainability, smart cities can enhance quality of life while reducing resource consumption [71].

Technology plays a transformative role in achieving these goals, but its implementation must be governed by strong regulatory frameworks, inclusive policies, and strategic urban planning [73]. Future smart cities must prioritize digital inclusion, sustainable economic models, and environmentally conscious infrastructure to ensure that urban progress aligns with global sustainability objectives [72].

While significant challenges remain, integrating technology-driven urban governance, AI-powered analytics, and green infrastructure development will be key to building sustainable smart cities that cater to the needs of all residents [73].

6.4 Technologies supporting sustainability in smart cities

6.4.1 Introduction

As urban centers face unprecedented challenges due to climate change, resource scarcity, and rapid population growth, technology has emerged as a pivotal force in driving sustainability within smart cities. AI, IoT and cloud computing are examples of cutting-edge technology that cities may integrate in order to improve operations, reduce environmental impact and create resilient, flexible urban environments [77], [9], [78], [79].

This section explores how these technologies support sustainable development in smart cities, while transforming theoretical sustainability goals into practical, effective and impactful solutions.

6.4.2 AI and ML

With their robust capabilities for data analysis, predictive modeling and process automation, AI and ML are leading the way in sustainable urban development and their contribution to sustainability is evident in a number of areas:

6.4.2.1 Smart energy management

AI technologies improve energy efficient usage through pattern recognition of energy demands and also through distribution optimization. For instance, AI-powered smart grids adjust energy flows in real-time, balancing supply and demand to reduce waste [77]. In smart buildings, AI-powered systems dynamically modify heating, ventilation and air conditioning (HVAC) in order to save energy. This way, they demonstrate these predictive capabilities [78].

6.4.2.2 Waste and water management

AI plays a critical role in optimizing urban waste management through smart shorting systems and efficient collection routes by analysing data from sensors and predicting waste generation trends. In doing so, they allow cities to proactively adapt their waste management practices [78], [80]. Similarly, AI-based water management systems promote efficient use and reduce water waste by detecting leaks and anomalies in water distribution networks [9].

6.4.2.3 Climate and environmental monitoring

AI-driven climate models support environmental sustainability, by offering precise predictions of weather patterns and possible environmental threats. AI systems can forecast floods, heat waves and other climate phenomena by combining data from several sources, enabling cities to take preventative actions and mitigate the potential damage of natural disasters [78].

6.4.3 IoT

As we have already mentioned before, the IoT is the backbone of smart cities, enabling real time monitoring and agile city management. IoT devices interconnected through a network, provide valuable data that drives sustainability efforts [11], [81].

6.4.3.1 Smart transportation systems

In urban mobility, IoT traffic sensors gather information on vehicle flow, which then gets used to optimize traffic signals and reduce congestion. This supports the objective of urban sustainability by reducing emissions and improving air quality [82], [83]. Furthermore, IoT in transportation improves service effectiveness by offering real time information and route modifications in response to customer demand [82], [84], [85].

6.4.3.2 Resource and infrastructure management

In order to identify wear and possible failures before they happen, IoT systems monitor urban infrastructure, such as roads, bridges and pipelines. This proactive maintenance strategy lowers resource consumption and increases the lifespan of city assets [83]. In the context of energy, IoT-based smart meters allow for accurate monitoring of water and electricity consumption in the energy context, enabling users to make informed choices about their use [82].

6.4.4 Edge and Cloud Computing

Edge computing and cloud computing technologies also play a vital role in supporting sustainability. The main ways they achieve this are by enhancing data processing capabilities and reducing the environmental impact of data centers.

6.4.4.1 Edge Computing for real-time processing

Data transmission to central servers is less necessary when edge computing processes data closer to the point of production. Main beneficiaries of this approach are applications such as real-time traffic management and environmental monitoring, due to the reductions in latency and energy consumption [86]. Additionally, edge-computing supports smart grids which make it possible to manage decentralized energy resources effectively [87].

6.4.4.2 Cloud Computing for data-driven decision making

Regarding use in big data analytics, cloud computing provides scalable storage and strong processing power. Cities can use the cloud to improve public services, anticipate future needs and optimize urban planning by combining and analyzing large datasets in a more efficient manner [87], [88]. This way, smart cities can design and build dynamic, flexible urban environments which will react quickly to change by incorporating cloud-based AI models [86].

6.4.5 Blockchain technology

Blockchain is another important technology that drives sustainability in smart cities. The fundamentals of blockchain design can deliver security and transparency, which smart cities are using to increase trust and speed up their processes.

6.4.5.1 Decentralized energy markets

Peer-to-peer energy trading handled by blockchain allows local entities to directly buy and sell excess renewable energy efficiently. In addition to the encouragement of renewable energy sources, this decentralized energy model gives communities the autonomy to independently manage a variety of energy needs. [89]. In this way, blockchain helps build trust in these market systems, guaranteeing transparent and unchangeable transaction records.

6.4.5.2 Secure urban governance

Blockchain also enables transparent resource management and decision-making in urban governance. Smart contracts reduce bureaucracy and enhance the efficiency of public services by using these automating functions. Additionally, data integrity is guaranteed by blockchain's secure framework, which is essential for handling sensitive data in industries like public safety and healthcare [89].

6.4.6 Conclusion

As we have seen, the integration of AI, IoT, cloud and edge computing and blockchain is essential in order to create sustainable, resilient and efficient smart cities. What makes the essential is that these technologies:

- Enhance resource management, from energy distribution to waste reduction.
- Improve urban mobility, lowering the environmental impact and improving navigation in the cities.

- Foster transparency and trust in urban governance, having as a result better community engagement and accountability.

However, strong infrastructure, encouraging governmental frameworks, and universal access to the internet are necessary for fully utilizing the potential of these technologies. By harnessing the power of these innovations, smart cities can turn sustainability goals into tangible urban realities, paving the way for a more sustainable and inclusive future [78].

6.5 Challenges and risks in implementing sustainable technologies

6.5.1 Introduction

As mentioned earlier, the transition towards sustainable smart cities is driven by cutting-edge technologies such as AI, IoT, blockchain, and cloud computing. However, the implementation of these technologies is not without challenges. While these innovations offer numerous benefits, they also introduce significant risks related to energy consumption, security vulnerabilities, and ethical concerns [90], [91].

For sustainable technologies to be effective in smart cities, policymakers must identify and address key barriers, ensuring that implementation aligns with environmental, social, and economic sustainability goals [92]. This section explores the three critical challenges that hinder the widespread adoption of sustainable smart city technologies:

- High Energy and Resource Consumption
- Security and Trust Issues
- Ethical and Societal Implications

6.5.2 Energy and resource consumption challenges

6.5.2.1 The environmental impact of digital infrastructure

Although smart cities aim to reduce carbon emissions and optimize energy efficiency, the growing demand for digital services, data centers, and AI-driven systems is leading to a paradox: high energy and resource consumption [90].

For example, AI algorithms used in smart traffic management, waste management, and predictive analytics require large-scale computing power. Data centers that store and process urban information contribute significantly to global electricity demand, with estimates suggesting that they could account for over 10% of global electricity consumption by 2030 [84], [90].

6.5.2.2 The challenge of sustainable energy supply

Smart grids, renewable energy integration, and IoT-driven energy efficiency tools can mitigate energy demand. However, many cities struggle with the infrastructure investment required to transition towards clean energy solutions. The intermittency of solar and wind power also poses a challenge, necessitating efficient energy storage systems to ensure consistent power availability [91].

6.5.2.3 Waste from smart city technologies

The rapid deployment of smart sensors, IoT devices, and digital infrastructure results in electronic waste (e-waste), raising sustainability concerns. Without effective recycling programs and circular economy models, smart city technologies could contribute to more environmental harm than good [92].

6.5.2.4 Potential solutions

To reduce the environmental footprint of smart cities, several strategies can be adopted:

- Implementing green AI algorithms that optimize computing efficiency [90].
- Investing in energy-efficient data centers, such as liquid-cooled and renewable-powered server farms [91].
- Encouraging e-waste recycling programs to repurpose electronic components [92].

6.5.3 Security and trust challenges

6.5.3.1 Cybersecurity risks in digital infrastructure

Smart cities rely on real-time data exchange between sensors, cloud platforms, and AI-driven decision-making systems. However, this dependence on digital infrastructure exposes urban systems to cybersecurity threats, including hacking, data breaches, and ransomware attacks [93], [94], [95], [96].

A major concern is the vulnerability of smart grids and IoT networks, which, if compromised, can disrupt essential urban services such as power distribution, transportation, and emergency response [97].

6.5.3.2 Trust and data privacy concerns

Smart city technologies collect vast amounts of personal and public data, raising ethical concerns regarding privacy, surveillance, and data misuse. For instance, AI-driven facial recognition and predictive policing algorithms have been criticized for bias and potential misuse [93].

A lack of transparency in data governance can erode public trust, making residents reluctant to adopt smart city initiatives. Although blockchain technology has been suggested as a way to increase data transparency and integrity, regulatory uncertainty has delayed its widespread adoption. [89].

6.5.3.3 Potential solutions

Smart cities need to take into account the following in order to address security and trust issues:

- Implement strong encryption and decentralized authentication for IoT networks [97].
- Establish clear data governance policies that prioritize user consent and transparency [94].
- Use blockchain for secure, tamper-proof data transactions, particularly in identity verification and public records [89].

6.5.4 Ethical and societal implications

6.5.4.1 Ethical AI

There are ethical issues with the use of AI-powered decision-making in law enforcement, healthcare and urban planning. According to studies, biased AI algorithms can disproportionately affect marginalized communities, resulting in unfair policies and discriminatory practices [93].

For example, because AI-based predictive policing frequently uses historically skewed datasets, it has been accused of sustaining racial and socioeconomic biases [94]. AI-driven automation in industries, public services, and transportation raises ethical questions as well because it may result in mass job losses [92].

6.5.4.2 Digital divide and technological exclusion

Although the goal of smart cities is to establish inclusive environments, there is a chance that underprivileged communities and low-income groups will be left behind because they have less access to digital infrastructure [93]. This way, instead of reducing social inequality, smart cities may make it worse if efforts are not made to close the digital divide [98].

For example, the expansion of smart public services and AI-driven education platforms may only benefit individuals with access to high-speed internet and digital literacy programs. This way, they further widening socio-economic disparities [92].

6.5.4.3 Potential solutions

In order to mitigate the ethical and social risks of smart city technologies, policymakers must consider:

- Mandate AI transparency and fairness audits to detect and correct biases in smart city applications [93].
- Invest in digital inclusion programs, ensuring equal access to smart services, public WiFi and digital education [98].
- Promote public participation in smart city governance, allowing this way the communities to voice concerns and shape policy decisions [92].

6.5.5 Conclusion

While smart city technologies have the potential to enhance sustainability, efficiency, and quality of life, their implementation carries a number of significant challenges and risks. To maintain inclusiveness, security and environmental responsibility, smart cities must carefully manage issues regarding high energy consumption, cybersecurity vulnerabilities, ethical dilemmas and digital inequality [92].

To address these challenges requires:

1. Sustainable technology adoption strategies, such as green AI, renewable energy integration, and circular economy models,
2. Robust cybersecurity frameworks and transparent data governance policies in order to build trust in digital infrastructure,

3. Ethical AI regulations and digital inclusion policies to ensure that smart city innovations benefit all citizens, regardless of socio-economic status.

By tackling these risks proactively, cities can ensure that technology serves as a tool for sustainability and social equity rather than a source of environmental and ethical concerns [91]. The future of smart cities depends not only on technological advancements but also on responsible implementation, inclusive governance, and long-term sustainability planning [92].

6.6 Environmental sustainability in smart cities

6.6.1 Introduction

The rapid urbanization of modern cities has led to increased resource consumption, pollution, and environmental degradation, necessitating a strategic shift towards sustainability. Environmental sustainability in smart cities refers to the integration of innovative technologies and policy frameworks to mitigate the negative ecological impacts of urban development while promoting climate resilience and resource efficiency [23], [99], [100].

Smart cities focus on sustainable urban planning, energy efficiency, waste reduction, water conservation, and climate adaptation to ensure that future generations can enjoy cleaner, healthier, and more resilient urban environments. Even though we have already briefly discussed environmental sustainability in smart cities, the fact that this is one of the most popular topics regarding sustainability made us realize that a more in-depth review is required. This section explores the key environmental challenges in smart cities and the technological and policy-driven solutions that support sustainable urban ecosystems [101], [102].

6.6.2 Core environmental challenges in smart cities

6.6.2.1 Rising carbon emissions and air pollution

Urban areas account for over 70% of global CO₂ emissions, with transportation, industry, and energy production being the primary contributors [99]. The increasing use of vehicles, fossil fuel-dependent industries, and inefficient energy grids exacerbates air pollution, leading to health concerns such as respiratory diseases and cardiovascular issues [101].

6.6.2.2 Waste management and resource depletion

The rapid expansion of cities has resulted in an unprecedented increase in waste generation, overwhelming existing waste management infrastructure. Many cities struggle with inefficient recycling systems, landfill overflows, and improper disposal of e-waste, which contain hazardous materials that pollute land and water sources [102].

6.6.2.3 Water pollution

Water resources in urban areas are under immense pressure due to overconsumption, climate change, and pollution. Many cities face severe water shortages, exacerbated by inefficient water distribution networks, leaks, and contamination from industrial and residential waste [23].

6.6.2.4 Climate change and urban heat islands

Climate change poses significant threats to urban resilience, with rising temperatures, extreme weather events, and sea-level rise impacting coastal and densely populated urban areas. Additionally, the Urban Heat Island (UHI) effect, caused by excessive heat absorption from concrete and asphalt, further escalates energy demand and public health risks [101].

6.6.3 Smart city solutions for environmental sustainability

6.6.3.1 Clean and renewable energy systems

The transition from fossil fuel-based energy systems to renewable sources is fundamental for environmental sustainability in smart cities. Several technologies can be utilized to achieve this, such as:

- Smart grids: These AI-driven energy networks optimize power distribution, integrating solar, wind, and hydroelectric energy sources while reducing energy waste [100].
- Decentralized renewable energy systems: Small-scale solar panels, wind farms, and energy storage solutions empower communities to generate and share clean energy [99].
- Green AI for energy efficiency: AI algorithms help monitor and optimize energy consumption in buildings, transportation, and industrial sectors, reducing unnecessary energy waste [101].

6.6.3.2 Smart waste management and circular economy

Cities are shifting towards a circular economy model, where resources are recycled, reused, and repurposed instead of being discarded. Innovations in waste management include:

- IoT-Enabled smart waste bins: These bins detect fill levels and optimize waste collection routes, reducing fuel consumption and emissions from waste collection trucks [102].
- Automated recycling facilities: AI and robotics sort and process plastic, metal, and electronic waste, ensuring efficient recycling and waste reduction [101].
- Waste-to-Energy technologies: Organic waste is converted into biogas and biofuels, reducing landfill dependency while generating sustainable energy [102].

6.6.3.3 Sustainable water management

Smart cities are incorporating green infrastructure and climate adaptation strategies to counteract climate change and urban heat effects. Key initiatives include:

- Expansion of green spaces: Urban forests, rooftop gardens, and vertical farms reduce carbon footprints and mitigate the UHI effect [99].
- AI-Powered climate prediction models: These models analyze historical climate data to predict extreme weather patterns and assist in proactive urban planning [101].
- Flood and stormwater management systems: Smart drainage systems monitor rainfall patterns and direct excess water to storage reservoirs or treatment facilities, reducing flood risks [102].

6.6.3.4 Sustainable and smart transportation

To curb emissions and improve air quality, smart cities are revolutionizing urban mobility through sustainable transport solutions such as:

- Electric and hydrogen-powered public transit: Cities are replacing diesel buses and trains with zero-emission alternatives [23].
- AI-optimized traffic flow: Traffic management systems powered by AI and IoT minimize congestion and reduce vehicle idling, decreasing emissions [101].
- Bicycle and pedestrian-friendly infrastructure: Investment in bike lanes, pedestrian zones, and shared mobility solutions encourages eco-friendly commuting [99].

6.6.4 Challenges in implementing environmental sustainability in smart cities

Despite these technological advancements, several barriers hinder the widespread adoption of environmentally sustainable solutions:

- High implementation costs: Transitioning to renewable energy, AI-driven waste management, and climate adaptation strategies requires significant investment, which many cities cannot afford without government subsidies or private sector involvement [101].
- Regulatory and policy gaps: Many cities lack clear sustainability regulations, slowing down the integration of green technologies and environmental policies [102].
- Resistance to change: Businesses and residents often resist sustainability initiatives due to lack of awareness, perceived inconvenience, or economic concerns [100].
- Data privacy and security risks: The use of IoT and AI in environmental monitoring raises concerns about data privacy and cybersecurity vulnerabilities [23], [95].

6.6.5 Conclusion

Environmental sustainability is a cornerstone of smart city development, ensuring that urban areas grow responsibly while preserving natural ecosystems. By leveraging AI, IoT, blockchain, and renewable energy innovations, smart cities can:

1. Reduce carbon footprints and enhance clean energy adoption.
2. Optimize waste management and circular economy initiatives.
3. Improve water conservation through AI-driven monitoring.
4. Adapt to climate change with predictive analytics and resilient infrastructure.

However, achieving true environmental sustainability requires strong governance, cross-sector collaboration, and public engagement. Cities must implement clear policies, invest in green innovation, and educate communities on the benefits of sustainable living [101]. By harnessing smart technologies, urban areas can transition towards a cleaner, more resilient future, ensuring long-term sustainability for generations to come [102].

6.7 Sustainable urban development and mobility

6.7.1 Introduction

As cities continue to expand due to rapid urbanization, sustainable urban development and mobility have become key priorities for achieving environmental, economic, and social sustainability. The challenge is to balance urban growth with the preservation of natural resources, reduction of carbon emissions, and equitable access to public services [77] - [82].

Sustainable urban mobility plays a crucial role in this transformation, as transportation remains one of the largest contributors to greenhouse gas emissions and urban air pollution. A well-designed mobility system can reduce congestion, improve air quality, and enhance accessibility, particularly for underserved communities. Smart mobility solutions leverage AI, IoT, and data analytics to optimize traffic flow, encourage the use of public transport, and integrate low-emission transportation options. This section examines strategies and technologies that support sustainable urbanization while addressing key challenges such as traffic congestion, pollution, and accessibility [103], [104], [105].

6.7.2 Challenges in urban development and mobility

Urbanization has increased housing demand, transportation needs, and environmental stress, creating significant challenges for smart cities:

6.7.2.1 Urban expansion and inefficient land use

Uncontrolled urban expansion, or urban sprawl, leads to increased car dependency, inefficient infrastructure, and the destruction of natural habitats. Poor urban planning often results in fragmented, car-centric cities with limited public transport options [103].

6.7.2.2 Traffic congestion and high emissions

Transportation is one of the largest contributors to carbon emissions, with vehicles accounting for nearly 25% of global CO₂ emissions. Traffic congestion in densely populated cities worsens air pollution, fuel waste, and economic productivity [105].

6.7.2.3 Limited public transport infrastructure

Many cities lack efficient public transit systems, leading to over-reliance on private vehicles. This creates unequal access to transportation, especially in low-income communities, further exacerbating social disparities [104].

6.7.2.4 Lack of green and urban spaces

As mentioned in a previous section, urbanization often results in the loss of green spaces, reducing biodiversity and increasing the UHI effect. Green infrastructure plays a crucial role in improving air quality, regulating temperature, and enhancing residents' well-being [103].

6.7.3 Smart urban planning for sustainable development

Sustainable urban development requires innovative planning strategies that optimize land use, promote eco-friendly infrastructure, and enhance urban resilience.

6.7.3.1 Compact and mixed-use urban design

Compact cities prioritize mixed-use development, reducing the need for long transportations and promoting walkability. This design integrates residential, commercial, and recreational spaces, fostering efficient land use and reducing transportation emissions [103].

6.7.3.2 Green infrastructure and nature-based solutions

As mentioned in a previous section, green infrastructure plays a key role in sustainable urban planning by enhancing ecological resilience. Cities are adopting:

- Urban forests and rooftop gardens to improve air quality and reduce heat buildup [105].
- Permeable pavement and smart drainage systems to prevent flooding and enhance water conservation [104].
- Sustainable building practices, including energy-efficient materials and passive cooling designs, to reduce urban carbon footprints [103].

6.7.3.3 Digital twin and AI-Driven planning

Smart cities are leveraging AI, big data, and digital twin technology to simulate and optimize urban development. These technologies allow urban planners to:

- Model future population growth and infrastructure demands [105].
- Predict the impact of climate change on urban spaces [104].
- Optimize real estate planning and traffic flow using AI-driven simulations [103].

6.7.4 Sustainable mobility solutions in smart cities

Smart cities prioritize sustainable mobility by promoting public transportation, EV, and active transport modes such as cycling and walking.

6.7.4.1 Intelligent public transportation systems

Efficient public transport systems reduce congestion and emissions while providing accessible, affordable mobility solutions. Cities are implementing:

- AI-driven transit optimization, where machine learning adjusts bus and metro schedules based on real-time passenger demand [105].
- IoT-enabled smart ticketing systems, which allow seamless, contactless payments across multiple transport modes [104].
- Autonomous and electric buses, which reduce carbon emissions and lower operational costs [103].

6.7.4.2 Expansion of cycling and pedestrian infrastructure

To encourage active mobility, cities are investing in:

- Protected bike lanes and pedestrian-friendly pathways to ensure safety and accessibility [103].
- Bike-sharing programs, integrated with smart mobility apps to encourage non-motorized commuting [105].
- Car-free zones in urban centers, reducing traffic congestion and improving air quality [104].

6.7.4.3 Electrification of transportation

EVs are a key component of sustainable urban mobility, reducing dependence on fossil fuels. Cities are supporting EV adoption by:

- Installing widespread EV charging stations, powered by renewable energy sources [103].
- Incentivizing electric car-sharing programs, reducing the number of private vehicles on the road [105].
- Integrating EVs into public transport fleets, ensuring sustainability in city-owned vehicles [104].

6.7.4.4 AI and IoT-enabled traffic management

Real-time data from IoT sensors and AI-powered analytics optimize traffic flow, reducing congestion and fuel consumption. Smart traffic management includes:

- AI-controlled traffic signals that adjust based on real-time congestion levels [103].
- Connected vehicle technology, where vehicles communicate with infrastructure to avoid bottlenecks [105].
- Dynamic congestion pricing, which encourages off-peak travel and reduces rush-hour gridlock [104].

6.7.5 Challenges in implementing sustainable urban mobility

Despite the potential of smart mobility solutions, several barriers hinder their implementation:

- High costs of infrastructure development: Transitioning to electric public transport, smart grids, and pedestrian-friendly infrastructure requires significant investment [105].
- Resistance to behavioral change: Many commuters prefer private vehicles over public transit, requiring public awareness campaigns and incentives to promote sustainable alternatives [104].
- Regulatory and policy barriers: Many cities lack clear policies supporting electric mobility and AI-driven transport systems, delaying implementation [103].
- Equity and accessibility issues: Sustainable transport must be affordable and accessible to all residents, ensuring that smart city innovations do not widen socio-economic disparities [105].

6.7.6 Conclusion

Sustainable urban development and mobility are key pillars of smart cities, ensuring that urban growth is eco-friendly, efficient, and inclusive, by integrating:

1. Smart urban planning strategies, such as compact city designs and green infrastructure.
2. Sustainable mobility solutions, including electric public transit and AI-driven traffic management.
3. Digital technologies, such as AI-powered simulations and IoT-based infrastructure monitoring.

Cities can significantly reduce carbon emissions, improve air quality, and enhance residents' quality of life [103]. However, achieving truly sustainable urban mobility requires policy alignment, public

engagement, and continued investment in green infrastructure and emerging transportation technologies [105]. By adopting smart, sustainable urban strategies, cities can create livable, accessible, and future-proof urban environments that benefit both current and future generations [104].

6.8 Frameworks and standards for smart sustainable cities

6.8.1 Introduction

The successful implementation of SSC requires a well-defined set of frameworks, guidelines, and standards that ensure consistency, scalability, and interoperability across urban systems. These frameworks help cities integrate technological innovations, sustainability goals, and governance strategies, aligning urban development with global sustainability agendas such as the SDGs (see 6.1) and the Paris Agreement on Climate Change [106], [107].

Standardization in smart city development is critical for data security, system compatibility, and policy enforcement, ensuring that cities implement sustainable and resilient infrastructure. Various organizations, including ISO (International Organization for Standardization), ITU (International Telecommunication Union), and IEEE (Institute of Electrical and Electronics Engineers), have developed guidelines to help urban planners, policymakers, and technology providers create more effective smart city initiatives [71].

6.8.2 Key frameworks for sustainable smart cities

6.8.2.1 ISO 37120 – Sustainable development of communities: Indicators for city services and quality of life

ISO 37120 is a globally recognized standard that provides a comprehensive set of indicators for measuring city services and quality of life. These indicators which are divided into social, economic and environmental categories, assist cities to monitor their advancement towards sustainability objectives. Among the important topics discussed are waste management, energy use, water efficiency and accessibility to public transportation [106].

The adoption of ISO 37120 can enable cities to compare their sustainability performance to international standards in order to better utilise evidence-based urban planning and data-driven decision-making. By enforcing the requirement for cities to make their sustainability indicators publicly available, this standard also drives accountability and transparency [107].

6.8.2.2 ITU-T Smart sustainable cities framework

The ITU has developed a specialized framework for SSC. This framework focuses on the role of ICT in urban development. It also provides guidelines for digital infrastructure, smart governance, cybersecurity and citizen engagement, ensuring in this way that smart city initiatives are technologically advanced and socially inclusive [107].

The ITU framework further emphasizes resilience and risk management and addresses challenges that pertain to climate adaptation, data privacy and digital inclusion. It also encourages cities to adopt 5G networks, AI-driven analytics and blockchain-based urban management for the purposes of ensuring compliance with sustainability principles [71].

6.8.2.3 The European smart cities model

The European Smart Cities Model provides a structured approach to smart city development and focuses on six main areas: smart governance, smart mobility, smart environment, smart economy, smart living and smart people. This model provides a comprehensive approach to smart city efforts by combining technology-driven urban design with environmental sustainability and community engagement [106].

The policy-driven approach which requires cities to coordinate their smart city initiatives with European Union (EU) directives on sustainability, energy efficiency and digital innovation, is one of the key strengths of this model. It also encourages cross-border collaboration which allows European cities to share best practices, pool resources and develop unified smart city policies [107].

6.8.2.4 The United Nations Economic Commission for Europe (UNECE) Framework

The UNECE SSC Framework is designed to help cities achieve SDG 11 (Sustainable Cities and Communities) by promoting smart infrastructure, low-carbon solutions and inclusive governance. The framework highlights key performance indicators (KPIs) which are imperative for assessing the effectiveness of smart grids, AI-powered environmental monitoring and IoT-based public services [71].

One of the main objectives of the UNECE framework is to bridge the gap between developed and developing cities and thus ensure that smaller urban centers have access to the same smart city innovations as global megacities. This is achieved through knowledge-sharing platforms, funding mechanisms and policy recommendations that help cities implement scalable sustainability solutions [106].

6.8.3 Standards for implementing smart sustainable cities

6.8.3.1 ISO 37122 – Indicators for smart cities

ISO 37122 builds on the foundation of ISO 37120 by introducing specific indicators for smart cities such as ICT adoption, AI-driven urban management and digital citizen engagement. This standard helps cities track the technological progress they have achieved and evaluates the impact of smart city initiatives on urban sustainability [107].

By implementing ISO 37122 cities can take advantage of standardized data collection, real-time performance monitoring and predictive analytics which will allow them to optimize resource allocation and assist them with fine-tuning urban policies based on AI-powered insights [71].

6.8.3.2 ISO 37123 – Indicators for resilient cities

In order to achieve true sustainability, resilience is a major requirement, particularly in the face of cyber threats, natural disasters and climate change. In order to make sure the existing urban infrastructure can tolerate unexpected shocks, ISO 37123 offers indicators which evaluate a city's resilience against environmental, economic and social disruptions [106].

This particular standard is a crucial tool for cities implementing climate adaptations and smart governance policies as it provides disaster risk reduction tactics, emergency response planning and digital infrastructure security [107].

6.8.3.3 IEEE P2784 – Guide for smart city planning and technology integration

The IEEE P2784 standard is a helpful guide for cities that want to bring AI, IoT, cloud computing and blockchain technologies into their urban systems. It offers best practices that make sure that smart city technologies operate seamlessly across different networks and platforms by providing best practices for data security, AI ethics and interoperability [71].

Cities make urban development more flexible and future-ready with the adoption of the IEEE P2784 guidelines. It can be utilised to avoid vendor lock-in, enhance cybersecurity measures and ensure interoperability between different smart city technologies [107].

6.8.4 Challenges in implementing smart city frameworks and standards

Despite the advantages of standardized smart city frameworks there are also several challenges which must be overcome before their widespread adoption:

- High implementation costs: Many cities, particularly in developing countries, struggle to fund the transition to ISO-compliant and ITU-recommended smart infrastructure [106].
- Regulatory and legal barriers: The integration of AI, blockchain, and IoT-based governance raises concerns about data privacy, ethical AI use, and digital rights [107].
- Lack of skilled workforce: Implementing smart city frameworks requires a workforce trained in big data analytics, AI governance, and cybersecurity, which many municipalities currently lack [71].
- Interoperability issues: Different cities adopt varying smart city standards, leading to compatibility challenges when integrating cross-border urban technologies [107].

6.8.5 Conclusion

The successful development of SSC relies on well-defined frameworks and global standards that ensure interoperability, security and efficiency. Some standards such as ISO 37120, ITU-T SSC Framework and IEEE P2784 provide essential guidelines for cities in order to implement AI-driven governance, smart mobility solutions and energy-efficient infrastructure.

However, widespread adoption faces challenges related to funding, regulatory hurdles and workforce readiness. Governments, private sector stakeholders and international organizations must work together to streamline smart city policies, invest in capacity-building and enhance public-private collaborations to accelerate the transition to sustainable urban living. By adopting globally recognized frameworks and standards, cities can ensure resilient, efficient, and technologically advanced urban ecosystems that align with global sustainability goals.

6.9 Conclusions and future directions

6.9.1 Conclusions

The development of SSC is a critical response to the challenges posed by rapid urbanization, climate change and resource depletion. In this chapter we explored the key requirements that smart cities must fulfill to be sustainable and emphasised in the role of technology, governance and strategic planning in shaping the urban environments of the future.

The integration of SDGs into smart city frameworks ensures that urban areas not only embrace technological advancements but also prioritize social inclusion, economic resilience and environmental protection [69]. We saw that various dimensions of sustainability -environmental, economic, and social- must be addressed simultaneously to create cities that are both highly functional and livable [19] - [21].

Among others, the adoption of technologies such as AI, IoT, blockchain and cloud computing has been instrumental in enhancing urban efficiency and sustainability. These innovations help to improve energy management, optimized resource utilization, improved waste disposal and real-time climate monitoring [77], [9], [78]. However despite their advantages, sustainable urban development and mobility continue to face significant challenges related to energy consumption, security risks, ethical concerns and digital inequality [90], [91], [93].

Frameworks and standards such as ISO 37120, ITU SSC Framework, and IEEE P2784 provide structured guidelines for implementing smart city initiatives effectively [106], [107], [71]. However, regulatory and financial barriers, as well as the lack of interoperability and skilled workforce, still hinder the large-scale deployment of sustainable smart city solutions [107].

6.9.2 Future directions

6.9.2.1 The next phase of smart city development

The future of smart cities will be shaped by greater integration of AI, automation, and decentralized urban management systems. AI-driven governance will enhance real-time decision-making, while blockchain will provide secure, transparent, and decentralized data management. Additionally, the next-generation IoT ecosystems will improve connectivity between urban infrastructure, public services, and residents [101], [108], [109].

Future urban developments should focus on:

- AI-Driven policy and decision-making: AI models will become increasingly responsible for analyzing big data trends in traffic management, energy distribution, and climate resilience [108].
- Decentralized energy systems: The expansion of peer-to-peer energy trading platforms will allow communities to generate, store, and trade renewable energy independently, reducing reliance on centralized grids [89].
- Hyperconnected cities with 6G networks: The transition to 6G and quantum computing will unlock new possibilities in real-time urban analytics, automated public transportation, and ultra-fast communication systems [87].

6.9.2.2 Addressing sustainability challenges

While smart city technologies have advanced rapidly, environmental concerns remain a major challenge. To mitigate ecological risks, cities must focus on:

- Circular economy models: Implementing waste-to-energy systems, AI-powered recycling programs, and sustainable material innovations to minimize waste generation and maximize resource efficiency [102].

- Nature-based urban solutions: Expanding green roofs, urban forests, and climate-adaptive infrastructure to enhance urban resilience and reduce carbon footprints [100].
- Carbon-Neutral smart cities: Accelerating the transition to net-zero emissions urban planning by investing in clean transportation, renewable energy grids, and smart building regulations [110].

6.9.2.3 Digital equity and inclusion

As smart cities grow more technologically advanced, bridging the digital divide will be crucial to ensuring that all residents, regardless of income or geography, benefit from urban innovations. Future smart city strategies must focus on:

- Affordable internet access and smart infrastructure: Expanding public WiFi zones, free digital literacy programs, and accessible smart services to promote inclusive urban growth [98].
- AI-Powered smart governance for social equity: Using predictive analytics to allocate resources fairly across different urban districts, ensuring that low-income communities have equal access to smart city benefits [92].
- Human-Centered smart cities: Prioritizing policies that empower citizens through digital tools, allowing them to actively participate in shaping urban governance and sustainability efforts [94].

6.9.3 Final Thoughts

The future of smart cities is undeniably linked to technological progress, environmental responsibility, and human-centric urban planning. While significant strides have been made in integrating sustainability and innovation, challenges related to policy regulation, ethical AI use, and digital inequality must be addressed.

By leveraging AI, blockchain, and data-driven governance, cities can accelerate their transition to sustainability, making urban environments more resilient, efficient, and inclusive. However, achieving a truly smart and sustainable future will require strong multi-stakeholder collaborations, long-term policy commitments, and continuous adaptation to emerging global challenges [104].

Ultimately, smart cities should not only be technologically advanced but also sustainable, just, and accessible to all, ensuring a better quality of life for current and future generations. The path forward lies in a bold vision for sustainability, backed by actionable policies and next-generation technological breakthroughs [110].

Chapter 7: Conclusion

In this thesis, we conducted an extensive research effort using a modified version of the SLNA methodology. Our objective was to critically investigate the role of AI in smart cities, identify the critical requirements for achieving sustainability, and explore how regional and cultural differences shape the adoption and effectiveness of AI technologies in diverse urban contexts. To achieve these goals, we formulated and addressed three interrelated research questions, each of which contributed to the comprehensive understanding of how smart cities can evolve responsibly in the era of advanced digital transformation.

Our first research question aimed to uncover the role and applications of AI in smart cities. Through the literature synthesis and mapping, we identified several critical domains where AI technologies are being increasingly adopted. ML, digital twins, cloud computing and AI are some of the technologies that have changed the way city systems operate, thus enabling critical data-driven decisions to be made more easily. The most discussed applications of AI according to the research are in the areas of smart mobility and public health. It is worth noting that real-time traffic optimization, autonomous vehicle management and health prediction are also of significant academic and political interest. At the same time, the role of AI in participatory governance and service delivery with the main goal of optimizing citizens' lives is constantly increasing and is resulting in more transparent, inclusive and responsive urban management frameworks.

The second research question focused on how regional and cultural differences influence the adoption and effectiveness of AI in smart cities. This part of the research provided important insights into how smart cities are developing across continents. With the use of comparative analysis and other international case studies, it was observed that local governance, levels of economic development, political values and public trust in technology, all play an important role in the implementation of AI solutions. For example, European cities prioritize sustainability and citizen participation, while Asian cities' main focus is on resilience and efficiency. On the other hand, cities in North America are putting more effort on inclusion and innovation, while others in the Middle East are more focused on technological excellence. In African countries, cities are leveraging AI for the accommodation of basic urban needs and boosting their economic development, while cities in Oceania are using smart technologies to improve the environment. These findings clearly remark the need for a strategic smart city development while respecting the needs and priorities of each region.

In our third research question, we investigated various critical requirements that smart cities must fulfill in order to be sustainable. According to the literature review, sustainability in smart cities is a diverse concept with plenty of social, financial and environmental elements. The integration of clean energy systems, efficient waste and water management, resilience to climate risks, inclusive digital governance and fair access to infrastructure and services are some of the most crucial factors which affect sustainability. Furthermore, AI, IoT and cloud computing are very important in order to address these needs since they allow real-time monitoring as well as predictive modelling and optimization of the use of resources. Still though, ethical values, privacy and digital inequality create challenges that persist. Cities emphasizing sustainability thus have to be guided not only by technological capabilities but also by governance frameworks and standards such as ISO 37120, ISO 37122, and the ITU SSC Framework, standards that promote accountability, scalability, and resilience.

Among our thesis's most significant contributions are the methodical categorization and thematic grouping of smart city applications, the sustainability requirements and the technological factors listed. The creation of a framework which emphasises the connection between AI applications, sustainability goals and regional dynamics has enabled the identification of the interdependence of technological adoption, urban policy and cultural adaptability. This framework may prove useful to policymakers, urban planners and technologists, whose goal is to create smart urban ecosystems that are sustainable and inclusive.

Despite the developments and opportunities that we have described throughout our thesis, there are still several challenges that need to be tackled. Some of the most crucial that we identified are: a) many smart city initiatives remain in pilot stages or have fragmented implementation, b) there is a need for more real-life applications and empirical evaluations of AI-based urban systems to assess their long-term sustainability, ethical implications and scalability in different socio-economic contexts and c) the integration of AI in urban environments poses significant risks related to energy consumption, cybersecurity and social exclusion. All of the above are important challenges that future researchers should address.

The final conclusion of our thesis is that while AI and emerging digital technologies have transformative potential for the development of sustainable smart cities, the real value lies in how these technologies are framed, governed and integrated into urban ecosystems. Smart cities of the future will need to ensure that technological innovation translates into meaningful social benefits. They can achieve this by prioritizing ethical governance, digital equity, interdisciplinary collaboration and citizen empowerment. Researchers and policymakers should aim to bridge the gap between technological capabilities and human-centered urban design, making the vision of truly sustainable and smart cities a global reality.

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