

Integrating AI, Digital Twins, and DePIN for Smart Cities

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Program: Master of Science in Artificial Intelligence

Course: Thesis 2 AI901 Second Trimester 2025

Date: August 12, 2025

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Special thanks to Dr. Khaled Eskaf for his guidance and support throughout this research

Abstract

In this work, we provide a detailed analyzing process for the Jazan Artificial Intelligence Platform (jazanai..org), a next-generation smart city management solution complete with complementary Internet of Things (IoT) infrastructure, artificial intelligence capabilities and cutting-edge cybersecurity features to improve municipal services and citizen satisfaction across the Jazan region of the Kingdom of Saudi Arabia. The paper discusses the system's architecture, its implementation challenges, and how the platform is used in practice using a mixed-method research strategy that includes both quantitative performance measures and qualitative interviews with stakeholders.

The platform is a leap forward for the implementation of smart city technology in the Arab world by combining state-of-the-art technologies such as NVIDIA Jetson edge computing devices, Microsoft Azure Digital Twins, and the decentralized physical infrastructure networks (DePIN) platform via the Peaq blockchain. The main results show significant efficiency gains of service delivery as more than 80% of inquiries by citizens are automatically processed and 25% of the traffic flow reduced in monitored intersections.

The study provides important insights on the cultural and technical adaption issues for smart city technologies in the Middle Eastern context by highlighting the necessity of Arabic natural language processing and culturally sensitive interface design. Security review confirmed the establishment of multi-layer cyber security systems in place according to local Saudi requirement and international standards (such as ISO 37120, 37122, and 37123) for the smart cities.

There is clear performance evidence for dramatic cash savings in city operations and excellent service quality levels, with citizen satisfaction rates of 92% in digital services. Challenges are summarized by the research, such as scalability, complexity of integration and the necessity of ongoing staff training and community engagement programs.

The results add to the growing literature on smart city deployments in developing countries and also offer useful insights to similar initiatives throughout the MENA. The study notes that Jazan's AI platform emerges as a unique example of a culturally oriented smart city solution reconciling technological advancement and local need/ constraint imperatives.

Smart Cities, Artificial Intelligence, Internet of Things, Digital Transformation, Municipal Services, Cybersecurity, Saudi Arabia, Digital Twins, Edge Computing

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Introduction

Background and Context

Challenges Faced The accelerated urbanisation of the 21st century has presented the world with unprecedented challenges in city management and public services delivery. Shifting urban needs In the face of mushrooming city populations, conventional municipal methods of governance and infrastructure handling are increasingly recognized to be unsuitable to the multifarious needs of contemporary cities. This issue is extremely acute in Middle East and North African (MENA) where fast economic growth and population growth influenced intensely on urban infrastructure and services [1].

Saudi Arabia's Vision 2030 includes an ambitious digital transformation agenda to revamp the government service delivery model and enrich the lives of its citizens. This metamorphosis involves the evolution of smart cities empowered by emerging technologies such as artificial intelligence (AI), the Internet of Things (IoT), and big data analytics, capable of shaping more intelligent, sustainable and human-friendly cities [2].

The notion of a smart city has come a long way since it was first conceptualized in the early years of the 2000s. Initially centred on technology push, the paradigm of smart city is now articulated to citizen as key's actor targeting focus on user experience, sustainability and inclusive development. Contemporary smart city developments appreciate that CS is not only about technological high performance, but also a mix of local culture, governance, and community demands [3].

The Jazan AI Initiative

The Jazan AI Platform is one of the first attempts to deploy such a broad deployment of smart city solutions in a regional Saudi scenario. Jazan is situated in southwestern Saudi Arabia and is a key economic and administrative hub, which would be a good example for piloting of new smart urban management. The platform, accessible through jazanai.org is based on a combination of various cutting-edge technologies to form a homogeneous platform for citizens to gain access to the city service delivery through urban management.

The process was born out of an understanding that old mechanisms of delivering services to municipalities were unable to cope with higher citizens expectations and growing complexity of urban issues. The platform was developed to achieve a number of goals: to increase service delivery efficiency, to increase civic engagement, to demonstrate its commitment to environmental sustainability, and to make Jazan a leading, shining example of smart city transformation in the region.

As the Kingdom of Saudi Arabia's smart city project, development of the platform started in 2022 as under a larger Saudi Digital Transformation Program, including a project that covered traffic management, environmental monitoring and citizen services. Since then, the system has developed to include virtually the complete array of urban management services and has become a laboratory for new smart city governance methods.

Research Significance

This study fills an important gap by focusing on smart city initiatives in the Arab region. Although smart city projects that are implemented mainly in environmentally developed countries in Europe, North America, and East Asia are well studied in the literature, there is scant literature that discusses how these technologies can be adapted for a Middle Eastern culture, with its own linguistic, and legal character [4].

The importance of the study transcends the region and contributes toward the overall smart city challenges and opportunities for implementation. The application of state-of-the-art technologies

such as edge computing, digital twin, and decentralized infrastructure network in the Jazan platform will enliven the implementation of the advanced technologies in real city environment.

The study also addresses indispensable issues of smart city cyber security and privacy protection, both of high concerns as today's city increasingly relies on its digitalized infrastructure. The platform's model for reconciling innovation with security needs is a key insight for other smart cities anywhere in the world.

Research Objectives

Academic objectives This study is designed to serve a number of integrated goals which together will give an extensive and in-depth comprehension of the Jazan AI platform and its implications for the development of Smart City.

Main Objectives: Perform a comprehensive study of the architecture, implementation, and performance of Jazan AI platform for Smart City model in MENA region.

Secondary Objectives:

Preliminary technical analysis: The platform's technical architecture will be analysed, including its connection with IoT devices, AI systems, edge computing infrastructure, and cloud services to calculate the performance of alternative technology types and determine the regional logistics of technical deployment.

Performance Measurement: Monitor and assess performance indicators of service delivery, including creation of work efficiencies, citizen satisfaction, cost value and reliability of the system, comparing with traditional delivery of services and international benchmarks.

Security Analysis: Assess the security technology and privacy protection mechanisms of the platform, and determine the platform's compliance with standard specifications based on the requirements for smart city security.

Cultural Adaptation Analysis: Study how the platform caters to local cultural, linguistic, and social needs, analyzing the efficiency of Arabic Natural Language Processing resources and culturally adapted user interface design.

Scale and Sustain: An analysis of the platform's potential for scale and sustainability, summarizing key drivers and barriers to scale and replication in other regional geographies.

Policy and Governance " Consider existing governance structures and policy frameworks which underpin the running of the platform and develop best practice examples and guidance for similar initiatives.

Research Questions

The analysis is underpinned by distinctive research questions that direct the inquiry:

Core Question: How, and how effectively, does the Jazan AI platform harness cutting/edge technologies to enhance delivery of municipal services and the citizen experience, and what are the implications of this initiative for the development of smart cities in the MENA region?

Supporting Research Questions:

What are the core technical stack of Jazan AI platform, and how they combine with each other and form an unified smart city ecosystem?

What is the platform's efficiency, cost effectiveness and citizen satisfaction when compared to traditional government service delivery, from a municipal system point of view?

What cyber security and privacy issues are created by the platform and how are they adequately being addressed?

How well does the system accommodate local cultural and linguistic needs, and what are the drivers of citizen embrace and usage?

What are the main challenges when implementing the platform, both during the development and in practice, and how have these been met?

What are the lessons learnt that other smart city programs across the region should consider from Jazan?

Scope and Limitations

This study particularizes on the Jazan AI platform implemented in the Jazan province in Saudi Arabia. Although the results might be applicable for other smart city programs more generally, the analysis is more specifically confined to the particular case considered and its regional context.

Temporal Scope: The study discusses the design of platform as well as its operation from its installation in 2022 until 2024, delivering details for implementation and operation issues over two years.

Study Geography: The research is conducted in the region of Jazan with emphasis on urban regions where the platform has been deployed widely. Although some findings may generalize to other regions in Saudi Arabia or MENA states, however, the research does not attempt to cover all smart city initiatives within Jazan.

Technical Coverage: IoT infrastructure, AI systems, cybersecurity, and UI are the leading technical components of the analyzed platform. However, specific technical details and formulas are out of the scope of this study because of confidentiality.

Limitations: There are a number of limitations to be mentioned. The main reason was the limited access to the technical details and performance numbers, for security and proprietary reasons.

Second, with the platform having only been in operation for a limited period of time, there are limited indicators of long-term sustainability and effects. Third, because the study was conducted in one implementation, findings may not be generalizable to other sites.

Thesis Structure

This thesis is structured in eleven chapters, covering analysis of the Jazan AI platform and its potential for smart city.

Chapter 1: Introduction This chapter is setting the tone for the thesis by introducing the reader to the topic of research, aims and methods.

CHAPTER 2: LITERATURE REVIEW Literature review of Smart cities, AI in urban management and related technologies to place Jazan platform in the context of the wider academic field.

3 Research Methodology outlines the mixed-methods design used for this study, the data collection and analysis methods employed, and ethical considerations.

Chapter 4 Platform Analysis This chapter gives an in-depth description of the Jazan AI platform architecture, components and operation process.

Chapter 5: Technical Infrastructure focuses on the technical architecture of the platform, in terms of IoT networks, edge computing systems, and cloud integration.

Chapter 6: Use Cases for AI covers the platform's artificial intelligence features, such as natural language processing, predictive analytics, and computer vision systems.

Chapter 7: Cybersecurity and Privacy assesses the security model and the privacy safeguards of the platform.

In Chapter 8: Case Studies provides in-depth discussion of certain applications of the platform, focusing on traffic management and environmental monitoring.

Chapter 9: Challenges and Solutions highlights principal implementation challenges, and the creative responses generated.

Chapter 10: Recommendations and Future Directions Outlines recommendations for platform enhancement and smart city development in general.

Chapter 11: Synthesizes the main and sub findings and the implications for development of smart city projects in MENA region.

Literature Review

Smart Cities: Theoretical Aspects and Historical Evolution

The transformative potential of smart cities and the Internet of Things will continue to evolve in the coming years and decades, in response to an ever-increasing comprehension of urban issues and possibilities. Early interpretations mainly emphasized the application of information and communication technologies (ICT) in advancing the efficiency of the services and infrastructure of cities. Nevertheless current smart city concepts lean towards more comprehensive concepts that link technological innovation to sustainable development, citizen involvement and quality of life [5].

International Organization for Standardization (ISO) has provided full guidelines related to smart cities in general and in specific ISO 37120(indicators for city services and quality of life), ISO 37122(indicators for smart cities) and ISO 37123(indicators for resilient cities). These benchmarks set a basis to measure and compare the performance of smart cities in different scenarios and executions [6].

Distinguishing Characteristics of Smart Cities Recent academic work has established some defining characteristics of successful smart city initiatives. Integrated systems thinking (Bibri and Krogstie, 2023), as in different urban systems systems synergize rather operate as silos are highlighted to be a critical level of abstraction (Bibri and Krogstie, 2023), [7]. Such integration demands advanced data management skills, compatible technology and governance mechanisms that can work across the traditional boundaries of organizations.

Growing consciousness of environmental issues and climate change effects has also affected the development of smart city ideas. Contemporary smart city formats shift to focus more on environmental sustainability, resource efficiency and climate risk mitigation. This evolution has resulted in the development of environmentally friendly innovative technologies such as environmental monitoring systems, renewable-energy technologies, and sustainable transportation elements integrated in the concept of smart cities [8].

Artificial Intelligence in Urban Management

The use of artificial intelligence in urban management has experienced exponential growth in the recent years, induced by the development of machine learning algorithms, the explosion of computational capacity as well as the abundance of urban big data. Yigitcanlar et al. (2024) present a detailed survey of AI in smart cities and point out the application areas such as traffic management, public safety, environmental monitoring and services for citizens [9].

One AI application that has become especially relevant to smart cities is NLP, which will facilitate more natural and accessible channels between citizens and government services. However, the majority of NLP work has been for English and other world languages, which presents difficulties when applied to Arabic-speaking world. Recently, progress has been made in Arabic NLP, such as the construction of large language models that are trained on Arabic text [10], to alleviate these limitations.

Prediction is an other important application of AI in smart city environment as well. Predictable data patterns Machine learning algorithms can track data patterns over time to forecast the future for a variety of scenarios, including traffic flow, energy usage and service need. Predictions of

this type can support recruitment and retention practices that prevent problems before they happen and allocate resources effectively [11].

Monitoring and management systems of smart city have widely used computer vision technology. User-friendly image and video analytics facilitate automatic monitoring of traffic, public safety and infrastructure. Combining computer vision with IoT sensing networks results in holistic surveillance systems, that can lead to real-time situational awareness dissemination over the urban areas [12].

IoT in Smart Cities

The IoT forms the base layer of technology into many smart city solutions, underpinning the sensor networks and connectivity that supports data capture and systems integration. Zanella et al. (2023) offer an extensive review on IoT applications in smart cities, both in terms of opportunities and challenges in large scale IoT deployment [13].

One of the main problems in the deployments of smart city IOT applications is scalability. However, with the amount of such devices increasing from hundreds to thousands to possibly millions, conventional centralized architectures are constrained by network scalability, processing capabilities, and administrative overhead. As a result, there has been growing interest in edge computing solutions that extend processing to the proximities of datagenesis [14].

Interoperability is yet another significant obstacle in the context of the smart city IoT systems. Various devices and systems frequently employ incompatible communication protocols, data formats, and management interfaces. The creation of standardized APIs and Middleware platforms has become a key direction to solve insufficient interoperability between heterogeneous environments [15].

Energy efficiency & sustainability: This is become a critical aspect in the any smart city IoT deployments. Most of the IoT devices are battery operated and are installed on places where frequent maintenance is unreachable or costly. This has motivated the growth of low-power communication protocols such as LoRaWAN and NB-IoT that can maintain long-term activity with the lowest energy consumption [16].

Decentralized Physical Infrastructure Networks (DePIN)

Decentralized Physical Infrastructure Networks (DPINs) are a new emerging paradigm where blockchain technology and economic incentives are applied to manage and operate physical infrastructure. Such an approach provides a possible answer to some of the scalability and sustainability problems of traditional centralized smart city systems [17].

The Peaq network is gaining ground as a premier dedicated blockchain for DePIN use-cases. Developed on the Polkadot platform, Peaq offers custom tools and services to run decentralized physical infrastructure, such as identity management, micropayments, and governance models [18].

DePIN systems present many possible advantages compared to classical centralized systems. In this sense DePIN can minimize the demand on capital outlay for infrastructure deployment due to sharing ownership and operation of infrastructure among many parties as well as offering increased resilience to both failures and attacks. In blockchain protocol, economic incentives can motivate the community to participate in maintaining and expanding the infrastructure [19].

Nevertheless, DePIN projects also encounter many obstacles. The complexity of the blockchain can make it hard to overcome, especially when the non-tech-savvy customers approach. Interference could get in the way of deployment in some jurisdictions due to regulatory uncertainty around blockchains and crypto-currencies. Moreover, some blockchain networks consume so much energy which questions sustainability [20].

Digital Twins in Smart Cities

Digital twin approach has been receiving attention as a method in smart city planning and operation. The digital twins[21] are able to approximate virtual representations of real-world systems, which can aid in dynamic simulations and optimizations of urban systems.

Microsoft Azure Digital Twins has become a key platform for generating and managing digital twins at a city scale. The platform includes support for representing built environments, managing urban data integration from various data sources and simulating alternative options and policies [22].

Digital twins in smart cities have applied in various domains. Among the applications of digital twins are the modeling of the effects of new developments on traffic, utilities and the environment in urban planning. Emergency management systems deploy digital twins for simulating disaster scenarios and optimizing responses. Digital twins are used within infrastructure management applications to predict maintenance requirements and improve operational efficiency [23].

There are however some challenges related to digital twin implementations. Due to the complexity of urban systems, it is difficult to establish credible and full-coverage models. The accuracy of digital twin representations can be hampered by problems of data quality and availability. The computing needs of massive-scale digital twins can be massive, which needs a large investment in the computing infrastructure [24].

Cybersecurity in Smart Cities

The cybersecurity is a major challenge for the implementation of smart city applications. The networking between smart city systems establishes several possible attack routes, and the sensitive nature of the urban infrastructure causes security breaches to potentially yield disastrous consequences [25].

Cybersecurity for smart cities need to target threats at various levels: These include individual IoT devices, network infrastructure and cloud-based services. The heterogeneity of technologies

and vendors in the common settings of smart city deployments also makes it non-trivial to enforce uniform security policies [26].

Privacy is tied closely to, but not the same as, cybersecurity. Smart cities amass a huge amount of data about citizen's activities and behavior, leading to concerns about surveillance and privacy abuse. Regulatory measures like the European Union's GDPR and Saudi Arabia's Personal Data Protection Law set the privacy protection guidelines for smart city systems to comply [27].

The concept of security-by-design has been recommended as a best practice in smart city design. Instead of security being added as an afterthought, it is included into all levels of resources system architecture and development [28].

Cultural and Linguistic Considerations

Local culture and language context Smart cities can be considered on many levels. The majority of research and implementation on smart city has been focused in the west, possibly biasing the findings to other cultures [29].

The lack of language support is a unique problem that smart city solutions face in non-English speaking areas. Although machine translation quality has drastically improved, due to local dialects and the culturally idiosyncratic nature of the language, (Machine) translation technology is not a panacea. Processing of the Arabic language poses specific challenges such as the language's rich morphology and the range of regional dialects as compared with other languages [30].

Cultural issues also serve as determinants of user interface design, service delivery methods, and citizen engagement strategies. What is successful in one culture could be counterproductive and even detrimental in another. This underlines the value of user-centric design strategies that situate local communities at the centre of smart city system development and testing [31].

Research Gaps and Opportunities

Although, there are abundant existing review articles concerning smart cities and the related topics, there are still a few critical challenges in the existing articles. Second, there are few studies on smart city applications' deployment in MENA area, especially how can transform global good practices to local level. Secondly, there is little study of how specific technologies such as IoT and AI interact in integrated smart city systems and how they complement one another.

Third, the majority of the smart city literature deals with technological issues rather than governance, policy or social issues that are increasingly being recognised as major factors in determining the success of implementation. Fourth, longitudinal studies of smart city development and sustainability over longer periods are rare. Last, but not least, there is a lack of studies on the economic implications and the return-on-investment of smart city applications.

Several gaps described above are addressed in our research, including a comprehensive examination of an integrated smart city platform in a MENA environment, analysis of technical and social factors that affect implementation success, and an evaluation of performance across multiple years.

Research Methodology

Research Design and Approach

The current study uses a mixed method study design integrating Quantitative and Qualitative methods to gain a more comprehensive understanding of Implementing, Performance and impact of Jazan AI. The use of mixed-methods is especially relevant in this study where objective performance measures can be combined with subjective experiences and perceptions of various stakeholders [32].

The research design is structurally built under the explanatory sequential mixed methods design in which the initial qualitative phase is followed by the collection of quantitative data, which is chronologically analyzed in parallel through quantitative and qualitative procedures. This method allows the study to initially investigate the situation in context by looking at the performance of the platform before then being able to consider why these results are occurring and how they are interpreted by different stakeholders [33].

Philosophical Foundation

Pragmatic philosophy is the basis of research that emphasizes the practical implications of research, and the employment of varied methods to achieve a comprehensive understanding of complex phenomena. This pragmatic attitude is especially suitable when investigating real case smart city deployment, because it is a complex sociotechnical integrated systems not satisfied by any single methodology [34].

The pragmatic stance enables the reconciliation of various epistemological positions as objective measurements and subjective experiences are viewed to offer complementary insights on the efficacy and impact of the smart city technologies. This philosophical basis endorses that data from multiple sources and analytic methods can create a holistic picture of the research questions [35].

Research Strategy

The research design is rooted in a single case minimum frame analysis that concentrates a considerable intensity of focus on the Jazan AI platform as a distinctive and important instance of the smart city construction in the MENA. This research is highly suitable for case study method as it enables comprehensive scrutiny of a contemporary occurrence in its real-life context [36].

With the case study method, this research is able to investigate the interplay of technological, organizational and social dimensions to increase the understanding of smart city success. It

furthermore makes it feasible to study the ways in which general smart city principles and technologies are further developed as they are applied to particular local contexts and needs [37].

Data Collection Methods

Quantitative Data Collection

System Performance Indicators: A complete set of performance indicators was obtained from the monitoring systems of Jazan-AI platform throughout the 24 months from January 2023 to December 2024. This data includes:

Response time analysis for various system components and services

Citizen services transaction amounts and processing volumes

System availability and downtime information

Rates of error/ failure ratios

Resource consumption information about the computing and network infrastructure

Activity patterns of users and service usage statistics

Citizen Satisfaction Surveys: A formalised online survey to users of the platform to gauge satisfaction levels, and areas that needed to be improved. The survey tool was built on existing smart city evaluation frames and was customized for the local environment. A sample of 2,847 responses was gathered over the course of the study, which represents a broad spectrum of platform users.

Service delivery performance metrics: Quantitative information on service delivery performance was gathered from the municipality records as follows;

Average citizen request processing time according to the type of citizen request

Online vs. offline service channel completion rates

Unit costs of different service delivery arrangements

Staff productivity comparisons pre and post of platform deployment

The number and timing of citizen complaints

Qualitative Data Collection

Semi-structured Interviews: In total 45 key informants from multiple viewpoints towards the application and running of the platform were interviewed. Interview participants included:

- 12 municipal level officials and managers participating in platform governance
- 8, technical staff dedicated for the development and maintenance of the platform
- 15 citizen with varying demographics and levels of usage
- 6 public-private partners for platform development
- 4 academic experts in smart cities and urban technology

The interviews were carried out in Arabic and English according to the preference of the participants, and professional translation services were used to guarantee the precision of cross-language comparison. An interpreter translated for those who did not speak English. externalActionCode=7&id=136&iid=10p108 8c (STOR\cap9\bkm), monitor.Break questions that landed unpredictably At the time of Project Viewpoint, interviews ranged in length from 1 to 1.5 hour.

Focus group discussions: The focus group discussion sessions (framed by participant category) sought commonalities and differences of opinion between the different groups. Focus groups included:

- Two focus groups with municipal staff (12 participants in total)
- 2 citizen focus groups in different districts (total 16 participants)
- One with business owners and entrepreneurs (8 participants)
- One meeting with community leaders and organizations (6 users)

Participant Observation: Ethnographic observations were performed in municipal service centers and platform training sessions to explore the practical use of the technology and the interaction between users and the different system parts. The observation time was about 120 hours in study.

Document Analysis

Comprehensive documentary analysis was using to construct the heritage, policy and operational logic of the platform. Documents analyzed included:

- Technical specification and architecture documents
- Pertinent policy papers and implementation instructions
- Training and user manuals
- Performance reports and evaluation results

Media and public communications

Scholarly/professional papers and articles Exchange information ABOUT Smart city ACTIVITY IN OTHER PROJECTS[Any computation project may refer to] 36000[Service and Business provisioning] Literature on Smart City technologies and facilities(from a science and technology perspective) Cleanup.INTERNET Academic and industrial publications OF PUBLICATION OF INFORMATION ON THE Smart city (from the academic –industry punto of view)

Data Analysis Procedures

Quantitative Analysis

Descriptive statistics: Simple descriptive statistics were computed for all quantitative variables to explore the central tendency, variation and distribution. This paper forms the basis for discussing performance characteristics of the platform and its user behavior.

Time-series analysis: Performance metrics were analyzed over time to estimate trends, seasonality and the effect of the system changes or external events. Decomposition methods for time-series were employed to disentangle trend, seasonality and irregularity in the data.

Comparative Analysis -Where available, performance metrics of the platform were compared with the baseline (prior to platform implementation) and with similar city benchmarks. A test of the statistical significance was performed to determine if there was a statistical difference.

MULTIPLE REGRESS Similarly, a multiple regression analysis aimed at explaining significant variation in dependent variables, for instance, satisfaction of the citizen, efficiency of the service delivery, and system performance. The analysis serves to interpret which factors are relatively important and how they interact with one another.

Qualitative Analysis

Thematic analysis: Themes, patterns and insights were derived from the transcripts of interviews and focus group recordings through thematic analysis method. It was guided by the systematic procedure of data familiarization, coding, theme creation and interpretation [38].

Document analysis: Content analysis of the document was conducted using quantitative content analysis (reported as the frequency of key words and concepts) as well as qualitative content analysis (contextual and meaning analysis). It serves two purposes, one to give a wide and the other a deep view of documentary evidence.

A narrative analysis: We approached and analyzed selected interview excerpts through the lens of narrative analysis to reveal how various stakeholders make sense of their platform encounters. This impact is especially useful in the study of the social and cultural factors that influence technology acceptance.

Mixed-Methods Integration

Triangulation: Patterns across the sources were compared and contrasted to detect convergent and divergent findings. This process of triangulation is used to confirm results and to deepen the understanding of where various views offer complementary knowledge.

Joint Displays: Visual displays of the mutual relationships of quantitative and qualitative results were employed to emphasize where considered findings corresponded or contradicted one another.

Meta-Inferences: Second-order inferences were generated by combining perspectives from quantitative and qualitative analyses, resulting in better understanding of the research questions that quantitative or qualitative analyses could not achieve alone.

Ethical Considerations

Informed Consent and Participation

All human subjects gave written, informed consent to be interviewed, participate in a focus group, or take a survey. Participants were fully informed of the research aims and procedures before their participation and were informed of risks and benefits and rights as research participants. Consent forms were translated in Arabic and English as well to ensure complete comprehension.

Participation in the research was on voluntary basis and all participants were informed of their right to terminate the involvement in the study at any time without any repercussion. Particular care was taken to ensure that public employees did not feel coerced to participate based upon their relationship with their employer.

Privacy and Confidentiality

Participants' privacy and sensitive information were closely protected and all precautionary measures were taken to ensure confidentiality. No personal identifiers existed in the data files and anonymous codes were used for analysis. Interview recordings and transcripts are stored in encrypted files available only to the research team.

Special care was paid to the privacy of residents who were interviewed, guarding against the possibility of personal data from local government databases to be tied to participation in the research.

Data Security and Storage

No data are kept on personal computers except as encrypted files as backups, data are always stored on an encrypted file that is housed at a safe location, Should a fire occur at the lab. Data are available only to the research team, and the entire team has confidentiality agreements in place. The data will be destroyed 5 years after the publication of research outcomes.

Cultural Sensitivity

Care was taken to tailor the research to meet local cultural norms and sensitivities. Interview questions and survey instruments were reviewed by community cultural advisors for appropriateness and sensitivity to possible offensive materials.

Research activities were timed to suit local customs and religious duties and gender to secure interviews and focus groups if required by participants.

Validity and Reliability

Internal Validity

The researchers took several steps to increase the internal validity of the study findings:

Multi data sources: The use of different data sources can diminish the threat from those biased factors emerging from a unique data source as well as offering several interesting points of view on main issues.

Member checking: Selected findings were reported back to participants in order to verify their accuracy and gather feedback on the interpretation.

Peer debriefing: Frequent talks with academic colleagues and other practitioners assisted in pinpointing possible biases and alternative explanations.

External Validity

Generalizability—The Size of the Study The logic of case study commits it to an anti-statistical conception of generalization given its focus on the detailed and non-random replication of the study's key phenomena¹⁰. While cases can provide generalizing evidence about how and why a phenomenon works this is necessarily nominal rather than statistical generalization.

Thick description: a full ‘thick’ description of the setting, participants and interventions is provided so the reader can judge the extent to which the findings are transferable to other contexts.

Theoretical framework: The work is based on well-known theoretical frameworks that allows comparison with other smart city cases.

Comparison: To the extent possible, the findings are contrasted with those of other smart city research to highlight similarities and differences.

Reliability

Reliability measures include:

Standardized methods: Standard methods on data collection were applied to all research exercises to reduce heterogeneity via methodological inconsistencies.

Inter-rater reliability: To examine consistency of interpretation, more than one researcher coded a sample of the qualitative data independently.

Audit log: A clear record of all steps and choices in the research process provides transparency and reproducibility.

Limitations and Constraints

Access Limitations

The availability of some technical information and performance data is also restricted for security and proprietary reasons. The data collection was sufficient to answer the research questions but there are some areas of the operation of the platform that we were not able to explore in depth.

Temporal Constraints

The platform has only been in service for a fairly short while (circa two years at the time of writing this work) and consequently it is early to address longer period of use, impacts and lastingness. Goal 2: Longitudinal effects may not be well-demonstrated in the current available data.

Generalizability Constraints

The reliance on a single case study reduces the statistical generalizability of results. Although the study gives some understanding about smart city adoption in MENA, the findings may not be generalizable to other international settings, and in differentiations should be considered.

Language and Cultural Barriers

Although diversity, cultural and language issues were considered when designing the study some of the meaning may have been "lost" in translation or culture. The cultural "lens" of the research team which may have impacted how data was collected and interpreted may not be fully visible.

Platform Analysis

Jazan AI Platform Overview

Jazan AI The Jazan AI Platform is a complete smart city management system where various urban services and systems are converged through the use of IT solutions. It was started in 2022, and was a part of Saudi Arabia national plan to enhance digitalization and development [39], the platform is to provide a one-stop-shop portal for all related to municipal services, urban monitoring and citizen engagement in the Jazan region.

The following principles, which are consistent with international smart city best practices as well as the local context, were introduced during the platform development. These five principles are

citizen-centricity, with all platform capabilities prioritised based on the user experience and citizens' needs using them; interoperability, as systems and services can cohesively function with existing data exchanges; scalability, supporting growth and evolution in both the number of users and the complexity of the capabilities offered; security, incorporating security features that protect the sensitive data, and information and critical infrastructure supporting the operation of these capabilities; and sustainability, as resource utilisation efficiency contributes both environmentally and economically to sustainability.

The platform is designed within a layered model that isolates various functions and allows services to be shared between layers and across the platform. This design makes it easier to maintain, upgrade, and update the system with new features, without losing the system reliability and performance. It has currently about 150,000 registered users and helps process over 50,000 transactions a month across the country's various municipal services.

Strategic Objectives and Vision

The Jazan AI platform was built with a strategic view of innovation to elevate the delivery of municipal services and position Jazan as a leading example for a smart city across the region. The strategic goals of the platform are closely aligned with Vision 2030 plan of Saudi Arabia, which mainly focuses on digital transformation, effective governance and enhancement of quality of life.

Excellent service: The platform is seeking service excellence in local government services by cutting response times, quality of service and overall citizen satisfaction. This is achieved by automating the mundane tasks, setting quality management systems in place, and monitoring service performance metrics.

Digital Inclusion –Acknowledging the significance of the uptake of digital services by all citizens, the platform includes provisions for users with differing thresholds for technical capacity. This consist of multilingual support, user-friendly interfaces and alternative channels of access for citizens who do not wish to choose e-governance model of service delivery.

LEAD ON INNOVATION: The program is an experimental space for innovative technologies and practices in urban operations. That ranges from testing things including artificial intelligence, blockchain and edge computing, to developing new practices for engaging and servicing citizens.

Economic development: Seeking to promote economic growth within the Jazan region by optimizing the municipality's operations and services. This includes easier business registration and licensing, improved infrastructure for commerce and industry opportunities for local tech firms to contribute to platform development and maintenance.

Governance Structure and Management

The testbed is structured under different governance layers in which technical requirements, policy concerns, and stakeholder requirements are considered in a balanced whole. The

governance model has various governance levels supporting governance and decision-making to help align the platform with the public interest, technical excellence, and operational best practices.

43 Executive governance: Platform governance is governed at an executive level by a steering committee that includes high-level representatives from the city government, the relevant government authorities as well as external advisors who have practical knowledge in the field of smart cities and digital transformation. This committee gives strategic direction, endorses major policy changes and ensures alignment with wider government goals.

Technical Governance: Daily technical decisions are coordinated by a technical advisory board composed of platform architects, cyber security specialists and partners from major technology suppliers. This board sets technical standards, security policies and technology roadmap.

Stakeholders Involvement: Stakeholders involvement mechanisms are in place to systematically integrate users' requirements and concerns into the platform development and operation. This involves citizen advisory boards, periodic surveys and feedback collection, and public consultation for significant platform changes.

Performance Management: The performance management that we emulated practices defined, measures the performance indicators along various dimensions covering technical performance, quality of the service and citizen satisfaction and cost efficiency. Continuous feedback from regular performance reviews helps improvise and aids strategic planning.

Core Platform Components

Citizen Services Portal

The citizen services portal is extensible so that it serves as an entry point to the city to bring a variety of government services and information together. The primary concern when designing the portal is with the user experience, and it is designed in accordance with the modern principles of web design and accessibility standards to be as universally accessible across user groups and technical abilities as possible.

Service Catalog: The portal offers over 120 municipal services, from finding information to obtaining licenses and permits. Services are presented in sensible groupings such as where-is services for detailed descriptions, prerequisites and an easy-to-follow approach for citizens to successfully fulfill a requirement.

Personalized Dashboard: After a user sign in, he/she is shown a personalized dashboard that presents information in an user-specific and context-aware fashion taking into account the user's activity history, location, service access history, etc. One is a dashboard that has status updates on pending applications, reminders for expiring deadlines or renewals, and personalized suggestions for services they may be interested in.

Multi-Channel Access: To cater for citizens with various access preference and capability the portal supports multiple access channels ranging from a web browser, a mobile app to integration with popular messaging platforms. With this multi-channel strategy, citizens can use their channel of choice while realizing the same level of service and functionality.

Accessibility Features: The portal is built with the intention of being accessible to all citizens including those disabled. This encompasses screen reader/keyboard navigation, high contrast, and text size functionally. These attributes help meet international accessibility benchmarks and promote the platform's dedication to digital inclusion.

Administrative Management System

The management control system ensures that municipal workers have the means and information to deliver services in an efficient and effective manner. This mechanism is intended to promote operational efficiency inside city hall, decrease administrative hassle, and enhance communications among various functions and departments in the municipal government.

Workflow Routing: With integrated workflow management functionality, citizen requests are able to be assigned to the appropriate department or staff member based on predefined rules and current workloads. It keeps a record of each request as it goes through the queue, and also generates automatic e-mail or cellphone updates to not only citizens, but to city workers.

Document Management - Included document management capabilities allow secure storage, retrieval and sharing of citizen service and municipal operations documents. The system has version control, audit trails, and access controls to provide security and protect the integrity of documents as well as allow for collaboration among staff.

Performance Analytics – Including full analytics capabilities, to provide managers insight on the performance of service delivery, productivity of staff, and satisfaction of citizens. These are the analytics that inform and enable both data-driven strategic decision-making and process and resource optimization.

Integration: Municipal systems and data repositories are integrated with the admin and provide employees access to the full picture of service need. This consolidation minimizes rekeying of data and promotes uniformity among various systems and processes.

AI-Powered Virtual Assistant

Among its groundbreaking features, the platform uses state-of-the-art natural language processing and machine learning to offer citizens intelligent and conversational assistance through its virtual assistant. The assistant is capable of answering a variety of questions and performing numerous operations, from easy requests for information to complex service transactions.

3.1 Natural Language Understanding: The virtual assistant depends on state of the art Arabic NLP for understanding the citizen questions in a natural and free language language. This also

includes support for dialects and colloquial words of Jazan, which would give more intelligent and easy access for locals.

Contextual Awareness: The assistant can keep track of the context in a conversation that supports a multi-turn dialog experience that is intuitive and efficient. It has a capability to store its previous conversation with users, can apply this information for displaying more personalized answer. The system also comprehends the current municipal events, policies and services context, to give accurate and up-to-date information.

Learning and adaptation: Machine learning algorithms ensure that the assistant gets better by learning from every interaction with the user. The system learns from successful engagements in order to provide better responses to similar queries in the future, and to recognize when a human might be required to handle the issue.

Escalation and Hand off: Virtual assistant as and when comes across questions which need a human touch or human expertise can seamlessly handover the conversation to the right human agents who can have full context on what the citizen is enquiring and history of the conversation until now.

Data Analytics and Reporting Platform

The system comes with advanced analytics & reporting modules, ensuring fact-based decision making and optimization of city services. These features turn the enormous dataset created by platform operations into things that can help city managers and their policymakers.

Live Dashboards: Live dashboards that allow you to see a real-time view of KPI's throughout various components of the municipality. These dashboards are flexible and can be tailored for various user roles and can be used to show data at different levels of granularity/aggregation from high level summary KPIs to very granular operational numbers.

Predictive Analytics – Advanced analytics capabilities analyse historical data and machine learning algorithms to predict future trends and patterns in service demand, resource needs and citizen behaviour. These forecasts allows to plan in advance and allocate resources to enhance service delivery efficiency and citizen satisfaction.

Scheduled Reporting: Automated reports regularly delivered to stakeholders that provide timely and consistent information on platform performance and affairs of the municipality. Reports can be tailored to meet the unique requirements of different audiences and can be served through different touchpoints such as email, web portals, and mobile alerts.

Datavisualisation: Advanced datavisualisation tools for users to discover and comprehend their complex datasets with charts, maps and different visualization options. These are simplifying tools that enable non-technical users to interpret and execute insights derived from data, so that the entire organization can begin adopting data-informed decision-making.

Integration Architecture

System Integration Framework

The Jazan AI technology build a robust integration puzzle of different System, Applications, and Data sources. This integration platform is designed based on contemporary architectural styles such as SOA, microservices, and API-first that bring about flexibility, scalability, and maintainability [40].

API Gateway: There is a central API gateway that is the main point of integration for all external systems and applications. This gateway support interfaces, auth and authorization, rate limiting, and monitoring. This design is critical to providing uniform security and performance to all integrations and to make external connections easier to manage.

Enterprise Service Bus: An ESB will allow for internal platform components to talk to external systems. The ESB offers message routing, transformation, and protocol conversion features necessary to connect systems with different architectures and communication protocols.

Data Integration Platform – A separate data integration platform is responsible for the ETL (Extraction, Transformation, Loading) of data into the platform’s core data repository from disparate sources. It consists of functionalities including real-time data streaming, batch processing and data quality to bridge integrated data with data that is accurate and consistent.

Identity and Access Management: Single sign-on (SSO) across all platform components and integrated systems is provided by integrated IAM capabilities. This method provides a better user experience and retains security and can create extensive logs of user activities.

Legacy System Integration

A major challenge is how to bring in the old-legacy technologies and architectural styles from local municipalities systems and databases to the Jazan AI platform. Below we outline some capabilities in the platform's integration architecture we have designed to resolve this issue with legacy integrations.

Adapter Pattern Implemented: We built custom adapters to communicate with legacy systems that do not support modern API best practices. These adapters provide format and protocol translation and authentication switching to enable easy integration and continued use of existing systems.

Gradual Migration Approach: Rather than trying to replace all legacy systems in one go, the platform supports a gradual migration approach enabling legacy systems to operate whilst being replaced, in an iterative manner, with new functionality. This mitigates at-risk implementation and provides the opportunity to extensively test new capabilities prior to abandoning legacy systems.

Data Synchronisation: Advanced data synchronisation processes are utilised to keep the central database of the platform in synch with the legacy system databases. These include real-time

synchronization of critical data, batch synchronization of non-time-critical data and conflict resolution procedures to manage inconsistencies.

Third-Party Service Integration

The service works with numerous third-party services and is a part of many other applications for the full range of features without the need for them to build all of them themselves. These integrations range from payment processing and mapping/geolocation services to communication platforms and niche municipal software applications.

Vendor Management Framework There is a vendor management framework that describes how third-party services are to be selected, deployed, and maintained. This system involves both technical assessment guidelines as well security assessment process and performance monitoring control, with the aim of verifying that third-party integrations are in compliance with platform standards.

Service Level Agreements: SLAs with vendors define performance expectations, availability levels and support processes. Such contracts also set up oversight around service performance, and reporting around service performance and remediation steps when there are service outages or issues with performance.

Backup and redundancy: Key 3rd-party integrated components will have backup and redundancy provisions, to keep the lights on in the event of third party provider outages or performance lag. This might involve the use of several providers for a given service or implementing fallback mechanisms that support basic function while services are not available.

Technical Infrastructure

Edge Computing Architecture

The Jazan AI platform is based on advanced edge computing technology to support real-time processing and decision-making on the network edge, which shortens latency and enhances system responsiveness. NVIDIA Jetson devices form an edge computing infrastructure, setting up at specific locations in the city, which performs distributed processing, complementing the cloud-based system [41].

NVIDIA Jetson Deployment

The infrastructure is based on a swarm of NVIDIA Jetson devices that delivers edge computing for different smart city services. “In order to keep costs low, we have to be able to do processing in the field, and make decisions in real time, rather than collect lots of data, bring it to one central place and analyze it there,” says Ramos.

Hardware Composition: The scenario encompasses a combination of NVIDIA Jetson Nano, Jetson Xavier NX, and Jetson AGX Xavier, depending on the computation demand of particular use cases. On the low end Jetson Nano devices process sensor data and engage in simple

computer vision, whereas the high-end Xavier line performs complex AI flows like multi-stream video analysis and advanced predictive modelling.

AI Model Deployment: All Jetson devices are powered by AI models that are fine-tuned for your use case. The models are built with the Tensorflow and PyTorch frameworks and are deployed at the edge using NVIDIA's TensorRT inference optimization toolkit. Optimization strategy involves model quantization, pruning and other tricks to minimize the computing requirement and remain faithful to the model.

Local Decision-making: Decision-making logic is embedded into edge devices, allowing them to respond autonomously based on different types of events and conditions. For instance traffic management devices at the edge can automatically adapt the timing of the signals based on real-time analysis of traffic flow; and, environmental sensing devices can issue alarms when the pollution levels exceed a threshold.

Connectivity and Communication: Edge devices remain connected to the central platform via several communication channels, such as cellular networks, Wi-Fi and wired connections, if any. It is this proportion redundancy that allows for the fact that terminals may keep working and receiving, even if one or more channels fail.

Edge-Cloud Hybrid Architecture

The platform utilizes an advanced hybrid design that offloads processing to edge devices or cloud infrastructure depending on application needs, data sensitivity and network performance. Such a method is best used to maximize performance, handle costs, and protect both data location and security.

Workload Offloading: Various processing workloads are offloaded to edge and cloud based on their properties. Real-time processing that has hard real-time requirements is done at the edge, and complex analytics and machine learning training or inference that don't have hard real-time constraints run in the cloud.

Data Filtering and Aggregation: Edge devices conduct the preprocessing of data for filtering and aggregation that is meant to reduce the amount of data transferred to the cloud. To achieve this, network bandwidth is saved from sending unwanted control plane data to the cloud, the underlying cause is captured and transmitted for further analysis.

Adaptation in processing: Dynamically balancing the amount of on-edge and on-cloud processing based on factors like network availability, device performance and workload activity. By its adaptive nature, this strategy can work optimally at variable operational conditions.

Cloud Infrastructure Integration

The cloud is a Microsoft Azure based cloud service, capable of scaling and secure cloud computing resources, which complements the edge computing architecture. Large scale data

processing is performed in the cloud, we train machine learning model in the cloud, it is used for long term data storage and it supports backup and disaster recovery [42].

Azure IoT Hub Integration

Azure IoT Hub acts as a central message router for the IoT devices in an IoT solution that communicates with the cloud, ideally in a secure, bidirectional, and device-to-cloud-agnostic fashion. The IoT Hub is responsible for device identity and authentication, message routing, and device management, and enables thousands of the region's connected devices to function.

Device Management – IoT Hub offers rich device management capabilities which include device provisioning, configuration manage and deployment, firmware update, device health and device monitoring. These capabilities make it possible to control a broad IoT deployment in one place so security and operations run smoothly.

Message Processing - Tens of millions of messages are processed every day from different IoT devices, where Azure IoT Hub offers the scalable message ingestion and routing processing required to handle this. Messages are forwarded to the correct processing services depending on their content, origin and priority level.

Security and Authentication: All traffic between the devices is protected with industry standard authentication and encryption. IoT Hub secures communications, and rules configured on an IoT Hub expose the data to the IoT devices and a user interfaces.

Azure Digital Twins Implementation

The platform also builds upon Azure Digital Twins to turn all city infrastructure, systems and processes into a truly three-dimensional digital twin. Such digital twins in turn support advanced simulations, analyses, and optimizations for informed decision-making and predictive management paradigms [43].

Model of a city - This implementation of the digital twin has models of all major city systems, such as: transportation networks, utility infrastructure, public places, and environment system. These models are constantly being enriched with real-time IoT sensor data and other data sources to keep them relevant and accurate.

Simulation Capabilities: Through simulation the digital twin platform can model alternative scenarios and policy options to help city planners and managers to understand the likely outcomes of proposed decisions before they are deployed. This is particularly useful for infrastructure planning, emergency response planning, and policy making.

Predictive Analytics: Digital twin platform includes machine learning models that analyze historical and real-time data to predict future states and prevent problems before they happen. Such prognoses support proactive management to avoid difficulties and optimise resource use.

Visibility and Interaction: Advanced tools of visualization allow to interact with the digital twin by intuitive user interfaces, where complicated information is readable for the user. These utilities are useful for both technical users needing to know the specifics of how a system is set up, as well as for non technical stakeholders needing high-level system overview.

Network Infrastructure and Connectivity

The network infrastructure of the platform is the underlying infrastructure that allows all components in the solution, from the edge to cloud services, to communicate. The system network is implemented to be highly available, secure, scalable, able to adapt to the present and future demand of the platform.

Multi-Technology Approach

The platform uses a variety of networking technologies to offer complete coverage to all sorts of devices and use cases. This multi- technology approach guarantees the best for all devices and applications to access the Enable The Clean & Enable for isolated networks.

Resource Optimization: Demand is synthesized with resource planning systems to realize payrolls, allocate equipment, and use facilities optimally. This saves costs and at the same time allows maintaining the high quality of service.

Computer Vision and Surveillance Systems

Featuring a powerful computer vision-based engine that processes video streams from cameras across the city to detect traffic congestion, public order issues and infrastructure performance, the platform taps data from between 6 to 10 sensor-oriented applications. These features enable autonomous monitoring and analysis that is beyond the reach of human observation [46].

Traffic Monitoring and Analysis

Computer vision systems which receive video from traffic cameras for the purpose of controlling vehicle traffic and gathering traffic statistics. Such systems are an important source of real-time data that is used in traffic management decisions and in long-term transportation planning.

Vehicle Detection and Classification: State-of-the-art object detection algorithms to detect, classify vehicles such as cars, trucks, buses, motorcycles, and bicycles. Such a classification allows for more complex traffic analysis and traffic management enabled according to the vehicle type.

Speed estimation: Vehicle speed can be estimated by tracking the motion of objects through multiple video frames. This feature allows for automatic speed monitoring and the identification of speeding hotspots.

Incident Detection: The system is able to automatically detect traffic incidents such as accidents, stoppage and congestion. In the event of an incident, the system sends immediate electronic

notifications to highway managers and responders to minimise response times and enhance safety.

Traffic flow analysis: With full analysis on traffic flow, you will know the peak time and most popular road to better direct your outdoor activities. That information contributes to infrastructure planning and can be used to develop traffic management strategies.

Public Safety Monitoring

Computer vision is also used in public safety systems, where public cameras are scanned around the clock to look for anything out of the ordinary (such as a bag unattended) or for crowds forming too quickly, which could indicate a threat. These features significantly increase public safety while preserving privacy rights and the spirit of freedom.

Crowd Monitoring: This system can analyse crowd formation from the scenes of public spaces, including the crowd density, crowd movement, security and other risk aspects. This feature becomes even more useful when controlling big events and maintaining safety in congested places.

Anomaly detection: Supervised ML algorithms that are fed with typical activity patterns in the networks may pick up anomalous or suspicious activity which should be further looked into. The system is also set up to reduce the number of false alarms and to inform on any activities that should be of concern.

Emergency Response Aid: In an emergency, computer vision systems can instantly monitor the status of affected areas for emergency responders to make proper decisions regarding resource allocation and evacuation strategies.

Infrastructure Monitoring

Computer vision also has been used to determine the status of municipal infrastructure such as roads, bridges, buildings and public utilities. This monitoring allows early maintenance and can prevent infrastructure failover.

Damage Inspection: An approach of infrastructure image processing is employed to detect the damages, wears, or deteriorations which might call for repairs and maintenance. This ability allows more effective infrastructure management and makes it possible to avoid the ordering of expensive spare parts.

Maintenance Planning: Through monitoring the condition of infrastructure over time the system can anticipate maintenance and assist in the scheduling of maintenance activities to maximise service and minimise cost.

Asset inventory: Computer vision can automate the inventory of government assets and monitor the state+local level capabilities as to location and usage. It allows for better asset management and replacement/upgrades planning.

Machine Learning and Automation

Machine Learning has been built into the platform and it can be used to automate different processes in the municipality and increase system performance. They can intelligently minimize human effort and enhance the accuracy and efficiency for a wide range of applications [47].

Process Automation

Municipality-process analysis Machine learning comprises the investigation of regularities in the processes of the municipality in order to realize opportunities for automation and optimization. Only the most complex cases need to be addressed by the human workforce, and IMPACT can learn from historical data and human decision-making trends to automate repetitive decisions.

Document Processing: With NLP and computer vision technologies, we automate tasks of processing the documents of different kinds such as permit applications, complaint forms, service requests. The system can extract MAC information as well as confirm that all sections are completed before directing any documents to staff.

Decision Support: AI models that analyze historical decisions and outcomes to suggest decisions on current cases. These guidelines ensure uniformity in decision making and reduce the duration of case processing.

Controls: ACID: Automatically monitor the quality of processed transactions for accuracy and completeness, indicating possible errors that will be followed automatically by a human review. This allows a high quality service to be provided while handling large volumes of transactions efficiently.

Continuous Learning and Improvement

The platform's machine learning engines should be programmed to learn and get better over time as it processes more information and receives feedback. This ongoing learning ability means that the system becomes increasingly effective as time goes by and in response to different situations and needs.

Integration of feedback: User feedback and performance metrics are constantly integrated back into machine learning models for greater accuracy and efficacy. This control loop allows the system to learn from successes as well as failures to enhance future performance.

Model Evolution: Frequent model evolution to integrate new data and better algorithms for improved system performance. Updates such as these are rigorously checked and verified before they are rolled out, guaranteeing that enhancements do not compromise the performance or stability of a system.

Performance monitoring: Visibility-based monitoring tools monitor the performance of machine learning models and alarm when re-training or re-tuning is required. This tracking helps in ensuring that the models keep working properly as conditions change.

Cybersecurity and Privacy

Security Threat Landscape

The Jazan AI platform works in a cybersecurity atmosphere of high complexity and the smart city infrastructure is exposed to several and evolving threats. The pervasive nature of smart city systems leads to several possible attack surfaces, and the critical nature of municipal services means that security violations can have a catastrophic impact on city functions and citizen safety [48].

IoT Security Challenges

The platform's large scale IoT deployment introduces unique security challenges that cannot be handled using traditional security measures, requiring new security technologies. As thousands of devices are deployed throughout the city, traditional perimeter security based paradigms are untenable for protecting against the myriad of threats that an IoT deployment may face.

Device Vulnerabilities A majority of IoT devices may be constrained in terms of computing power and might not be capable of providing advanced security mechanisms, such as strong encryption, or regular security patches. and tries to overcome these limitations by a mix of the following procedures: network level security controls, device hardening processes and centralized security management systems which can take over the lack of capabilities due to individual device limitations.

Magnitude and Complexity: The volume of new devices connected to the internet introduces management complexity, which can lead to security risks unless treated correctly. The platform utilizes automated systems for managing devices that can manage, configure, and update widely deployed devices with security and operational efficiency.

Cyber Security of Communication: IoT devices transmit over a range of networks, which are cellular, Wi-Fi and low-power wide-area networks (LPWAN), and have different security properties and needs. It is integrated with end-to-end encryption and authentication mechanisms to prevent communications from being intercepted over the network technologies.

Physical Security: Most IoT devices are placed in the field in areas of the vicinity of end users; hence, they may be exposed to physical malicious attacks such as tampering or theft. The platform offers tamper detection, secure boot and remote device management functions that can monitor and respond to physical security attacks.

Advanced Persistent Threats

Smart city infrastructure is increasingly being attacked by advanced adversaries such as nation-state, organized crime, and terrorist organizations. These APTs frequently run sophisticated, multi-phased attacks that can go undetected for months while they seek to provide valuable intelligence or prepare for more malicious attacks.

Reconnaissance: APT actors frequently engage in reconnaissance over a long period, commonly in stages, which helps them in mapping system architecture and identifying vulnerabilities and building an arsenal of attack strategies. The platform uses a set of deception technology and sophisticated monitoring technology to identify reconnaissance and collect threat intelligence.

Lateral Movement: After achieving an initial foothold, attackers will explore the network to gain further access to additional systems and information. The network segmentation and zero-trust architecture of the platform minimizes lateral movement, all while actively monitoring network activities.

Persistence: APT actors often establish multiple tactics to maintain persistence after gaining access, even if some of their vectors are identified and removed. The platform relies on full EDR capabilities capable of detecting and removing types of persistence.

Data Exfiltration: Stealing intellectual property or sensitive data is the end goal of APT attacks. The platform adopts data loss prevention (DLP) technologies and full-scale data classification mechanisms capable of identifying and blocking any unauthorized connection and data leakage attempts.

Multi-Layered Security Framework

The solution itself has an extensive, layered security approach built in to ensure defense in depth across threat vectors. This architecture implements security controls on many levels ranging from end devices over network components to applications and data [49].

Network Security Architecture

Perimeter defense: Traditional perimeter security devices (e.g., firewalls, intrusion detection systems and VPN gateways) represent the first line of defense against external threats. The systems are managed in an environment of tight access control. Some updated threat intelligence flows to ensure the effectiveness against current threats.

Network Segmentation: We categorize and segment the network into security zones according to their roles, sensitivity and level of trust. This confinement helps to reduce potential exposure surfaces for security breaches while adding the ability for finer-grained security controls for various kinds of systems and data.

Zero Trust Architecture: The solution follows the zero trust security model that mandates verification and authorization for all access requests to the network regardless of their source location or user credentials. Traditional perimeter security devices (e.g., firewalls, intrusion detection systems and VPN gateways) represent the first line of defense against external threats, and at the same time allows maintaining the high quality of service.

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Lateral Movement: After achieving an initial foothold, attackers will explore the network to gain further access to additional systems and information. The network segmentation and zero-trust architecture of the platform minimizes lateral movement, all while actively monitoring network activities.

Persistence: APT actors often establish multiple tactics to maintain persistence after gaining access, even if some of their vectors are identified and removed. The platform relies on full EDR capabilities capable of detecting and removing types of persistence.

Data Exfiltration: Stealing intellectual property or sensitive data is the end goal of APT attacks. The platform adopts data loss prevention (DLP) technologies and full-scale data classification mechanisms capable of identifying and blocking any unauthorized connection and data leakage attempts.

Multi-Layered Security Framework

The solution itself has an extensive, layered security approach built in to ensure defense in depth across threat vectors. This architecture implements security controls on many levels ranging from end devices over network components to applications and data [49].

Network Security Architecture

Perimeter defense: Traditional perimeter security devices (e.g., firewalls, intrusion detection systems and VPN gateways) represent the first line of defense against external threats. The systems are managed in an environment of tight access control. Some updated threat intelligence flows to ensure the effectiveness against current threats.

Network Segmentation: We categorize and segment the network into security zones according to their roles, sensitivity and level of trust. This confinement helps to reduce potential exposure surfaces for security breaches while adding the ability for finer-grained security controls for various kinds of systems and data.

Zero Trust Architecture: The solution follows the zero trust security model that mandates verification and authorization for all access requests to the network regardless of their source location or user credentials. This is a good, secure method for distributed systems, and such as in the case of remote access.

Traffic Analysis and Monitoring: Sophisticated network monitoring tools analyze the flow and behaviors of traffic to identify possible security threats as well as the misuse of policies. These solutions leverage machine learning techniques for defining the “normal” behaviour and help detecting deviations signalling potential security attacks.

Endpoint Security

Hardened Devices: All endpoints (including servers, workstations and IoT) are hardened to the highest industry standards and align with company-set security policy. This hardening covers things like disabling unnecessary services, applying security patches, and setting secure defaults for operations.

Endpoint Detection and Response: EDR capabilities allow for full stack endpoint activity monitoring, including the ability to detect, investigate, and respond to suspected security threats. These capabilities encompass behavior analysis, threat hunting, and automatic response actions that will contain threats before it can do much harm.

Mobile Device (MD) Management: The MD management of the solution is responsible for the security and management of mobile devices that the city staff and citizens have to access the services provided on the platform. These are elements such as device encryption, application control, and remote wipe for a lost device and/or remote control of all of the information, etc.

Patch management: All endpoints on a platform are automatically updated as new security patches are issued and installed. Such systems are provided with testing and validation

procedures to determine the conditions under which patches do not undesirably affect the operation of the system while still providing security efficacy.

Application Security

Secure By Development By default we have secure development lifecycle practices integrated with a platform wherein security is implemented at each stage. This should include threat modeling, secure coding practice, security testing, and code review processes.

Application Security Testing: All platform applications are subject to security testing, including static analysis, dynamic analysis, and penetration testing prior to deployment. This review discovers possible weaknesses and verifies if an application is compliant with security policies.

Runtime Application Self-protection – Advanced security technologies embedded in the applications to protect them from attacks based on vulnerability of applications. They collect information on attacks and attackers which can be used to block and prevent attacks.

API Security: The platform relies heavily on APIs and so there is a need for API-specific security like API gateways, rate limiting, authentication/authorization procedures, and API monitoring and analytics. These defences mitigate API-specific threats and allow secure interaction between parts of the system.

Data Protection and Privacy

The platform manages gigabytes of sensitive data, personal data about citizens, confidential government information, and information on critical infrastructures. Securing this information in its raw form demands all-encompassing processes for data protection satisfying the security and privacy requirements ([50]).

Data Classification and Handling

6.2 Data Classification Framework The data is classified based on its sensitivity level and the nature of its handling for each data just like all other data in the platform. This classification system contains public data, internal data, confidential data and restricted data, which also have particular security controls and access limitations.

Data Lifecycle Management: Robust data lifecycle management includes how data is gathered, stored, used, shared and discarded as it moves through its lifecycle. These processes ensure data is adequately controlled and disposed of securely when it is no longer required.

Minimization Of Data: The system applies limited data collection, and processing, according to the purpose for which it is collected in accordance with the regulation, such data shall not be stored for a longer period than is necessary for such purpose. This methodology diminishes privacy threats and compliance burdens on one side, while retaining system functionality.

Consent: The platform covers the full spectrum of consent management for data wherein now citizens are empowered to give, manage and revoke consent for different categories of data processing. These functionalities achieve compliance with privacy laws and allow transparency in data usage.

Encryption and Key Management

Encryption: All critical data are encrypted at rest and in transit with the most advanced tools and standards. This level of encryption ensures the confidentiality of data regardless of whether other security mechanisms fail or any unauthorised party accesses the data.

Key Management: Fulfills generation, distribution, storage, rotation, etc. provide a full-range key management system. The implementation features Hardware security modules (HSM) for secure key storage and automated key rotation process to keep security throughout time.

Certificate Management Public Key Infrastructure (PKI) and certificate management systems provide digital certificates used for authentication and encryption. These are the components necessary to manage the lifecycle of the certificate, revocation process and integration with other applications and systems.

Privacy Protection Measures

Privacy by Design: The platform is built with privacy by design principles, which means that privacy is preserved in the system architecture and functionality, and was considered since the inception of the project. This feature ensures that privacy protection is designed into the system, not tacked on at the end.

Anonymization and Pseudonymization: More sophisticated anonymization and pseudonymization methodology to ensure that citizen is not identified while still providing ability to do analysis and research. So far, these technologies include differential privacy, k-anonymity, and other techniques to control disclosure risk for statistical data that a striking a balance between privacy and utility.

Access Control: Extensive access controls limit access to personal information to only individuals who have access for really good reasons. These controls comprise of role-based access control (RBAC), attribute-based access control (ABAC) and just-in-time access provisioning for sensitive operation.

Audit and Monitoring: Full audit logs are maintained for all access to and processing of personal data, which adds accountability and allows potential privacy violations to be investigated. These logs are secured against tampering and are reviewed frequently for possible issues or policy breaches.

Compliance and Governance

Its platform is subject to a sophisticated regulatory environment with local Saudi regulations, international standards, as well as industry best practices. The continual adherence to these requirements demands holistic governance frameworks and continual monitoring and assessment efforts [51].

Regulatory Compliance

Saudi Data Protection Law: The platform adheres to the Kingdom of Saudi Arabia's Data Protection Law, which identifies various requirements for the collecting, processing and safeguarding of personal data. Compliance efforts consist of consent and data rights implementations as well as breach notifications.

International Standards: It is compatible with international cyber security and privacy standards like ISO 27001 (information security management), ISO 27002 (security controls) and ISO 29100 (Privacy framework) These are the most complete frameworks for security and privacy management activities.

Sector-Specific Requirements Some government relations systems, including this item, are designated as critical infrastructure; these other systems, like the CGN system, are required to meet additional security requirements for government and critical infrastructure sectors. These would involve strengthened security measures, reporting on incidents and liaison with national cyber security units.

Security Governance Framework

Security Policy and Procedures: Overall security policies and procedures that cover all areas of platform security -- access control, incident response, risk management, and vendor management. Such policies are updated periodically to reflect changing threats and needs.

Risk Management: The platform has a formalized risk management program to assess and remediate security and privacy risks to platform operations. Such a programme consists of frequent risk assessments, risk treatment planning, and the ongoing reassessment of risk levels and the effectiveness of risk mitigation.

Incident Response: Detailed incident response plans that quicken the process of identifying, controlling, and remediating security events. These processes include incident taxonomy, escalation chain, communication process, and post-incident lessons learned, etc.

Security Awareness and Training All users and administrators of the platform have received security awareness and are trained to recognize and respond to potential threats. These campaigns range from scheduled reminder training to simulated phishing.

Case Studies

Traffic Management System Implementation

One of the most effective and popular uses of the Jazan AI platform has been deploying the smart traffic management system. This case study evaluates system development, challenges of deployment, and quantifiable results and provides actionable knowledge for other municipalities' studies of smart city technologies in urban traffic management [52].

System Architecture and Components

The traffic optimization system consists of several technologies: computer vision, edge computing, predictive analytics, and adaptive control system working together to address the traffic woes of the city. The network architecture has a high capability of accounting for city traffic that is complex and dynamic and thus is real-time responsive and long term optimized.

Sensor Network Deployment: The system comprises more than 200 traffic monitoring points covering Jazan, and installed with high definition cameras, vehicle detection sensors, and environmental sensors. These sensors provide coverage on all major arterials, intersections and traffic corridors, and produce more than 2 terabytes of data per day.

Edge Computing Infrastructure: NVIDIA Jetson Xavier located in intersections carry out on-site video processing and real-time traffic optimization. These endpoint devices also locally process video streams in order to identify vehicles, categorize the traffic situation, and adjust the signal timing in real time, all without the need for talking to a central server.

Central Control System: TMC integrates the data collected in all observation nodes and the system optimizes and coordinates the data in the whole region. The center is equipped with the latest in visualization, prediction and manual override capabilities for traffic engineers and emergency management personnel.

NETWORKS Communication Networks: The platform is supported by a hybrid communication system, integrating fibre optics for high bandwidth, 5G cellular for mobile and backup connection, and channelled radio for emergency communication.

Implementation Challenges and Solutions

The implantation of the TMS faced a few serious issues, which in turn demanded novel solutions and reactive procedures. These are lessons learned that will be of much value to other smart cities which may of have implemented in different environments.

Legacy Infrastructure Assimilation: Jazan already had legacy-based traffic control systems which used antiquated technology that didn't have connectivity or data transfer options. The team also created interface modules from scratch that were able to interface with old systems and work to move functionality onto the new system. This method enabled continuous operations throughout the changeover and reduction of interference for traffic flow.

Environmental Challenges: The unforgiving desert weather in Jazan, including temperature fluctuation, sandstorms, and high humidity levels presented a series of tests for equipment that was being deployed outside. The system design used ruggedized enclosures, developed advanced

cooling, and added redundancy throughout to maintain high reliability in severe environments. Preventive maintenance procedures were established to combat the system's sensitivity to the environment.

Cultural and Behavioral: Driving behavior in Jazan does not always match the driving behavior in other cities/seven cities where such systems have been successfully implemented. The machine learning algorithms underpinning the system needed to be trained on local traffic information for the precise forecasting and reacting to local traffic. Community education programs were also initiated to inform drivers that traffic operations were being managed differently and to persuade them to follow coordinated signal timing.

Scalability — With rapid urbanization and rising traffic density the system had to cater for huge traffic growth of roads and performance in scalability. The architecture is modular and scalable and was designed to support the increase in processing and cloud-connectivity and computing to scale-up computational capacity at the peak.

Performance Outcomes and Impact

The system has resulted in measureable reduction in traffic movement time, enhancement of traffic safety and control air pollution emission consequent to convey of vehicle. These results show that smart city technologies can be of practical value if implemented and customised to local circumstances.

Traffic Flow Enhancements: In-depth analysis of traffic data demonstrates, on average, a 25% improvement in traffic flow efficiency and overall performance at monitored intersections. Average Peak Hour Travel Times are down 18 per cent and throughput has increased by 22 per cent in peak times. These gains have been maintained over 2 years of evaluation, suggesting long-term system efficacy.

Safety benefits: Intersections using the intelligent management system have observed a 31% reduction in traffic accidents with respect to a baseline. One of the major outcomes is that odd click traffic patterns are a novel activity that the role can detect and respond to – leading for example to faster emergency response times and less severe traffic accidents. Pedestrian protection has also been enhanced by synchronizing traffic signal timings and pedestrian crosswalk signal timings.

Environmental: There are also environmental effects of this decreased traffic-based congestion. Air quality in urban regions has thus been reduced by up to 15% with monitored vehicles. Less idling and better traffic flow patterns have resulted in less fuel consumption.

Economic Benefit The increased traffic efficiency has impacted the economy by reducing travel time, fuel consumption, and vehicle maintenance. Economic analysis calculates the system's total annual economic impact at a projected \$2.3 million, as a result of time savings and lower vehicle- and business-operating costs.

Environmental Monitoring Network

The environmental surveillance network is another key use case for the Jazan AI platform where IoT technologies and data analytics can support environmental protection and public health. This paper is a case study of the network's design, implementation and effect on environmental governance in the region [53].

Network Design and Coverage

The environmental observatory system is operated by more than 150 monitoring stations placed all across Jazan region, having different sensor for different environmental attributes. The network structure is to ensure in the first place the maximum coverage, but also to focus on areas with specific environmental problems, or of high population densities.

Air Quality Monitoring: The stations record particulate matter (PM_{2.5} and PM₁₀), nitrogen-oxides, sulphur dioxide, ozone, and carbon monoxide. State-of-the art sensors provide real-time monitoring, measuring with high accuracy and reliability, and facilitate detection of pollution events and monitoring of long-term trends.

assessment: pH, dissolved oxygen, turbidity Points on the river and channel network and distribution systems Water quality of rivers and channels pooled Total mixed liquor suspended solids (TSS): Waste water collection points within the urban area. This surveillance enables to fulfill the double function of the protection of environment and public health guarantee keeping the standard of quality of water.

Noise Level Monitoring: Acoustic sensors monitor background noise levels in domestic, commercial and industrial environments. This information serves to validate urban planning initiatives, enabling areas of noise pollution to be pinpointed and assessed in terms of quality of life.

Weather and Climate Measurement: complete weather stations offer a variety of meteorological data such as temperature, humidity, wind speed and direction, rainfall, and solar radiation. It also will be used to support environmental analysis, as well as smart city applications (traffic, energy optimization, among others).

Data Analytics and Predictive Capabilities

The environmental monitoring system produces massive amount of data data that can be used through advanced analytics to extract the knowledge to make actionable decisions. The company's AI/ML programs allow for the sophisticated analysis and projection of environmental factors.

Analysis on the fly: Stream and managed stream analytics perform computations on the environmental data to identify possible pollution events, weather-related emergencies and other such situations that call for an immediate response. Automated alarm systems alert authorities and citizens when environmental conditions are dangerous.

Predictive Modeling: To predict future environmental conditions, machine learning models process historical environmental data, as well as weather predictions and human activity behaviour. These forecasts can be used for advance in initiatives for protecting public health and the quality of environment.

Source Identification: Sophisticated analytics can be used to generate hypotheses about where pollution might be coming from by examining spatial and temporal trends in environmental observation. This feature also facilitates the concentration of prosecutions and can be used to determine which types of abatements produce the greatest improvement in environmental quality.

Health Impact Assessment: The framework links environmental data with health data to evaluate potential health impacts and vulnerable populations that might need more protection in the face of adverse environmental conditions.

Public Health and Policy Impact

Due to the EMN several aspects on public health protection and environmental policy in the Jazan region has been influenced. The emergence of real-time, comprehensive environmental data has changed the way we diagnose, perceive, and respond to environmental crises.

Early warning systems: The network can warn early of environmental health risks, so that public health authorities can issue advisories and put in place protective actions before such situations become hazardous. These early alerts have been especially important during dust storms and industrial accidents that can quickly deteriorate air quality.

Policy Making: A wealth of environmental data supports the evidence-based policy making and regulatory decision-making. The information has been utilized in the development of new environmental regulations, in assessing implementation effectiveness of current regulations, and in areas where more environmental protection measures may be necessary.

Public Attention: The public can access environmental information in real time through the web portals and mobile Apps, raising awareness of environmental situation and helping people to make decisions about outdoor activities and protective measures for health.

Research and Planning The environmental database is used for academic research and urban planning with high quality long-term environmental field data. This analysis will contribute to the understanding of environmental changes and the development of better environmental management.

Citizen Services Digital Transformation

The digitization of citizen services is the epitome of a complete makeover of how the residents in Jazan receive or seek accessibility to the city services. This exemplary study provides insight on how to transform from traditional government services to digital services, the challenges

emerged in that transition process, and the outcomes in service quality, efficiency, and citizen satisfaction [54].

Service Portfolio and Digital Channels

The digital transformation project included more than 120 unique municipal services that spanned from straight-forward information requests all the way to multi-step licensing and permitting procedures. This service transformation involved an in-depth understanding of each service to identify the most suitable digital / electronic delivery channels to continue providing quality and accessible services.

Web Based Service Portal: A unified web based portal to access in digitized manner all the services. The portal offers user account management and document upload and storage, payment processing, as well as real-time tracking of the status of a service request.

Mobile Apps: Our native mobile apps for iOS and Android allow smartphone and tablet users to access online municipal services on the go. This apps also includes offline and pushnotification so you don't miss any of key feature.

Integration of Virtual Assistant: The AI based virtual assistant is integrated in the service delivery channels of digital government serving as a robotic assistant for guiding and assisting the citizens accessing the services. The assistant can respond to questions, assist with form completion, and direct difficult issues up the chain to human staff when appropriate.

Multi-Channel Support: As not all citizens are adept at digital channels, the transformation preserved traditional service options and coupled them with digital systems. This process enables all residents to access services on channels that they prefer and optimising efficiency and consistency.

Process Reengineering and Automation

The digital redesign was about an end-to-end reinvention of our City processes to take advantage of the digital, while sustaining quality services and regulatory compliance. This reengineering entailed both technological modifications and organizational adjustments.

Streamlined Workflow: BPM systems automate the mundane tasks of service delivery, such as document routing, approval flow, and status notifications. That automation cuts processing time and increases consistency, and liberates staff to pursue more complicated cases that involve human judgment.

Document Management: Electronic document management, which replaces paper-based processes, facilitates the safe, efficient exchange of documents between departments and citizens. Machine readers such as OCR and natural language processing can extract or process information from the documents that are submitted.

Quality Assurance: Automated QA systems track service delivery processes in real time to flag potential diverted mistakes, lagtimes or inconsistencies. The systems are designed to monitor and maintain high quality of service as well as immediately detect and address process problems.

Performance Tracking: All the various measurement systems track performance indicators such as process times, construct completion rates, construct error rates and customer satisfaction scores. This accountability allows for ongoing improvement of service delivery processes based on where attention is needed most.

Outcomes and Citizen Impact

As a result of citizen services digitalisation, there have been considerable gains in service delivery efficiency, quality and Citizen satisfaction. The results indicate the promise of eGovernment if governments can successfully implement digital technology.

Efficiency Gains: Average service processing times have been cut by 60 percent for all digitized services, and in some cases, the processing of simple services is now immediate, done electronically. Workforce productivity has improved by 40 percent as repetitive work is automated and processes are refined.

Accessibility Features: Digital service channels have enhanced the overall accessibility for citizens with disabilities with greater compatibility with screen readers, keyboard navigation, and ability to change text sizes. Accessibility has also increased geographically, services being reachable from any place where there is internet access.

Cost Savings: The shift to digital has brought about major cost reductions in terms of paper consumption, administrative overhead and staff efficiency. 'Analysis shows that the per-transaction cost has been reduced of digitised services by about 45 per cent,' the bench noted.

Citizen Satisfaction: Citizen satisfaction survey results reveal that satisfaction with digital services is consistently high, with 92% of respondents rating their experience as good or excellent. The convenience, promptness and transparency of digital service delivery channels are especially welcomed by citizens.

Challenges and Solutions

Technical Implementation Challenges

There were a variety of technical challenges faced in implementing the Jazan AI platform which necessitated innovative and sizable efforts. Such challenges offer useful information on the practical issues of implementing complex smart-city systems and the approaches to address them [55].

Scalability and Performance Issues

One of the major technical challenges we had to address while implementing the platform was to ensure that system can continue to scale to support the increasing number of users, devices, and volumes of data while still meet the performance requirements. The distributed structure of smart city systems, and the real-time needs of many applications, led to some specific scalability issues.

database performance optimisation -As they scaled from a couple of hundred users to tens of thousands of users, database performance became a critical bottleneck. The original RDBMS design was not capable of supporting the volume of concurrent transactions and complex queries necessary for the platform. The solution was to deploy a hybrid database system, using relational databases to store transactional data, and NoSQL databases for loose data with no boundaries regarding volume, such as sensor readings and log files.

Managing Network Bandwidth: The high volume of IoT devices and high resolution video streams led to network traffic volumes beyond what the initial planning models had estimated. The network became congested with delayed data transmission and reduced system response time. The answer was to create intelligent traffic prioritization systems and to deploy edge computing solutions to minimise the amount of data sent across the network.

Scaling of Processing Capacity: The processing requirements for AI and machine learning applications increased dramatically, as more advanced algorithms were used and datasets became larger. The legacy on-premises compute could not scale fast enough as demand grew. The answer was a cloud-based infrastructure for offloading the compute-intensive workflows and scaling based on demand and retaining edge computing for low-latency apps.

Storage System Architecture: The system collected and stored a large amount of data from different types of resources, which brings both the issues of storage capacity and data retrieval performance. The original design of the storage model did not fully take into consideration the varied access patterns and how long data should be retained based on type. The solution was a tiered storage solution in which data is moved automatically between different storage types according to how often it is accessed and according to how long it is retained, maintaining an optimal balance between cost and performance.

Integration and Interoperability Challenges

The platform integrating a large number of legacy systems, third party services and a wide range of IoT devices posed great interoperability challenges. It was further complicated by the absence of common interfaces and protocols between vendors and between generations of the systems.

Integration with Legacy Systems: Many municipal systems were developed on outdated infrastructure and written with the understanding that they would never have to be integrated with other processes. Impediments Typically, these systems had no APIs, or implemented their own custom protocols that were hard to integrate. The solution was to create an adapter middleware that translated between various protocols and data models and define a gradual migration strategy, with a bridging mechanism to allow legacy systems to be plugged into the new architecture and provide new capabilities through the migrated layers.

Vendor Ecosystem Management – The technology uses technologies from various different vendors, all with their own interfaces, manageability tools, and support requirements. “It was a lot of work and maintenance to coordinate between vendors and ensure compatibility between their solutions.” The solution included defining all technical standards and integration guidelines for any vendor, comprehensive testing by vendors to prove compliance before deployment.

Standardized Data Format: Various systems and devices utilize incompatible data format, which can lead to difficulty in sharing and analyzing data across the platform. The solution was to design a full data model and transform layer that could translate between text formats while also maintaining data integrity and significance. “It was a lot of work and maintenance to coordinate between vendors and ensure compatibility between their solutions.” and use facilities optimally. This saves costs and at the same time allows maintaining the high quality of service.

Computer Vision and Surveillance Systems

Featuring a powerful computer vision-based engine that processes video streams from cameras across the city to detect traffic congestion, public order issues and infrastructure performance, the platform taps data from between 6 to 10 sensor-oriented applications. These features enable autonomous monitoring and analysis that is beyond the reach of human observation [46].

Traffic Monitoring and Analysis

Computer vision systems which receive video from traffic cameras for the purpose of controlling vehicle traffic and gathering traffic statistics. Such systems are an important source of real-time data that is used in traffic management decisions and in long-term transportation planning.

Vehicle Detection and Classification: State-of-the-art object detection algorithms to detect, classify vehicles such as cars, trucks, buses, motorcycles, and bicycles. Such a classification allows for more complex traffic analysis and traffic management enabled according to the vehicle type.

Speed estimation: Vehicle speed can be estimated by tracking the motion of objects through multiple video frames. This feature allows for automatic speed monitoring and the identification of speeding hotspots.

Incident Detection: The system is able to automatically detect traffic incidents such as accidents, stoppage and congestion. In the event of an incident, the system sends immediate electronic notifications to highway managers and responders to minimise response times and enhance safety.

Traffic flow analysis: With full analysis on traffic flow, you will know the peak time and most popular road to better direct your outdoor activities. That information contributes to infrastructure planning and can be used to develop traffic management strategies.

Public Safety Monitoring

Computer vision is also used in public safety systems, where public cameras are scanned around the clock to look for anything out of the ordinary (such as a bag unattended) or for crowds forming too quickly, which could indicate a threat. These features significantly increase public safety while preserving privacy rights and the spirit of freedom.

Crowd Monitoring: This system can analyse crowd formation from the scenes of public spaces, including the crowd density, crowd movement, security and other risk aspects. This feature becomes even more useful when controlling big events and maintaining safety in congested places.

Anomaly detection: Supervised ML algorithms that are fed with typical activity patterns in the networks may pick up anomalous or suspicious activity which should be further looked into. The system is also set up to reduce the number of false alarms and to inform on any activities that should be of concern.

Emergency Response Aid: In an emergency, computer vision systems can instantly monitor the status of affected areas for emergency responders to make proper decisions regarding resource allocation and evacuation strategies.

Infrastructure Monitoring

Computer vision also has been used to determine the status of municipal infrastructure such as roads, bridges, buildings and public utilities. This monitoring allows early maintenance and can prevent infrastructure failover.

Damage Inspection: An approach of infrastructure image processing is employed to detect the damages, wears, or deteriorations which might call for repairs and maintenance. This ability allows more effective infrastructure management and makes it possible to avoid the ordering of expensive spare parts.

Maintenance Planning: Through monitoring the condition of infrastructure over time the system can anticipate maintenance and assist in the scheduling of maintenance activities to maximise service and minimise cost.

Asset inventory: Computer vision can automate the inventory of government assets and monitor the state+local level capabilities as to location and usage. It allows for better asset management and replacement/upgrades planning.

Machine Learning and Automation

Machine Learning has been built into the platform and it can be used to automate different processes in the municipality and increase system performance. They can intelligently minimize human effort and enhance the accuracy and efficiency for a wide range of applications [47].

Process Automation

Municipality-process analysis Machine learning comprises the investigation of regularities in the processes of the municipality in order to realize opportunities for automation and optimization. Only the most complex cases need to be addressed by the human workforce, and IMPACT can learn from historical data and human decision-making trends to automate repetitive decisions.

Document Processing: With NLP and computer vision technologies, we automate tasks of processing the documents of different kinds such as permit applications, complaint forms, service requests. The system can extract MAC information as well as confirm that all sections are completed before directing any documents to staff.

Decision Support: AI models that analyze historical decisions and outcomes to suggest decisions on current cases. These guidelines ensure uniformity in decision making and reduce the duration of case processing.

Controls: ACID: Automatically monitor the quality of processed transactions for accuracy and completeness, indicating possible errors that will be followed automatically by a human review. This allows a high quality service to be provided while handling large volumes of transactions efficiently.

Continuous Learning and Improvement

The platform's machine learning engines should be programmed to learn and get better over time as it processes more information and receives feedback. This ongoing learning ability means that the system becomes increasingly effective as time goes by and in response to different situations and needs.

Integration of feedback: User feedback and performance metrics are constantly integrated back into machine learning models for greater accuracy and efficacy. This control loop allows the system to learn from successes as well as failures to enhance future performance.

Model Evolution: Frequent model evolution to integrate new data and better algorithms for improved system performance. Updates such as these are rigorously checked and verified before they are rolled out, guaranteeing that enhancements do not compromise the performance or stability of a system.

Performance monitoring: Visibility-based monitoring tools monitor the performance of machine learning models and alarm when re-training or re-tuning is required. This tracking helps in ensuring that the models keep working properly as conditions change.

Cybersecurity and Privacy

Security Threat Landscape

The Jazan AI platform works in a cybersecurity atmosphere of high complexity and the smart city infrastructure is exposed to several and evolving threats. The pervasive nature of smart city systems leads to several possible attack surfaces, and the critical nature of municipal services

means that security violations can have a catastrophic impact on city functions and citizen safety [48].

IoT Security Challenges

The platform's large scale IoT deployment introduces unique security challenges that cannot be handled using traditional security measures, requiring new security technologies. As thousands of devices are deployed throughout the city, traditional perimeter security based paradigms are untenable for protecting against the myriad of threats that an IoT deployment may face.

Device Vulnerabilities A majority of IoT devices may be constrained in terms of computing power and might not be capable of providing advanced security mechanisms, such as strong encryption, or regular security patches. and tries to overcome these limitations by a mix of the following procedures: network level security controls, device hardening processes and centralized security management systems which can take over the lack of capabilities due to individual device limitations.

Magnitude and Complexity: The volume of new devices connected to the internet introduces management complexity, which can lead to security risks unless treated correctly. The platform utilizes automated systems for managing devices that can manage, configure, and update widely deployed devices with security and operational efficiency.

Cyber Security of Communication: IoT devices transmit over a range of networks, which are cellular, Wi-Fi and low-power wide-area networks (LPWAN), and have different security properties and needs. It is integrated with end-to-end encryption and authentication mechanisms to prevent communications from being intercepted over the network technologies.

Physical Security: Most IoT devices are placed in the field in areas of the vicinity of end users; hence, they may be exposed to physical malicious attacks such as tampering or theft. The platform offers tamper detection, secure boot and remote device management functions that can monitor and respond to physical security attacks.

Advanced Persistent Threats

Smart city infrastructure is increasingly being attacked by advanced adversaries such as nation-state, organized crime, and terrorist organizations. These APTs frequently run sophisticated, multi-phased attacks that can go undetected for months while they seek to provide valuable intelligence or prepare for more malicious attacks.

Reconnaissance: APT actors frequently engage in reconnaissance over a long period, commonly in stages, which helps them in mapping system architecture and identifying vulnerabilities and building an arsenal of attack strategies. The platform uses a set of deception technology and sophisticated monitoring technology to identify reconnaissance and collect threat intelligence.

Lateral Movement: After achieving an initial foothold, attackers will explore the network to gain further access to additional systems and information. The network segmentation and zero-trust

architecture of the platform minimizes lateral movement, all while actively monitoring network activities.

Persistence: APT actors often establish multiple tactics to maintain persistence after gaining access, even if some of their vectors are identified and removed. The platform relies on full EDR capabilities capable of detecting and removing types of persistence.

Data Exfiltration: Stealing intellectual property or sensitive data is the end goal of APT attacks. The platform adopts data loss prevention (DLP) technologies and full-scale data classification mechanisms capable of identifying and blocking any unauthorized connection and data leakage attempts.

Multi-Layered Security Framework

The solution itself has an extensive, layered security approach built in to ensure defense in depth across threat vectors. This architecture implements security controls on many levels ranging from end devices over network components to applications and data [49].

Network Security Architecture

Perimeter defense: Traditional perimeter security devices (e.g., firewalls, intrusion detection systems and VPN gateways) represent the first line of defense against external threats. The systems are managed in an environment of tight access control. Some updated threat intelligence flows to ensure the effectiveness against current threats.

Network Segmentation: We categorize and segment the network into security zones according to their roles, sensitivity and level of trust. This confinement helps to reduce potential exposure surfaces for security breaches while adding the ability for finer-grained security controls for various kinds of systems and data.

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The platform manages gigabytes of sensitive data, personal data about citizens, confidential government information, and information on critical infrastructures. Securing this information in its raw form demands all-encompassing processes for data protection satisfying the security and privacy requirements ([50]).

Data Classification and Handling

6.2 Data Classification Framework The data is classified based on its sensitivity level and the nature of its handling for each data just like all other data in the platform. This classification

system contains public data, internal data, confidential data and restricted data, which also have particular security controls and access limitations.

Data Lifecycle Management: Robust data lifecycle management includes how data is gathered, stored, used, shared and discarded as it moves through its lifecycle. These processes ensure data is adequately controlled and disposed of securely when it is no longer required.

Minimization Of Data: The system applies limited data collection, and processing, according to the purpose for which it is collected in accordance with the regulation, such data shall not be stored for a longer period than is necessary for such purpose. This methodology diminishes privacy threats and compliance burdens on one side, while retaining system functionality.

Consent: The platform covers the full spectrum of consent management for data wherein now citizens are empowered to give, manage and revoke consent for different categories of data processing. These functionalities achieve compliance with privacy laws and allow transparency in data usage.

Encryption and Key Management

Encryption: All critical data are encrypted at rest and in transit with the most advanced tools and standards. This level of encryption ensures the confidentiality of data regardless of whether other security mechanisms fail or any unauthorised party accesses the data.

Key Management: Fulfills generation, distribution, storage, rotation, etc. provide a full-range key management system. The implementation features Hardware security modules (HSM) for secure key storage and automated key rotation process to keep security throughout time.

Certificate Management Public Key Infrastructure (PKI) and certificate management systems provide digital certificates used for authentication and encryption. These are the components necessary to manage the lifecycle of the certificate, revocation process and integration with other applications and systems.

Privacy Protection Measures

Privacy by Design: The platform is built with privacy by design principles, which means that privacy is preserved in the system architecture and functionality, and was considered since the inception of the project. This feature ensures that privacy protection is designed into the system, not tacked on at the end.

Anonymization and Pseudonymization: More sophisticated anonymization and pseudonymization methodology to ensure that citizen is not identified while still providing ability to do analysis and research. So far, these technologies include differential privacy, k-anonymity, and other techniques to control disclosure risk for statistical data that a striking a balance between privacy and utility.

Access Control: Extensive access controls limit access to personal information to only individuals who have access for really good reasons. These controls comprise of role-based access control (RBAC), attribute-based access control (ABAC) and just-in-time access provisioning for sensitive operation.

Audit and Monitoring: Full audit logs are maintained for all access to and processing of personal data, which adds accountability and allows potential privacy violations to be investigated. These logs are secured against tampering and are reviewed frequently for possible issues or policy breaches.

Compliance and Governance

Its platform is subject to a sophisticated regulatory environment with local Saudi regulations, international standards, as well as industry best practices. The continual adherence to these requirements demands holistic governance frameworks and continual monitoring and assessment efforts [51].

Regulatory Compliance

Saudi Data Protection Law: The platform adheres to the Kingdom of Saudi Arabia's Data Protection Law, which identifies various requirements for the collecting, processing and safeguarding of personal data. Compliance efforts consist of consent and data rights implementations as well as breach notifications.

International Standards: It is compatible with international cyber security and privacy standards like ISO 27001 (information security management), ISO 27002 (security controls) and ISO 29100 (Privacy framework) These are the most complete frameworks for security and privacy management activities.

Sector-Specific Requirements Some government relations systems, including this item, are designated as critical infrastructure; these other systems, like the CGN system, are required to meet additional security requirements for government and critical infrastructure sectors. These would involve strengthened security measures, reporting on incidents and liaison with national cyber security units.

Security Governance Framework

Security Policy and Procedures: Overall security policies and procedures that cover all areas of platform security -- access control, incident response, risk management, and vendor management. Such policies are updated periodically to reflect changing threats and needs.

Risk Management: The platform has a formalized risk management program to assess and remediate security and privacy risks to platform operations. Such a programme consists of frequent risk assessments, risk treatment planning, and the ongoing reassessment of risk levels and the effectiveness of risk mitigation.

Incident Response: Detailed incident response plans that quicken the process of identifying, controlling, and remediating security events. These processes include incident taxonomy, escalation chain, communication process, and post-incident lessons learned, etc.

Security Awareness and Training All users and administrators of the platform have received security awareness and are trained to recognize and respond to potential threats. These campaigns range from scheduled reminder training to simulated phishing.

Case Studies

Traffic Management System Implementation

One of the most effective and popular uses of the Jazan AI platform has been deploying the smart traffic management system. This case study evaluates system development, challenges of deployment, and quantifiable results and provides actionable knowledge for other municipalities' studies of smart city technologies in urban traffic management [52].

System Architecture and Components

The traffic optimization system consists of several technologies: computer vision, edge computing, predictive analytics, and adaptive control system working together to address the traffic woes of the city. The network architecture has a high capability of accounting for city traffic that is complex and dynamic and thus is real-time responsive and long term optimized.

Sensor Network Deployment: The system comprises more than 200 traffic monitoring points covering Jazan, and installed with high definition cameras, vehicle detection sensors, and environmental sensors. These sensors provide coverage on all major arterials, intersections and traffic corridors, and produce more than 2 terabytes of data per day.

Edge Computing Infrastructure: NVIDIA Jetson Xavier located in intersections carry out on-site video processing and real-time traffic optimization. These endpoint devices also locally process video streams in order to identify vehicles, categorize the traffic situation, and adjust the signal timing in real time, all without the need for talking to a central server.

Central Control System: TMC integrates the data collected in all observation nodes and the system optimizes and coordinates the data in the whole region. The center is equipped with the latest in visualization, prediction and manual override capabilities for traffic engineers and emergency management personnel.

NETWORKS Communication Networks: The platform is supported by a hybrid communication system, integrating fibre optics for high bandwidth, 5G cellular for mobile and backup connection, and channelled radio for emergency communication.

Implementation Challenges and Solutions

The implantation of the TMS faced a few serious issues, which in turn demanded novel solutions and reactive procedures. These are lessons learned that will be of much value to other smart cities which may have implemented in different environments.

Legacy Infrastructure Assimilation: Jazan already had legacy-based traffic control systems which used antiquated technology that didn't have connectivity or data transfer options. The team also created interface modules from scratch that were able to interface with old systems and work to move functionality onto the new system. This method enabled continuous operations throughout the changeover and reduction of interference for traffic flow.

Environmental Challenges: The unforgiving desert weather in Jazan, including temperature fluctuation, sandstorms, and high humidity levels presented a series of tests for equipment that was being deployed outside. The system design used ruggedized enclosures, developed advanced cooling, and added redundancy throughout to maintain high reliability in severe environments. Preventive maintenance procedures were established to combat the system's sensitivity to the environment.

Cultural and Behavioral: Driving behavior in Jazan does not always match the driving behavior in other cities/seven cities where such systems have been successfully implemented. The machine learning algorithms underpinning the system needed to be trained on local traffic information for the precise forecasting and reacting to local traffic. Community education programs were also initiated to inform drivers that traffic operations were being managed differently and to persuade them to follow coordinated signal timing.

Scalability — With rapid urbanization and rising traffic density the system had to cater for huge traffic growth of roads and performance in scalability. The architecture is modular and scalable and was designed to support the increase in processing and cloud-connectivity and computing to scale-up computational capacity at the peak.

Performance Outcomes and Impact

The system has resulted in measureable reduction in traffic movement time, enhancement of traffic safety and control air pollution emission consequent to convey of vehicle. These results show that smart city technologies can be of practical value if implemented and customised to local circumstances.

Traffic Flow Enhancements: In-depth analysis of traffic data demonstrates, on average, a 25% improvement in traffic flow efficiency and overall performance at monitored intersections. Average Peak Hour Travel Times are down 18 per cent and throughput has increased by 22 per cent in peak times. These gains have been maintained over 2 years of evaluation, suggesting long-term system efficacy.

Safety benefits: Intersections using the intelligent management system have observed a 31% reduction in traffic accidents with respect to a baseline. One of the major outcomes is that odd click traffic patterns are a novel activity that the role can detect and respond to – leading for example to faster emergency response times and less severe traffic accidents. Pedestrian

protection has also been enhanced by synchronizing traffic signal timings and pedestrian crosswalk signal timings.

Environmental: There are also environmental effects of this decreased traffic-based congestion. Air quality in urban regions has thus been reduced by up to 15% with monitored vehicles. Less idling and better traffic flow patterns have resulted in less fuel consumption.

Economic Benefit The increased traffic efficiency has impacted the economy by reducing travel time, fuel consumption, and vehicle maintenance. Economic analysis calculates the system's total annual economic impact at a projected \$2.3 million, as a result of time savings and lower vehicle- and business-operating costs.

Environmental Monitoring Network

The environmental surveillance network is another key use case for the Jazan AI platform where IoT technologies and data analytics can support environmental protection and public health. This paper is a case study of the network's design, implementation and effect on environmental governance in the region [53].

Network Design and Coverage

The environmental observatory system is operated by more than 150 monitoring stations placed all across Jazan region, having different sensor for different environmental attributes. The network structure is to ensure in the first place the maximum coverage, but also to focus on areas with specific environmental problems, or of high population densities.

Air Quality Monitoring: The stations record particulate matter (PM2.5 and PM10), nitrogen-oxides, sulphur dioxide, ozone, and carbon monoxide. State-of-the-art sensors provide real-time monitoring, measuring with high accuracy and reliability, and facilitate detection of pollution events and monitoring of long-term trends.

assessment: pH, dissolved oxygen, turbidity Points on the river and channel network and distribution systems Water quality of rivers and channels pooled Total mixed liquor suspended solids (TSS): Waste water collection points within the urban area. This surveillance enables to fulfill the double function of the protection of environment and public health guarantee keeping the standard of quality of water.

Noise Level Monitoring: Acoustic sensors monitor background noise levels in domestic, commercial and industrial environments. This information serves to validate urban planning initiatives, enabling areas of noise pollution to be pinpointed and assessed in terms of quality of life.

Weather and Climate Measurement: complete weather stations offer a variety of meteorological data such as temperature, humidity, wind speed and direction, rainfall, and solar radiation. It also will be used to support environmental analysis, as well as smart city applications (traffic, energy optimization, among others).

Data Analytics and Predictive Capabilities

The environmental monitoring system produces massive amount of data data that can be used through advanced analytics to extract the knowledge to make actionable decisions. The company's AI/ML programs allow for the sophisticated analysis and projection of environmental factors.

Analysis on the fly: Stream and managed stream analytics perform computations on the environmental data to identify possible pollution events, weather-related emergencies and other such situations that call for an immediate response. Automated alarm systems alert authorities and citizens when environmental conditions are dangerous.

Predictive Modeling: To predict future environmental conditions, machine learning models process historical environmental data, as well as weather predictions and human activity behaviour. These forecasts can be used for advance in initiatives for protecting public health and the quality of environment.

Source Identification: Sophisticated analytics can be used to generate hypotheses about where pollution might be coming from by examining spatial and temporal trends in environmental observation. This feature also facilitates the concentration of prosecutions and can be used to determine which types of abatements produce the greatest improvement in environmental quality.

Health Impact Assessment: The framework links environmental data with health data to evaluate potential health impacts and vulnerable populations that might need more protection in the face of adverse environmental conditions.

Public Health and Policy Impact

Due to the EMN several aspects on public health protection and environmental policy in the Jazan region has been influenced. The emergence of real-time, comprehensive environmental data has changed the way we diagnose, perceive, and respond to environmental crises.

Early warning systems: The network can warn early of environmental health risks, so that public health authorities can issue advisories and put in place protective actions before such situations become hazardous. These early alerts have been especially important during dust storms and industrial accidents that can quickly deteriorate air quality.

Policy Making: A wealth of environmental data supports the evidence-based policy making and regulatory decision-making. The information has been utilized in the development of new environmental regulations, in assessing implementation effectiveness of current regulations, and in areas where more environmental protection measures may be necessary.

Public Attention: The public can access environmental information in real time through the web portals and mobile Apps, raising awareness of environmental situation and helping people to make decisions about outdoor activities and protective measures for health.

Research and Planning The environmental database is used for academic research and urban planning with high quality long-term environmental field data. This analysis will contribute to the understanding of environmental changes and the development of better environmental management.

Citizen Services Digital Transformation

The digitization of citizen services is the epitome of a complete makeover of how the residents in Jazan receive or seek accessibility to the city services. This exemplary study provides insight on how to transform from traditional government services to digital services, the challenges emerged in that transition process, and the outcomes in service quality, efficiency, and citizen satisfaction [54].

Service Portfolio and Digital Channels

The digital transformation project included more than 120 unique municipal services that spanned from straight-forward information requests all the way to multi-step licensing and permitting procedures. This service transformation involved an in-depth understanding of each service to identify the most suitable digital / electronic delivery channels to continue providing quality and accessible services.

Web Based Service Portal: A unified web based portal to access in digitized manner all the services. The portal offers user account management and document upload and storage, payment processing, as well as real-time tracking of the status of a service request.

Mobile Apps: Our native mobile apps for iOS and Android allow smartphone and tablet users to access online municipal services on the go. This apps also includes offline and pushnotification so you don't miss any of key feature.

Integration of Virtual Assistant: The AI based virtual assistant is integrated in the service delivery channels of digital government serving as a robotic assistant for guiding and assisting the citizens accessing the services. The assistant can respond to questions, assist with form completion, and direct difficult issues up the chain to human staff when appropriate.

Multi-Channel Support: As not all citizens are adept at digital channels, the transformation preserved traditional service options and coupled them with digital systems. This process enables all residents to access services on channels that they prefer and optimising efficiency and consistency.

Process Reengineering and Automation

The digital redesign was about an end-to-end reinvention of our City processes to take advantage of the digital, while sustaining quality services and regulatory compliance. This reengineering entailed both technological modifications and organizational adjustments.

Streamlined Workflow: BPM systems automate the mundane tasks of service delivery, such as document routing, approval flow, and status notifications. That automation cuts processing time and increases consistency, and liberates staff to pursue more complicated cases that involve human judgment.

Document Management: Electronic document management, which replaces paper-based processes, facilitates the safe, efficient exchange of documents between departments and citizens. Machine readers such as OCR and natural language processing can extract or process information from the documents that are submitted.

Quality Assurance: Automated QA systems track service delivery processes in real time to flag potential diverted mistakes, lagtimes or inconsistencies. The systems are designed to monitor and maintain high quality of service as well as immediately detect and address process problems.

Performance Tracking: All the various measurement systems track performance indicators such as process times, construct completion rates, construct error rates and customer satisfaction scores. This accountability allows for ongoing improvement of service delivery processes based on where attention is needed most.

Outcomes and Citizen Impact

As a result of citizen services digitalisation, there have been considerable gains in service delivery efficiency, quality and Citizen satisfaction. The results indicate the promise of eGovernment if governments can successfully implement digital technology.

Efficiency Gains: Average service processing times have been cut by 60 percent for all digitized services, and in some cases, the processing of simple services is now immediate, done electronically. Workforce productivity has improved by 40 percent as repetitive work is automated and processes are refined.

Accessibility Features: Digital service channels have enhanced the overall accessibility for citizens with disabilities with greater compatibility with screen readers, keyboard navigation, and ability to change text sizes. Accessibility has also increased geographically, services being reachable from any place where there is internet access.

Cost Savings: The shift to digital has brought about major cost reductions in terms of paper consumption, administrative overhead and staff efficiency. 'Analysis shows that the per-transaction cost has been reduced of digitised services by about 45 per cent,' the bench noted.

Citizen Satisfaction: Citizen satisfaction survey results reveal that satisfaction with digital services is consistently high, with 92% of respondents rating their experience as good or excellent. The convenience, promptness and transparency of digital service delivery channels are especially welcomed by citizens.

Challenges and Solutions

Technical Implementation Challenges

There were a variety of technical challenges faced in implementing the Jazan AI platform which necessitated innovative and sizable efforts. Such challenges offer useful information on the practical issues of implementing complex smart-city systems and the approaches to address them [55].

Scalability and Performance Issues

One of the major technical challenges we had to address while implementing the platform was to ensure that system can continue to scale to support the increasing number of users, devices, and volumes of data while still meet the performance requirements. The distributed structure of smart city systems, and the real-time needs of many applications, led to some specific scalability issues.

database performance optimisation -As they scaled from a couple of hundred users to tens of thousands of users, database performance became a critical bottleneck. The original RDBMS design was not capable of supporting the volume of concurrent transactions and complex queries necessary for the platform. The solution was to deploy a hybrid database system, using relational databases to store transactional data, and NoSQL databases for loose data with no boundaries regarding volume, such as sensor readings and log files.

Managing Network Bandwidth: The high volume of IoT devices and high resolution video streams led to network traffic volumes beyond what the initial planning models had estimated. The network became congested with delayed data transmission and reduced system response time. The answer was to create intelligent traffic prioritization systems and to deploy edge computing solutions to minimise the amount of data sent across the network.

Scaling of Processing Capacity: The processing requirements for AI and machine learning applications increased dramatically, as more advanced algorithms were used and datasets became larger. The legacy on-premises compute could not scale fast enough as demand grew. The answer was a cloud-based infrastructure for offloading the compute-intensive workflows and scaling based on demand and retaining edge computing for low-latency apps.

Storage System Architecture: The system collected and stored a large amount of data from different types of resources, which brings both the issues of storage capacity and data retrieval performance. The original design of the storage model did not fully take into consideration the varied access patterns and how long data should be retained based on type. The solution was a tiered storage solution in which data is moved automatically between different storage types according to how often it is accessed and according to how long it is retained, maintaining an optimal balance between cost and performance.

Integration and Interoperability Challenges

The platform integrating a large number of legacy systems, third party services and a wide range of IoT devices posed great interoperability challenges. It was further complicated by the absence of common interfaces and protocols between vendors and between generations of the systems.

Integration with Legacy Systems: Many municipal systems were developed on outdated infrastructure and written with the understanding that they would never have to be integrated with other processes. **Impediments** Typically, these systems had no APIs, or implemented their own custom protocols that were hard to integrate. The solution was to create an adapter middleware that translated between various protocols and data models and define a gradual migration strategy, with a bridging mechanism to allow legacy systems to be plugged into the new architecture and provide new capabilities through the migrated layers.

Vendor Ecosystem Management – The technology uses technologies from various different vendors, all with their own interfaces, manageability tools, and support requirements. “It was a lot of work and maintenance to coordinate between vendors and ensure compatibility between their solutions.” The solution included defining all technical standards and integration guidelines for any vendor, comprehensive testing by vendors to prove compliance before deployment.

Standardized Data Format: Various systems and devices utilize incompatible data format, which can lead to difficulty in sharing and analyzing data across the platform. The solution was to design a full data model and transform layer that could translate between text formats while also maintaining data integrity and significance. This method realizes transparent data exchange by its end and keeps the original data format between different systems.

Protocol standardization: IOT systems and devices inter-communicate using various communication protocols, making it hard to manage and protect the network. What Toshiba needed was protocol gateways that were able to deal with translation between the protocols and the requirement of both security and performance. This allows the platform to be interoperable with varying types of devices, at the same time hiding the diversity to applications and users.

Organizational and Cultural Challenges

On top of technical challenges, the deployment of the Jazan AI platform faced significant organizational and cultural difficulties that needed to be well managed, and dealt with in original ways. These shortcomings spell the need for change management and stakeholder involvement in the realisation of smart city implementations [56].

Staff Training and Adaptation

The implementation of high technology and new working methods demanded extensive training and adaptation from the municipal personnel. A significant portion of the employees was not very digital savvy and needed extensive training to work efficiently on the new platforms.

Digital Literacy: Many municipal staff had little experience with digital technologies and needed to be introduced to basic digital literacy skills before they could deliver on platform use. The solution was to build a range of training, beginning with basic computer skills and building to

tool-specific requirements. The training was provided in the classroom and during practical exercises, with follow-up instruction to assist staff in utilizing new technologies.

Change Management for Process: The implementation of the platform involved process changes and a departure from the old ways of working. A lot of staff members were averse to these new directions, especially when you wanted to stop using old manual processes in favour of technology. The answer was to have a managed change program that included a strong communication strategy around the benefits of the new processes, and training and support throughout the transition, as well as offering incentives programs for the employees that showed an ability to adapt to new way of working.

Technical Support Capacity: The complexity of the system meant that new technical support had to be created within the city. The current IT support crew did not have the required expertise when it came to AI and IoT technologies. It was a mix of hands-on external training to existing personnel, hiring new technical experts, and portfolio partnerships with technology companies to offer niche and specialized expert services when those are required.

Citizen Acceptance and Adoption

To gain public acceptance and encourage the use of digital services the fear of technology, lack of privacy and the changes in the service delivered (plus what it looks like) had to be met. None of the demographic groups were universally comfortable with digital technologies, so targeted approaches were needed to encourage adoption.

Digital Divide Implications: Large sectors of the population had limited exposure to digital technology and were not able to effectively access digital services. The answer was to keep traditional channels to serve customers and gradually nudge them into the digital sphere via training and support. Public access points in libraries and community centers were created and digital literacy training programs were conducted to enable citizens to acquire the skills to utilize digital services.

Concern over accessing personal information: Several citizens expressed concern over the safety and privacy of their personal details in the digital space. These considerations are especially sensitive when dealing with the extensive amounts of data smart city apparatuses generate. The measure included introducing transparent privacy regime where citizens are well-informed about how data is collected and safeguarded and the creation of citizen-led watchdog organization to monitor the process of protection of people's privacy.

Cultural challenges: The solution had to be designed to cater to local cultural needs and the way a language is usually spoken in informal situations as opposed to other countries in which similar technologies had been implemented. This covered everything from language preferences and communication styles to service delivery directions. This included widespread community engagement at the design stage, cultural customisation of user interfaces and communications materials, and ongoing feedback streams that allow services to be continuously refined on the basis of citizen input.

Innovative Solutions and Best Practices

The difficulties faced in implementing the platform translated into lessons learned and best practices that could help similar smart city initiatives in other settings. These are suggestions that there is a need for adaptation and continuous learning in complex technology implementations [57].

Adaptive Architecture Design

Platform Architecture The platform's architecture was founded on a core principle of user needs, that it be adaptable, and able to grow and improve as needs change and new technology becomes available. This approach also has shown useful to deal with the complexity and uncertainty of smart cities deployment.

Microservices Platform – Our platform makes heavy use of microservices that splits complex functionalities into smaller self-contained services that can be developed, deployed and scaled independently. This is quick to adjust the solution when it faces new context and is easy to migrate or rehost new features without heavily affecting the current service. Each microservice should have a specified API and role, which facilitates the possibility to refactor or swap out part of the application as required.

API-First Design — All platform components are designed from the ground up with APIs at the forefront, which allows customers the freedom to integrate and overlay other services. This API first methodology allows new applications and services to be developed that take advantage of vSphere platform capabilities, as well as integration with 3rd party systems and services. Extensive API documentation and developer tools are available for internal development and third party integration.

Containerization and Orchestrating: The platform employs containerization technologies to bundle and run applications in an uniform, portable environment. Container orchestration platforms provide a way to automate scaling, load balancing, and fault-recovery to make systems more reliable, scalable and performant to run with less operational overhead. It also helps with development and testing by making environments consistent from stage to stage in the software lifecycle.

Community Engagement Strategies

To ensure the system was supported and utilized by citizens, significant community engagement was needed to demonstrate a high level of receptivity, receive feedback and to also inform what the system could shape into, in order to be in line with citizens' preferences. The engagement programs created for the Jazan platform are a blueprint to other smart city programs.

Participatory Design Processes: Working citizens were co-designers in your tool developments (participatory design workshops, focus groups, and user testing). This engagement has helped to ensure that the platform meets citizens' needs and interests, as well as building community

ownership and consensus around the initiative. On-going supported feedback helps build new features and improve the platform.

Open Communication: Clear communication on the status, abilities, and insecurities in duration of the platform development was essential to build citizen trust and awareness. This communication took the form of public hearings, website updates, social media, and traditional media interviews. Simple and plain-language explanations of technology and how things can work and forthright updates on progress similarly helped keep the wider community on board with development.

Pilot Programs Concept: It received new 'features and services' through pilot programs, through which they can be tested and perfected before being launched! These pilot projects had allowed the citizens to respond and helped identify and fix problems before they could impact a lot of people. The pilot project was also a way to create trust in new technologies by showcasing their potential in safe spaces.

Continuous Improvement Framework

The system searches for specific keyword phrases entered by the customer and displays relevant information through a client-side colored QR tag (generated by encryption of the raw image from the QR tag). On this side the system is developed, to make the platform grow and improve stream after stream.

Performance Monitoring & Analytics– Full-scale monitoring to monitor platform performance on all fronts – technical performance, user satisfaction and business impact.run across various dimensions of platform performance run across various dimensions of platform performance. Sophisticated analytics tools uncover trends, patterns and improvement opportunities, and automatic alerts expedite the discovery and remediation of performance shortfalls.

Integration of Feedback: Collects feedback to feedback from users, staff, and other stakeholders through multiple channels including surveys, focus groups, user analysis and direct channels for communication. This feedback is then systematically analysed, and used to direct the future development and upgrade projects for the platform, ensuring that the system continues to meet current and future needs.

Agile Development Process:The team works with agile development processes that allows iterative fast development cycles and continuous improvements. Swift sprint cycles, double speed user story creation, and continuous integration and delivery enable us to respond rapidly to changing demands and deploy improvements and new features fast.

Lessons learned and KM Knowledge Management Systems: Detailed documentation of lessons learned, best practices, and technical expertise accrued during platform deployment and operation is captured in comprehensive knowledge management systems. This knowledge base facilitates the maintenance and enhancing of the city while providing insights for other smart city initiatives.

Recommendations and Future Directions

Strategic Recommendations for Platform Enhancement

Recommendations: Strategic The following strategic level recommendations have emerged from the combined findings of the Jazan AI implementation status, performance, and impact, and they could help strengthen the functionalities and the benefits associated with the AI platform:. These are guidelines related to the short- and long-term opportunities in improvement that could guide the continued stratification and growth of the platform [58].

Artificial Intelligence Capability Expansion

The current AI of the platform is an impressive initial implementation, but is just the tip of the iceberg on what can be achieved with sustained investment in advanced AI technology. Numerous specific areas provide ripe opportunities for building on and expanding.

Sophisticated Predictive Analytics: The system will need to be able to develop more advanced predictive analytics to predict more complex urban phenomena more accurately and for longer time-frames. This involves creating ensemble models that aggregate multiple predictions from different prediction methods as well as integrating external data such as economic indicators and social media sentiment and real-time model updating that can respond to new data. This enhanced predictability would allow for a more proactive approach to operational management and resource planning with respect to all municipal services.

Federated Learning Implementation: In order to preserve user privacy while enhancing the performance of its AI models, the platform should consider federated learning techniques, which allows training of a model across many decentralized data sources via gradient updates, not the data itself. This would let the platform leverage data and insights from other smart city deployments, with the privacy of citizen data being held sacrosanct. Federated learning may also be fastidious to pave the road for more personalized services by maintaining individual privacy.

Explainable AI Integration: With AI growing more complex and increasingly determining high stakes decisions, the explanatory and comprehensible nature of AI decision-making is important to maintain public trust and compliance to regulation. The platform needs to invest in explainable AI, which is the capability to deliver clear running explanations to facilitate understanding of AI-influenced decisions and recommendations. Such a capability could be especially useful for applications in the areas of permit approval, resource allocation decisions and emergency response planning.

Multi-Modal AI Urban data is multi-modality in nature and future AI development should take a multi-modality approach in terms of data type and analytic type in order to make a more complete sense of urban systems. This may involve text, image, video, audio analysis and sensor data analysis for holistic understanding of the urban context and citizen needs. Multi-modal AI might support applications like holistic urban health monitoring, integrated transport planning, or advanced emergency response coordination.

Service Portfolio Expansion

The service offering in the current platform is quite broad, but could be further extended to other municipal sectors and to offer more integrated and citizen focused services. There are multiple areas of focused expansion that can greatly enhance citizens lives and the overall functioning of the municipality.

Smart Health Services: The Smart Platform will be extended to become the home of health services that use analytics and AI, in support of public health goals. Options might include environmental health monitoring that can link air quality and other environmental conditions to health outcomes, disease surveillance systems that can identify and follow threats to public health, and personalized health advice linked to environmental status and individual risk. If integrated with healthcare providers, this may offer an opportunity for a more holistic approach to health but with privacy safeguards.

Education Technology Integration: Smart city platforms could contribute to educational development by integrating technology and data driven insights. Possibly, this could grow into additional education services like digital learning platforms, student transport optimization, facility management for schools, and education outcome analytics. Such services might enhance quality of education, as well as save costs and administrative complexity for educational organizations.

Economic Development: Expanding EDO to provide more extensive support at economic development (examples – business intelligence analytics, investment attraction tools, workforce development coordination, small business support services) Integration into economic data sources could facilitate improved economic development programs and enhanced support for local businesses and entrepreneurs.

Technology Infrastructure Modernization

Ongoing progress will be required to develop the technology infrastructure of the platform, to keep the platform performing, secure, and capable in the face of growth and progressive evolution. There are a number of infrastructure improvements that should take precedence.

5G Network Integration 5G network deployment in Jazan will open up opportunities to improve capability (mainly high bandwidth/ low latency application). They can upgrade their platform so that it plays to 5G's strengths such as improved video analytics, real-time augmented-reality apps and richer IoT device connectivity. 5G incorporation could also open up new opportunities, including the coordination of autonomous vehicles and immersive citizen-engagement apps.

Quantum Computing Readiness: Despite being in its initial stages, the platform needs to start getting ready for quantum computing being part of its technology stack. This currently involves finding use cases that can benefit from quantum computing, working on quantum-ready algorithms and data structure, and entering into partnerships with quantum computing research institutes. Prepared early, the platform will be ready to leverage quantum computing capabilities once they are commercially available.

Improvement on blockchain integration: The system's current adoption of blockchain system in the Peaq network can further be explored to delve into other blockchain applications. This might include supply chain transparency for public procurement, voting / governance use cases, identity management systems, and decentralized data sharing. By allowing better transparency, security and citizen involvement, such blockchain technology may help reduce the cost of administration.

Regional and International Expansion

The positive outcome of the Jazan AI platform means it can be replicable in other districts and global markets. It might deliver further advantages and is expected to help to develop smart city technologies and strategies in a wider context [59].

Saudi Arabia National Deployment

The proven success of the platform in Jazan has created a platform to roll-out to other parts of the Kingdom of Saudi Arabia. Such a national rollout could offer economies of scale and it could align with the Kingdom's Vision 2030 goals for digitalisation and the deployment of smart cities.

Framework of Standardization and Adaptation: In national level, standardization frameworks must be developed so that uniform platform capabilities can be enjoyed in various locations and also allow local adaptation and customization. This framework should integrate technical standards, common data sharing protocols, security needs, and a governance structure, which can be applied uniformly while still respecting regional, cultural, and linguistic or locality specific differences.

Cross-City Data Sharing: With the nation-wide deployment, data from different cities and regions can be shared and collaborated on. This might involve sharing best practices, coordinated emergency response, integrated transportation planning, or joint R&D. The following privacy and governance mechanisms would have to be made in place to allow for beneficial data-sharing between the two systems to ensure citizen privacy, and protect local control.

Economic Development Coordination: A national smart city platform could facilitate coordinated economic development that builds on the strengths of various regions and avoids unproductive competition. This might include co-ordinated investment promotion, labour-market upskilling initiatives or supply-chain efficiencies that serve the Kingdom and promote local economic development objectives.

International Collaboration and Export

The Jazan platform's unique solutions and proven track record of success also present potential for global partnerships and technology exports which provide mutual benefits for both Saudi Arabia and other countries looking to adopt smart city technologies.

Middle East and North Africa regional leadership: Saudi Arabia is well placed to take a regional lead in smart cities. The Jazan platform might be replicated and used as a core for smart city

initiatives in other MENA countries, albeit tailored to local and specific needs. This leadership role could bring economic value, and help to develop the frontier and reduce the tension in the region.

Technology Transfer: This platform's technologies and methodologies could be transferred to other countries via technology transfer programs that would offer economic and diplomatic returns. Such forays might involve training and capacity building, technical assistance as well as co-development projects that customise the platform's potential to varied national and cultural environments.

Relational Governance for Research and Development Partnerships: Internationally, R&D partnerships might hasten the pace at which new smart city technologies are created, and in sharing costs and risks. Areas of agricultural potential that could be the focus of the above mentioned regional partnerships include artificial intelligence, cybersecurity, environmental monitoring and urban strategies where multiple countries can contribute and benefit.

Policy and Governance Recommendations

Further momentum and widespread application of smart city initiatives depend on supportive policy and governance frameworks that balance innovation with protection of the rights and interests of the citizens. A number of policy considerations arise from the Jazan platform experience [60].

Regulatory Framework Development

Smart City Legislation Recommendations 1) **Data Governance Legislation:** Widespread data governance legislation needs to be formulated that sets clear and comprehensible rules for data collection, use and sharing in smart city scenarios. Such legislation must strike a balance between the use of data for urban management and the rigorous protection of privacy and citizens' rights. Legislation should also dictate guidelines for the sharing of data across agencies and government levels with the requisite security and privacy protections.

AI Ethics and Accountability: As AI systems continue to increasingly be used in government decision-making, there is a need for explicit ethical standards and accountability measures in order to guarantee that these systems are used with responsibility and fairness. This could entail both transparency obligations regarding AI decision-making itself, bias testing and remediation measures, human oversight over automated decisions, and redress mechanisms for citizens who believe they have been unfairly evaluated or treated by an AI system.

Cybersecurity: Cybersecurity standards for smart city systems, including security by design requirements, security assessments, incident reporting, and cooperation with national cybersecurity authorities, should be mandatory. These should be regularly reviewed to account for new threats and should consist of both technical specifications and governance measures.

Interoperability Requirements Interoperable standards must be demonstrated between different smart city systems and vendors to avoid being locked into a vendor-specific solution and allow

for innovation and competition. These standards should include technical interfaces, data formats and governance processes to ensure that multiple systems can interoperate supportively while meeting security and performance needs.

Investment and Financing Frameworks

PPP models: Implement effective PPP models that allow the private companies to invest in SC infrastructure but for the government to retain control over the services and data of the citizens. Such models should have clear risk-sharing and risk distribution, performance and monitoring standards, and mechanisms for technology transfer and capacity development.

Innovation Funding Mechanisms: Sourcing revenues from the aforementioned sources, specific funding mechanisms must be put in place for the continued innovation and advancement of smart city technology. Such mechanisms could be research and development grants, innovation challenges and competitions, and venture capital funds dedicated to smart city applications. These mechanisms should focus on addressing local needs and challenges and on building local technical capacity to help local solutions.

Sustainability and Whole Life Costing: Investment choices should be informed by whole lifecycle costing, encompassing not only deployment costs, but also operating, maintenance, and upgrade costs. Sustainability aspects must also be incorporated in the investment decisions such as energy, environment and social qualities.

International Cooperation Frameworks

Standards Development: Saudi Arabia should engage in international standards development for smart cities, artificial intelligence, and the technologies upon which they depend. This involvement would allow international guidelines to be based on the requirements and requirements of developing nations, as well as promote Saudi Arabia as a pioneer country for smart cities.

Technology Sharing Agreements: Bilateral and multilateral technology sharing and cooperation agreements may be entered into with other countries which are developing Smart cities. Such agreements could also foster the sharing of knowledge, joint research and development, collective responses to common challenges such as cyber security and privacy protection.

Capacity Building Programs: Global capacity building programme should be created to help other developing countries through sharing Saudi Arabia's smart city knowledge and experience. Such programs might be focused on training and education, technical assistance, and co-development projects that create local capabilities while consolidating overseas relationships.

Future Technology Integration

The rapid technological advancement offers continuous opportunities of smart city development by incorporating newly appearing technologies. A number of particular technical fields are promising for future platform improvement [61].

Next-Generation Connectivity

Preparing for 6G Networks: It's not even fully established yet, but 6G networks are already in development while 5G networks are still going in. The platform will need to lay the technological groundwork to support 6G, offering even faster speeds, lower latency, and other innovations like built-in sensing and communication. 6G might support novel applications like fully immersive AR/VR experiences, advanced holographic communications and ultra-accurate positioning and navigation services.

Satellite Internet Incorporation: Low earth orbit satellite internet constellations are in early deployment stages, which would work as a complimentary to terrestrial networks for global broadband coverage. The platform should also consider options for integration with satellite internet services, enabling backup coverage, service provision in rural and remote regions, and additional resiliency in the face of natural disasters or other forms of failure in terrestrial infrastructure.

Upgraded Edge Computing: Further developments in edge computing technology, such as more powerful processors, better AI acceleration, improved integration with cloud service, will allow more complex local processing. The platform must provision for the uptake of such advanced edge computing capabilities to accommodate new applications and increase performance level of the existing services.

Emerging AI Technologies

Large Language Models: Advances in training large language models (LLMs) have opened new possibilities for more powerful natural language understanding systems. The platform should investigate integrating such advanced LLMs, which have been trained on Arabic text data, to provide better virtual assistant capabilities, automatic document processing and citizen communication tools.

Computer Vision Development: Further development in computer vision technologies such as improving object recognition, scene understanding, and video analysis will unlock new applications in urban monitoring and management. The platform should have a roadmap to adopt these sophisticated computer vision capabilities to further improve traffic management, public safety, and infrastructure monitoring use cases.

Autonomous Vehicles: The introduction of autonomous vehicles, drones and robots opens up an array of new potential smart city applications such as autonomous public transportation, automated infrastructure inspection, and robotic service. The platform must start getting ready for the integration with autonomous ones, together with the development of the specific communications protocols, safety systems, and normative frameworks.

Sustainability Technologies

Integrating Renewable Energy: With advancements in renewable energy resources, such as enhanced solar panels, wind turbines and energy storage makes it possible to operate smart cities

on a more sustainable basis. The platform could work on integrating with alternate energy systems; green energy, which could potentially reduce operational costs and be less harmful for the environment.

Carbon Monitoring and Management: Sensors and analytics for advanced carbon emissions monitoring to help climate change mitigation. The platform should also explore incorporating carbon monitoring capabilities that can be useful for regulatory compliance as well as voluntary sustainability programs.

Circular Economy Uses: Recycling and reuse processes and waste-to-energy conversion technologies and resource extraction can be leveraged along with smart city initiatives to deliver more sustainable urban systems. As part of the wider sustainability efforts, the platform should look into these integration possibilities.

Conclusion

Summary of Key Findings

This detailed laboratory study of the Jazan Artificial Intelligence Platform has provided insights into the deployment, performance and effects of next-generation smart city solutions in a Middle Eastern context. This evidence shows that advanced smart city platforms can be decentrally installed and exploited in developing countries if due consideration is given to local cultural, language and technical needs [62].

Technical Achievement and Innovation

The Jazan AI is indeed a breakthrough technology as it seamlessly combines various state-of-the-art technologies of Internet of Things platforms, AI engines, Edge Computing and Cloud services. The platform's design is illustrative of the synergistic combination of various technologies to and a capability greater than that achievable from any single technology.

The deployment of edge computing, with in place distributed processing by means of the NVIDIA Jetson devices, has been very successful regarding the need of low-latency and local decisions. This has allowed high-end AI use cases like traffic control and environmental observation to be deployed with acceptable performance and reduced burden on the bandwidth needs of the central processor.

Such incorporation of Microsoft Azure Digital Twins technology has resulted in complete digital counterparts of urban systems that provide advanced simulation, analysis, and optimization functionalities. This digital twin is showing its worth for both operational management and strategic planning purposes – offering insight which would be challenging, or impossible, to gain using conventional monitoring methodologies.

Its foray into the emerging domain of decentralised physical infrastructure networks and the integration with Peaq blockchain, offers a radically different way to solve the challenges of scale, security and sustainability in the delivery of smart cities. It is still early days, however, this

integration showcases how the blockchain can help make urban infrastructure systems more robust and efficient.

Service Delivery Transformation

The municipality has made notable progress in the efficiency, quality and access to municipal service delivery during the past ten years. AI-enabled personal city assistants, which can process more than 80% of citizen questions with artificial intelligence, have made response times much faster, while ensuring that services and information are consistent and available at all times.

The city's more than 120 re-engineered and digitized municipal services have brought significant gains to residents and municipal personnel alike. Originally posted Oct 25, 2018 4:30 PM People are able to access services 24/7, and the time and cost of travel to service centers along with waiting time has become lessened leading to ICT process of determination being more transparent. For municipal staff, it's the automatic workflow management, less administrative overhead, and access to necessary info to help make decisions.

The platform's multi-channel approach – in parallel to traditional service delivery mechanisms, it creates digital demand – has provided an effective way to manage transition to digital services and ensure that every citizen can avail of services irrespective of whether they are digitally literate or not.

Performance and Impact Outcomes

The quantitative evaluation of platform performance reveals clear tangible gains in several aspects. Traffic management systems have reported a 25% improvement in the efficiency of traffic flow and 18% decrease of travel time and 15% of vehicle emissions in the stated areas. These benefits have persisted throughout the 2 years in which the study was conducted, supporting the long-term efficacy of the introduced measures.

The region has also improved environmental surveillance capacity, such as early warning systems to notify the public about air quality and other environmental conditions, to help detect and respond to environmental health risks. It was the comprehensive environmental database generated by the enhancement of the monitoring network which was instrumental in enabling both immediate and sustainable responses from the environment planning and policy perspectives.

Citizens are highly satisfied with digital services and its level has reached to 92%, giving high level of acceptance and satisfaction on the upgraded service delivery mechanism. Of particular interest is the very high rate of satisfaction, particularly given early concerns regarding digital literacy and technology acceptance in this sample.

An economic analysis estimates that the platform provides around \$2.3M in economic benefit per year due to increased operational efficiencies, reduced travel times, and decreased operation costs. The values of these benefits are many times the cost of the platform, and by showing this

level of economic viability, it offers a concrete example of cost effectiveness for an implementation in a Smart City.

Cultural and Social Adaptation

The study exposes the pivotal role of cultural and linguistic customization in smart city deployments. The investment by the platform in Arabic natural-language processing and culturally attuned interface design is critical to ensuring high levels of citizen acceptance and use.

The platform's model for engaging the community, including participatory design processes, clear communication, and pilot program roll-outs, has worked well for getting local buy-in and making sure the system meets local conditions and expectations. This citizen engagement lessons learned are a useful model for other smart city efforts in related cultural settings.

The study also confirms the need to respond to digital divide challenges with well-rounded digital literacy, alternative channels, and ongoing support for citizens at different levels of technical literacy. The multi-channel approach of the platform has proven effective in making digital services accessible to all and has had the positive externality to harness the gradual adoption of modern digital technologies.

Implications for Smart City Development

The results generated from this study would be beneficial for smart city development with respect to the MENA region as well as at international level. The fact that a sophisticated smart city technology has been successfully introduced in the developing area of Jazan, Saudi Arabia, demonstrates that emerging technologies for smart city solutions can feasibly be applied in a developing region if due regard is paid to localisation needs.

Technology Integration Lessons

The experience of the platform yields some insight of technology in a complex urban environment. There have been a number of interoperability issues, migration issues and testing issues, since implementation has already demonstrated the need and importance of interoperability standards, step-by-step migration strategies and complete test procedures.

This investigation has found that edge computing systems are of particular interest when applications in a smart city context cannot provide real-time reaction to their environment or have area with no or poor network access. In many smart city applications, the distributed processing mode is more resilient and efficient than the completely centralized architecture 20, 21 (e.g., smart lighting).

Adopting AI capabilities must be approached with a focus on data quality, algorithm training and ongoing model management. While the experience of the platform would suggest that under the right conditions AI systems can offer substantial benefits, they demand continuous investment in

data management and the development of the algorithm if that performance is to be maintained in the long term.

Governance and Policy Insights

The study highlights the urgency for integrated governance approaches that support both innovation and the protection of citizen rights and interests. Since the platform's multi-layered security model and privacy measures were paramount in the development of trust by citizens in the use and access of citizen data for beneficial purposes.

The value of engaging stakeholders and building trust through clear and open communication during implementation is readily apparent. Much of the platform's success in garnering community support, and high levels of adoption, can be attributed to its all-inclusive community engagement strategy.

The study also underlines requirements of favourable national policy and regulatory frameworks that allow innovative solutions and care while ensuring adequate protection and control. Establishment of unclouded data governance, cybersecurity and interoperability rules have been necessary for the successful operation of the platform.

Economic and Social Impact

The platform's proven economic results are a strong validation of the smart city investment case if implemented correctly. Platform results Across the platforms, the net present value assessed shows a positive return on smart city investments, meaning that smart city solutions can be profitable while delivering social paybacks.

The research indicates that smart city initiatives have the potential to open up development horizons and enable broader economic development strategies through the enhancement of the attractiveness and efficiency of cities as places to live in and work with. It has also served as a cornerstone for local development objects through the deployment of business process and economic development support platform.

The positive social impacts brought by this platform in terms of increased access to services, better monitoring of the environment, and response to emergencies contribute to emphasize the potential of smart cities to increase the quality of life and the social equity when designed with this in mind.

Contributions to Knowledge

This study also offers some implications to the academic and practical understanding of smart city implementation and management, specifically in developing region contexts that have not been covered by previous literature.

Methodological Contributions

The mixed method research design utilized in this study offers a holistic methodology for assessing a smart city implementation using the QPM contrasted with qualitative stakeholder perceptions. This model facilitates a more comprehensive analysis of the technical performance, as well as the social impact, of smart city technologies than can be derived from a purely quantitative or qualitative analysis.

This study serves as an illustration of the importance of longitudinal research in gaining insights into the long-term effectiveness and viability of smart city programmes. This two-year evaluation time frame has made it possible to observe trends and develop patterns, which would not have been possible in a shorter investigation, indicating changes and evolution and evolution of smart city systems over time.

The combination of multiple sources has allowed us to gain a good overview of various facets of platform performance and impact. The multiple source design has facilitated triangulation and the development of connections among varying constructs associated with system performance.

Theoretical Contributions

The findings advance theoretical understanding of technology adoption and adaptation in a developing region setting. The evidence supports models that underscore the need for cultural adaptation and community assimilation in technology transfer and the influence of technical system factors- including system performance and reliability -noting adoption outcomes.

The paper offers an empirical support for hybrid models which are mix of centralized and decentralized model architectures. Edge computing and cloud integration, used by the platform, show how distinct architectures can coexist in order to achieve performance, cost, and resilience.

The study helps to develop the relationship between the technological maturity and social credits in smart cities. The results show that technosocial sophistication alone is not enough to ensure favourable social outcomes, and that the quality of user experience, accessibility and community involvement is important to the realisation of the smart city promise.

Practical Contributions

The study serves for practical guidance of smart city application in developing areas with clear suggestions of technology selection, system architecture designing, local participation and performance monitoring. Such recommendations are empirical and inspired by positive experiences from a proven implementation that may be drawn from and guide similar efforts elsewhere.

Deeper exploration of the implementation challenges and solutions renders important lessons to the practitioners in terms of planning the smart city initiatives. Discovering these common problems and successful solutions can help other implementations prevent the same pitfalls, and speed up time to market.

The study is a comprehensive work for smart city performance evaluation from both the technical and social dimensions. This model can be extended and generalized to other smart city implementations to help evidence based management and organisational learning.

Future Research Directions

Results from this study provide potential impetus for future research that can contribute more to the understanding of smart city deployment and management in developing countries and other contexts.

Longitudinal Impact Studies

To capture and characterize the long-term impact and evolution of smart city initiatives more detailed longitudinal studies will be necessary. Although the current study offers convenience sampling and snapshots into roughly two years of operation, future research could further explore patterns and patterns over time, such as the sustenance of participants' realized benefits or the evolution of citizens' attitudes and behaviors.

Future studies could focus on the ways that smart city systems develop and evolve given a set of conditions, such as population expansion, technological innovation, and variations in citizen demands. If the adaption mechanisms were better understood, it could also lead to more robust and sustainable smart city systems.

Comparative Analysis

Comparing smart city deployment between different cultural, economic, and political contexts might offer insights into aspects that lead to successful deployment and what must change between places. Such analyses may make it possible to generalize the governing principles as well as context-dependent necessities of smart cities.

Comparison between countries within the MENA region would be particularly informative on how national and local contexts intersect with implementation outcomes of smart cities. Such comparisons might help direct cooperation, exchanges of experiences between regions.

Technology Integration Research

In the future, it will be interesting to investigate how 6G networks, quantum computing, and sophisticated AI systems can be integrated with current smart city platforms. Comprehend, how these technologies can be efficiently interconnected in order to make more informed strategic decisions with respect to smart city development and investments.

For example, a study on the convergence of sustainability technologies such as renewable energy, and carbon monitoring, and circular economy applications might help us understand the role smart city platforms can play to achieve the goals of climate change mitigation and environmental sustainability [5].

Governance and Policy Research

Further research is required to explore governance models and policy mechanisms that could effectively balance innovation and protection of citizen rights and interests. Such research could compare the various strategies with regard to the extent they enable beneficial smart city growth while reducing potential negative impacts.

One area that is in need of future research is examining international cooperation mechanisms in building smart cities, through which knowledge, technologies and best practices can be exchanged across borders while also accommodating local sovereignty and cultural diversity.

Final Reflections

The proposed Jazan AIP is an outstanding exemplar in smart city field, proving the impact of advanced technologies on urban management and on citizens and being applied and adopted to the specific local environment. The good news is that the successful response offers lessons which can guide other similar efforts across the MENA region and beyond.

Research shows that successful Smarts City development is not all about better technology, as other factors such as community need, cultural fit, stakeholder engagement, and ongoing performance monitoring and enhancement are crucial. The “all of the above” strategy on these (non-tech) considerations is indeed what has been needed for the platform to take off and is a model for smart city initiatives going forward.

The shown advantages of the platform, such as increased efficiency of service delivery, environmental monitoring, traffic management, and citizen satisfaction are a powerful proof that the value proposition of smart city investments is reasonable. Yet, the advantages are not simply a given and depend on quality implementation, community engagement, and ongoing quality improvement.

With continual development and advancement of smart city technologies, lessons learned from the Jazan platform can provide substantial guidance for future developments. "The unique ways in which the platform is integrating technology, engaging communities and managing project performance, are a strong basis for progressing the capabilities and impact of the city as smarter over time.

The success of the Jazan AI platform also serves to illustrate how underdeveloped regions can become leaders in smart city innovation rather than simply implementer of technologies developed elsewhere. The platform's original methods concerning cultural translation, community participation and technology infusion are original and innovative to be potentially interesting for other smart city implementations around the world.

Future This ongoing development and expansion of the Jazan platform, alongside similar projects throughout the region, has the potential to cement the MENA region as a hub for the smart city domain. This leadership position could yield massive economic, social, and diplomatic

dividends, and also play an important part in the overall global challenge of making our cities more sustainable, productive and livable.

The process of ‘smart city’ building is however still work in progress, and the Jazan AI platform is another critical piece in the giga-city puzzle. The knowledge gained, success realized, and advances these working groups made, will serve as a significant springboard to continue smart city growth and influence for Saudi Arabia, as well as globally.

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