Master of Science Thesis

Digital Twin of Nicosia

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Master of Science Thesis

<u>Digital Twin of Nicosia</u>

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In my master's journey, I had the chance to dive deep into the intriguing universe of Computer Science. This isn't just a subject for me, but a key that unlocks endless possibilities in problem-solving and creative innovation. We live in a digital age, where the power of this field is evident everywhere. It draws me in with its capacity to push limits, bring together minds from across the globe, and reshape our world for current and future generations. It's a source of inspiration that fuels my drive, shaping me and my future aspirations. As I continue to learn and grow, my passion for Computer Science stays at the core, making me excited to contribute to its progress.

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Abstract

As large cities around the world grapple with numerous challenges such as traffic congestion, resource management, environmental concerns, and infrastructure maintenance, innovative solutions are needed to ensure sustainable growth and improved quality of life. One major problem that urban planners face is the lack of real-time data for effective decision-making and problem-solving. This vital data includes information on traffic flow and density, temperature fluctuations, humidity levels and rainfall records. This master's thesis investigates the development and implementation of a digital twin for Nicosia, the capital of Cyprus, as a Proof of Concept (PoC) to overcome data challenges and address pressing urban issues.

A digital twin is like a virtual representation of a real-world object or place, such as a city or a building. It uses sensors to collect real-time data about what's happening, which is then used to update a 3D model, a digital copy of that real thing. It uses data analytics and machine learning to simulate the city's behavior in real-time. In short, a digital twin helps us to understand and predict real-world events by creating and studying a live, virtual copy of it.

The research starts by exploring the key problems Nicosia currently faces, including traffic management, energy consumption, waste disposal, and disaster risk mitigation. The study emphasizes the difficulties in obtaining and integrating accurate, up-to-date data needed to develop effective strategies and interventions to tackle these urban issues. Advanced modeling techniques and machine learning algorithms are utilized to analyze and visualize data, enabling informed decision-making and effective problem-solving. Research presents the structure of the digital twin PoC, examining software architecture and programming languages employed in its development. The study discusses design principles, architectural components, and technical considerations that underpin the digital twin system, providing insights into the tools and techniques used to create a scalable, robust, and effective proof of concept solution. The outcome of this master's thesis is the successful development of a proof-of-concept digital twin for Nicosia, the capital of Cyprus.

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LIST OF ABBREVIATIONS

3D	Three (3) Dimensions
10-Gigabit Ethernet	A version of Ethernet with a nominal data rate of 10 Gbit/s, ten times faster than Gigabit Ethernet.
AI	Artificial Intelligence
AMD	Advanced Micro Devices
API	Application Programming Interface
C6H6	C6H6 Benzene
CesiumJS	A JavaScript library for creating 3D globes and 2D maps in a web browser
CO	Carbon Monoxide
CPU	Central Processing Unit
Cyens	Cyprus Research and Innovation Center
DDR	Dual Double Rate (reference to memory). DDR4 and DDR5 are types of synchronous dynamic RAM.
Fiber Optic Connections	A type of Ethernet connection that uses light, rather than electrical signals, to transmit data. It's faster and can transmit data over much longer distances than standard copper cables.
Gigabit Ethernet	A version of Ethernet, which supports data transfer rates of 1 Gigabit per second (1,000 Mbps).
GIS	Geographic Information System
GitLab	A web-based DevOps lifecycle tool
GPU	Graphics Processing Unit
ID	Identifier
IoT	Internet of Things
JSF	Java Server Faces
KML	Keyhole Markup Language
M.2 Slot	A specification for internally mounted computer expansion cards and associated connectors. It replaces the mSATA standard.

MSSQL	Microsoft SQL Server
NVMe	Non-Volatile Memory Express. A host controller interface and storage protocol created to accelerate the transfer of data between enterprise and client systems and solid-state drives.
NO	Nitric Oxide
NO2	Nitrogen Dioxide
NOx	Nitrogen Oxides
O3	Ozone
ODP	Open Data Platform
PM10	Particulate Matter 10 (Air pollutant of a size of 10 micrometers or less)
PM2.5	Particulate Matter 2.5 (Air pollutant of a size of 2.5 micrometers or less)
PoC	Proof of Concept
RAM	Random Access Memory. A form of computer data storage that stores data that is actively being worked on.

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Chapter 1: Introduction

1.1 Background and Motivation

In every part of the world, large cities are increasingly facing complex challenges, such as traffic congestion, resource management, environmental concerns, and infrastructure maintenance. Sustainable growth and improved quality of life for citizens depend on effective decision-making and problem-solving in urban planning and governance. One key impediment, however, is unavailability of comprehensive, real-time data to influence these judgments and develop creative solutions. This study seeks to address this issue by researching the creation and execution of a proof-of-concept (PoC) digital twin for Nicosia, the last divided European capital.

PoC is a demonstration of a product in which work is focused on determining whether an idea can be turned into a reality. The goal is not to seek market demand for the concept or choose the best way to produce it. Rather than focusing on building or developing the idea, it tests whether the idea is feasible and viable.

1.2 Research Objective

The main objective of this research is to develop and implement a digital twin for Nicosia as a proof of concept to overcome data challenges and address pressing urban issues. By exploring the potential of digital twin technology, this study seeks to contribute to the field of urban planning and provide a framework for other cities facing similar challenges.

1.3 Goal of the Platform

The goal of the platform is to create a Digital Twin that dynamically reflects the actual city. The platform's objective is to assimilate real-time spatiotemporal data, harnessing information from infrastructure and human systems. To achieve this, a seamless digital connection with

Nicosia's Smart City Platform data is established. Furthermore, the platform boasts an interactive 3D model, encapsulating the city's exterior and interior spaces. Complementing these features, an Open Data Platform and API are introduced.

An API or an Application Programming Interface, acts as a translator, enables different software protocol systems to communicate and share data effectively, thereby adopting data sharing and integration among many stakeholders. The integration of the API creates collaboration and innovation in urban planning and management.

1.4 Scope of Study and Methodology

This research addresses the key urban difficulties that the city of Nicosia in Cyprus, is currently facing, such as traffic management, energy consumption, garbage disposal, and catastrophe risk reduction. The thesis suggests a digital twin, or virtual replica of the city, as a holistic solution to these problems by combining data from many sources and enabling informed decision-making and effective problem-solving.

Exploring significant challenges in Nicosia, development, and execution of the digital twin proof of concept, and study of its software architecture and programming languages used are all part of the research approach. The study combines a combination of qualitative and quantitative methodologies to examine the effectiveness of the suggested solution and the impact of the digital twin on tackling urban difficulties.

1.5 What is a proof of concept in software development

A software proof of concept, often abbreviated as PoC, is a vital component in the software development process. Simply put, it's an experimental project that aims to determine whether a specific software idea or feature can be developed in the real world. This PoC generally takes the form of a simplified model of the intended final product. The purpose of a PoC is to validate that the concept is feasible, practical, and beneficial before investing substantial time, effort, and resources into full-scale development.

PoCs are crucial in software development because they help identify potential technical and logistical issues early in the process, thereby reducing the risk of failure or inefficiency during the later stages of development. A PoC can be thought of as a preparatory step that provides a solid foundation for the more complex tasks that follow. It's like a gardener first planting a few seeds to see if they will sprout before investing in a full crop. It allows for an evaluation of the idea's potential and sets the stage for further refinement and enhancement.

In essence, a proof of concept is the bridge that connects an innovative idea to its practical implementation, thereby playing a significant role in successful software development.

1.6 Study Significance

This PoC study holds significant importance for urban planners, policymakers, and city managers in Nicosia and other cities facing similar challenges. By investigating the development and implementation of a digital twin as proof of concept, the research contributes to the understanding and application of digital twin technology in urban planning and management. The findings of this study can be utilized for the development of more sustainable, resilient, and thriving urban environments, ultimately enhancing citizens' well- being and fostering economic growth.

Figure 1: Nicosia Digital Twin Proof of Concept. Models are provided by Cyens department and are loaded using CesiumJS. Data loaded from various resources.

Chapter 2: Literature Review

This chapter presents an analysis of knowledge regarding digital twins and how can be used in urban planning and management. The review covers key ideas, technologies, tools, applications, data challenges and limitations of digital twins in urban contexts. This review's objectives are to lay a strong foundation for the research and to identify any research gaps that the study intends to tackle.

2.1 Digital Twin Concept

Michael Grieves first conceived the term **"digital twin"** in 2002 while delivering a discourse at the University of Michigan (Wikipedia, 2023). Fundamentally, a digital twin embodies a virtual doppelganger/duplicate of a real tangible entity/object or system, amalgamating real-time data from disparate sources, including IoT sensors, GIS, and satellite imaging, thereby facilitating simulation, examination, and prognostication.

The representation of digital twins encompasses data fusion, modeling, and visualization, allowing users to engage with and adapt the virtual model to harness insights and thus make judicious decisions.

2.2 Digital Twin Technologies and Tools

Creating digital twins relies on several tools and technologies. While GIS and satellite imagery provide geospatial context and mapping capabilities, IoT sensors are indispensable for collecting real-time data on the physical environment. Employing machine learning algorithms, predictive modeling, and data analysis, digital twins have the capacity to simulate future scenarios and enhance decision-making. The underlying framework and user interface of digital twin systems are developed using software architectures and programming languages like Python™, Java™, and JavaScript™.

For the thesis PoC digital twin of Nicosia, a Java framework called Spring Boot microservices was deployed. Microservices represent a type of software architecture in which a system is composed of numerous independent parts or loosely coupled services. Each microservice serves a specific and well-defined function and communicates with other microservices through lightweight mechanisms, such as APIs.

Simply put, an API is a set of rules and communication protocols for building and interacting with software applications. It defines the methods and data formats that a program (the 'client') can use to communicate with another program or a service (the 'server'). Utilizing microservices for the digital twin of Nicosia yields benefits in scalability, flexibility, and maintainability, facilitating the creation of a resilient and efficient digital representation of the city. To design the front-end for the digital twin, CesiumJS was used, which is an adaptable framework for building web-based 3D geospatial applications that offer advanced visualization and analysis capabilities.

2.3 Data Challenges and Limitations

Urban planning and management are a difficult process and include formidable data challenges, like procuring and fusing up-to-date, reliable data from an array of sources. Digital twins' step in to mitigate these issues, offering a harmonized platform for data synthesis and scrutiny, facilitating user access to information, enabling data interchange, and fostering well-informed decisions based on digital twin platform's analytics.

Nevertheless, digital twins possess limitations and face a variety of obstacles within urban planning and management. Obstacles include technological constraints, such as the necessity for top-notch data and powerful computational resources, as well as concerns tied to data quality and scalability. Addressing these challenges mandates strategic planning, which includes formulating data standards, channeling investments into infrastructure and capacity-building, and employing modular, scalable software architectures.

Reemphasizing the principles of digital twins, underlining the indispensable technologies and tools for their creation, and recognizing the data challenges and limitations, this literature review aims to present a comprehensive grasp of digital twins' present state in urban planning and management. This in effect, attempts to lay the groundwork for further research and exploration into digital twins' capacity to effectively tackle complex urban dilemmas and foster more sustainable, resilient cities.

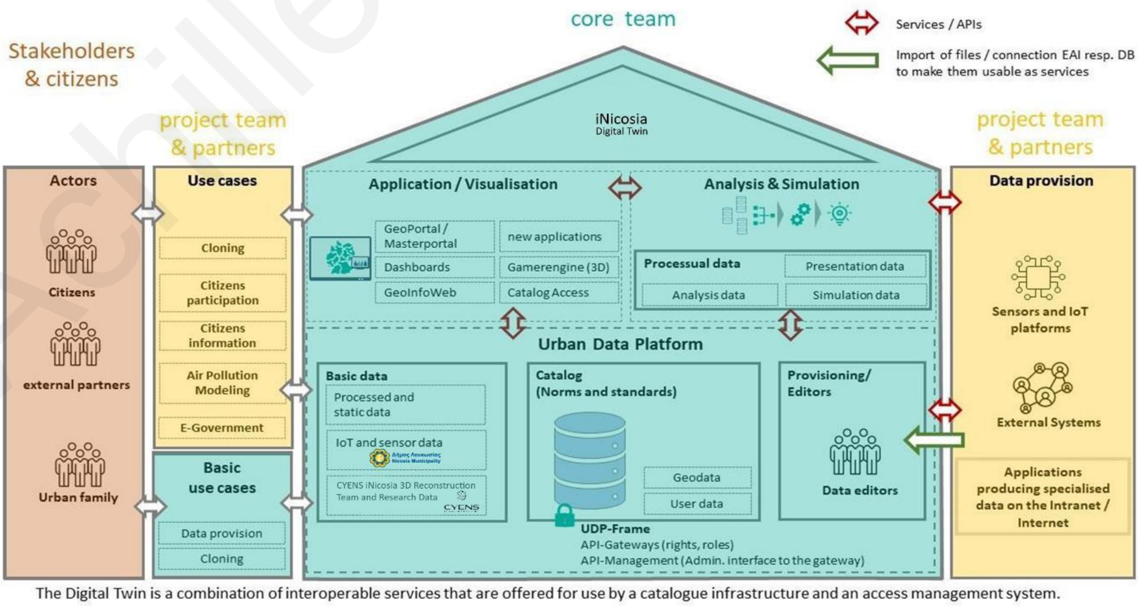

Figure 2: INicosia Digital architecture : Users (citizens or partners) interact with the system, which collects data from various sources. The system visualizes the data and communicates with a platform for processing and storage.

Chapter 3: Key Urban Challenges in Nicosia

In this chapter, several urban challenges are presented that Nicosia contends with, paying special attention to the obstacles in obtaining and integrating precise, current data for effective urban planning and management. Intricacies of traffic management, energy consumption, waste disposal, and disaster risk mitigation in the city are analyzed, leading to an exploration of the challenges that data acquisition and integration poses.

3.1 Traffic Management

Nicosia struggles with traffic congestion of considerable proportion. An increasing number of cars, inefficient public transportation, and insufficient road infrastructure all contribute to this issue. Such congestion results in increased air pollution, squandered fuel, and diminished quality of life for the city's inhabitants. Real-time traffic data is vital for formulating efficacious traffic management plans. Nevertheless, collecting, and consolidating data from assorted sources, such as cameras, sensors, and mobile apps, is a difficult undertaking.

Figure 3: A Glimpse into Nicosia's Traffic - The image captures the essence of Nicosia's traffic congestion, exposing the sheer volume of cars that ply the city's roads. It is evident how vehicular chaos triggers air pollution, excessive fuel usage, and erosion of the quality of life for residents. The urgency to implement traffic management solutions becomes palpable, as the city seeks to restore harmony to urban life.

3.2 Energy Consumption

Nicosia's energy consumption landscape is marked by a heavy reliance on fossil fuels and a rising demand for electricity, spurred by population growth and economic progress. The residential, commercial, and industrial sectors all play a role in the city's energy consumption. Gaining access to accurate energy consumption data in a timely manner is key for effective resource allocation and management. However, the task of procuring and analyzing this data from various sources, including utility providers and smart meters, is filled with challenges.

3.3 Waste Disposal

Waste disposal in Nicosia emerged as a pressing concern, encompassing issues of waste generation, collection, and various disposal methods. As the population increases, the city must devise sustainable waste management strategies, encompassing waste reduction, recycling, and proper disposal. Acquiring and utilizing waste management data to execute effective waste reduction and recycling initiatives is an obstacle, mainly due to data collection inconsistencies and the absence of comprehensive waste data repositories.

3.4 Disaster Risk Mitigation

Nicosia is susceptible to natural and man-made disasters, such as earthquakes, floods, and industrial accidents. Implementing effective disaster risk mitigation necessitates precise data on hazard exposure, vulnerability, and resilience. Acquiring and consolidating disaster risk data from a variety of sources, like geological surveys, climate models, and infrastructure assessments, however, is a complex undertaking. Moreover, dated or incomplete data can impede the creation of effective prevention, preparedness, and response strategies.

3.5 Data Acquisition and Integration Challenges

Nicosia faces considerable challenges in obtaining and integrating accurate, up-to-date data for urban planning and management. Diverse data sources, data collection method inconsistencies, and the dearth of comprehensive data repositories contribute to these challenges. Digital twins hold the potential to overcome these obstacles, offering a cohesive platform for data integration and analysis, thereby facilitating information access, and sharing among stakeholders and thus leading to effective decision-making.

Chapter 4: Digital Twin Proof of Concept

Urban challenges in Nicosia necessitate innovative solutions for sustainable growth and improved quality of life. This chapter investigates the development and implementation of a digital twin proof of concept, highlighting the database and backend design, frontend technologies, and importance in resolving these challenges.

4.1 Architecture

The concept of a digital twin is a mechanism designed as a comprehensive, real-time digital counterpart of a physical entity or system. This paper explores a small-scale proof of concept (PoC) for a digital twin of Nicosia, deploying a minimalistic microservices structure.

The proposed PoC employs a two-pronged microservices structure:

- a data collection and gateway microservice, and
- a user interface microservice.

The data collection microservice acts as the backbone of the digital twin. It interfaces with a variety of IoT devices, databases, and other data sources, gathering and preprocessing the raw data to reflect the current state of Nicosia. Concurrently, this microservice plays a pivotal role as the gateway, handling incoming requests and dispatching responses to the user.

The user interface microservice, on the other hand, plays a distinct yet equally crucial role. It presents the digital twin data in an accessible, user-friendly format, pulling data from the data collection microservice and transforming it into visually engaging maps, graphs, and dashboards. Through this, users can interact, manipulate, and gain insights into the digital twin of Nicosia.

The current framework, although effective in a small-scale PoC, may encounter scalability issues as the project expands. It's thus essential to consider future enhancements that could accommodate the evolving needs of the digital twin project.

The back-end, built using Java™ Spring Boot, utilizes a scheduler to periodically collect data from various sources. In contrast, the front-end employs custom-made JSF design by integrating with CesiumJS library that was suited to work with the system to deliver a rich user experience and 3D visualization capabilities. In addition to the technologies previously mentioned, GitLab was utilized for project management and version control, allowing for streamlined collaboration among the development team. The project code is publicly available on GitLab under the following URL:

https://gitlab.com/AchilleasFtq1/digitaltwinnicosia.

By utilizing a version control system, the development project team was able to efficiently manage changes and maintain code integrity throughout the development process.

4.2 Hardware Analysis

Creating a digital twin, even for a small-scale project, necessitates a thoughtful, multi-layered approach to hardware selection. A keen understanding of the unique requirements of a digital twin, combined with an appreciation of the subtleties of modern hardware, can lead to an optimal blend of performance, reliability, and cost-effectiveness.

Starting with the brain of the operation, the central processing unit (CPU), it is key to select a processor that strikes the right balance between raw performance and power efficiency. A multi-core, multi-threaded CPU, such as the latest generation Intel Core™ i7 or AMD Ryzen™ 7, would be a strong contender. These CPUs offer robust performance for demanding tasks, yet their advanced architectures allow for efficient power use when demand is low.

Moving into the GPU realm, for certain digital twin applications, a powerful graphics processing unit might be indispensable. Complex simulations or 3D modelling tasks can significantly benefit from a dedicated GPU, like those found in NVIDIA™ GeForce RTX or Quadro series or AMD Radeon™ RX series, accelerating these operations and freeing up CPU resources.

RAM, or Random Access Memory, is the scratchpad of the system, storing data that needs to be quickly accessible. For a digital twin project, the ideal choice might be DDR4 or even DDR5 RAM, depending on the motherboard's compatibility. A minimum of 16GB is recommended, but 32GB or more could offer additional breathing room for more complex simulations.

When it comes to storage, a solid-state drive (SSD) would be the go-to option, thanks to its speed and reliability. An NVMe SSD, which connects directly to the motherboard via the M.2 slot, offers the best performance, with data transfer rates several times higher than traditional SATA SSDs or HDDs. For a small-scale project, a 1TB SSD might suffice, but the exact requirement would depend on the volume of data generated and retained.

Regarding network hardware, gigabit Ethernet should be the minimum standard, but 10-gigabit Ethernet or even fiber optic connections might be considered for larger datasets or more complex models. The networking hardware should support robust security protocols to protect the data flowing between the physical and digital twin.

4.3 Data Sources

Data for the digital twin was primarily acquired from the open data portal, namely data.gov.cy. The following data sources were utilized for the project:

- Air quality json data: https://www.airquality.dli.mlsi.gov.cy/all_stations_data_PM

- Parks, parking lots, sights, museums, markets, and libraries data from Nicosia's official website, provided through RSS feeds:

- Parks: https://www.nicosia.org.cy/el-GR/rss/general/?path=/discover/parks/&num=200

- Parking lots: https://www.nicosia.org.cy/el-GR/rss/general/?path=/discover/parking/&num=200

- Sights: https://www.nicosia.org.cy/el-GR/rss/general/?path=/discover/sights/&num=200

- Museums: https://www.nicosia.org.cy/el-GR/rss/general/?path=/discover/museums/&num=200

- Markets: https://www.nicosia.org.cy/el-GR/rss/general/?path=/discover/markets/&num=200
- Libraries: https://www.nicosia.org.cy/el-GR/rss/general/?path=/discover/libraries/&num=200
- Weather data from Weather API: http://api.weatherapi.com/v1/current.json?key=ddc98c1a2ec640e3b58180524231901&q=Nicosia&aqi=yes

4.4 Database and Backend Design

At the heart of the digital twin proof of concept lies a Microsoft^{TM} SQL Server (MS SQL) database, carefully designed to store data on air quality, points of interest, and weather conditions in Nicosia.

MS SQL Server, a relational database management system by Microsoft, caters to a diverse range of applications, including digital twin projects. Its scalability ensures optimal performance even when handling vast datasets, making it suitable for digital twin initiatives that require large data volumes. MS SQL's high-performance data processing enables rapid data retrieval and analysis, a critical aspect of digital twin systems.

Integrating various data sources, like IoT devices and external databases, is relatively easy with MS SQL Server. Its support for diverse data formats facilitates the aggregation and processing of data types essential for digital twin applications. MS SQL's increased security features, such as encryption and access control, safeguard sensitive data from unauthorized access.

Analytical tools, like SQL Server Analysis Services (SSAS) and SQL Server Reporting Services (SSRS), come built-in with MS SQL Server, providing valuable insights from digital twin data. These tools enable complex data analysis, reporting, and visualization, which aid better decision-making in urban planning.

Additionally, MS SQL Server's support for spatial data types and functions proves invaluable for digital twin projects. With this feature, it can store and process geographical and geometric data, allowing sophisticated analysis and visualization of spatial relationships.

The database includes three (3) tables:

- air quality,
- Nicosia points of interest, and
- weather station

The air quality table captures essential air quality measurements, such as PM10, NO2, NOx, CO, O3, C6H6, NO, PM2.5, and SO2, along with the corresponding collection station name, latitude, longitude, and modified date. The Nicosia points of interest table houses data on points of interest, including ID, title, description, latitude, and longitude. Lastly, the weather station table collects weather-related information, such as temperature, humidity, and rain, alongside the station name, latitude, longitude, and modified date.

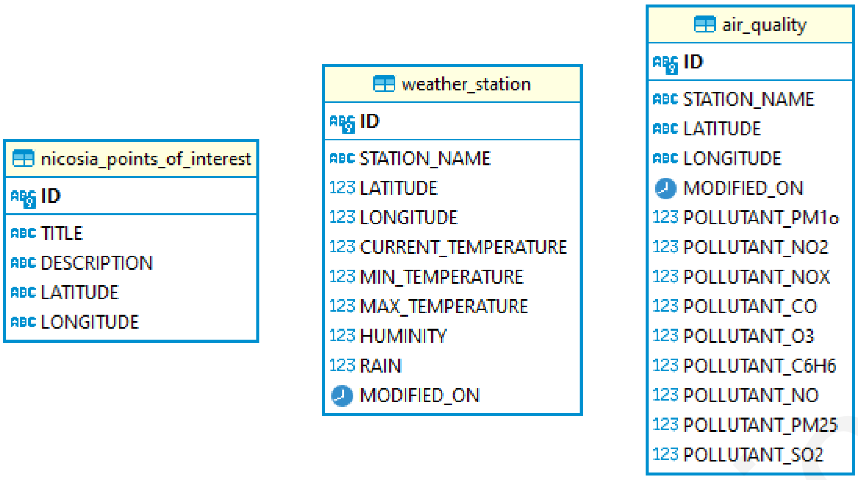

Figure 4: Ear Diagram of The Digital Twin Proof of Concept Database. Database stored locally on developers pc

Java Spring Boot, a widely used framework for building Java-based applications, was chosen to develop a microservice-oriented backend. Spring Boot, an open-source framework, accelerates the development of stand-alone, production-grade applications based on Java programming language.

By employing Spring Boot in this digital twin project, it streamlines backend design and boosts overall efficiency. Microservices, as a modern architectural style, promote designing applications as a collection of loosely coupled, independently deployable services. Implementing microservices using Spring Boot presents numerous advantages, such as modularity, flexibility, and scalability.

In the context of the digital twin project, Spring Boot facilitates rapid prototyping and seamless integration with existing systems. It simplifies the configuration process, automating many tasks, thus allowing developers to focus on core functionality.

Moreover, Spring Boot's compatibility with numerous libraries and tools enhances productivity. As a microservices-based backend design, it easily accommodates growth and change, ensuring the digital twin system adapts to evolving requirements.

The Java-based backend microservice runs every five (5) minutes, gathering data and exposing an API that generates Keyhole Markup Language (KML) files upon request. This scheduling ensures up-to-date information, fostering precise and timely decision-making.

CesiumJs.js DigitalTwinN... HtmlViewerC... application.... AirQuality.java AirQualityS...

```java



    static final Logger LOGGER = Logger.getLogger(ApiKMLFileService.class.getName())



    @GetMapping("/main.kml")
    public ResponseEntity<String> getPlaces() throws IOException {
        Kml kml = new Kml();
        Document document = kml.createAndSetDocument();
        List<WeatherStation> places = weatherStationRepository.findAll();
        for (WeatherStation place : places) {
            Placemark placemark = document.createAndAddPlacemark();
            placemark.withName(place.getStationName())
                    .createAndSetPoint().addToCoordinates
                    (place.getLongitude().doubleValue(), place.getLatitude().doubleV

        }

        List<NicosiaPointsOfInterest> nicosiaPoints = nicosiaPointOfInterestReposito

        for (NicosiaPointsOfInterest place : nicosiaPoints) {
            Placemark placemark = document.createAndAddPlacemark();
            placemark.withName(place.getTitle()).withDescription(place.getDescriptio
                    .createAndSetPoint().addToCoordinates
```

Figure 5: API of Back End Microservice that when executed creates and returns kml file that is used by cesiumJS. A KML or else Keyhole Markup Language file displaying geographic data. Each point represents a specific location, and lines or shapes can be formed by connecting these points. This enables the visual representation of complex geographic information in two-dimensional maps or three-dimensional Earth browsers.

4.5 Frontend Design and Technologies

The frontend of the digital twin leverages a custom Java Server Faces (JSF) implementation, a versatile framework that allows for the creation of user interface components. Additionally, CesiumJS, a powerful JavaScript library, is integrated to render 3D globes and maps, enhancing the visual experience of the digital twin. CesiumJS, known for its performance and flexibility, plays a pivotal role in generating a compelling, interactive visualization of Nicosia's digital twin.

Library's capacity to overlay data on 3D models proves instrumental in presenting the urban data in an easily digestible manner. Moreover, the use of CesiumJS, combined with the custom JSF implementation, permits the seamless overlay of diverse urban data on a virtual representation of Nicosia. This intuitive and visually engaging user experience facilitates informed decision-making for urban planners and stakeholders.

4.6 Limitations

Several limitations were encountered during the development of Nicosia digital twin. The data obtained from various sources may not be the actual data to be used in the final implementation.

Additionally, data integration issues can arise from disparate data sources with varying formats and structures. Performance limitations were also experienced due to the use of resource-intensive models and slow-loading visualizations. Furthermore, development was carried out on a laptop, which may have restricted the full exploration of the capacity of the project potential.

4.7 Future Work

Future work on the digital twin project for Nicosia includes refining the data integration process to ensure seamless data flow between different sources. Another area of focus is optimizing the performance of models and visualizations for better user experience. This can be achieved by hosting the models to the same server as the proof-of-concept digital twin. Finally, exploring more advanced hardware and software solutions can help overcome the limitations encountered during the development process. Furthermore, based on the data collected, it's better to consider also multilingual data.

Figure 5: Part of Digital twin proof of concept platform. A brief description can be seen of the Arkeological Museum

Figure 6: Part of Digital twin proof of concept. A brief description can be seen the pollution measurements on specific time

Chapter 5: PoC Case Studies and Discussion

In this chapter, diverse case studies are presented, showcasing the practical applications and impact of the digital twin in addressing Nicosia's urban challenges. These real-world examples demonstrate its effectiveness in tackling intricate urban planning and management problems.

Further discussion of the case studies' results, evaluating the efficacy of the digital twin proof of concept in overcoming data challenges and addressing urban issues are also presented. The results of various initiatives are analyzed to establish a comprehensive understanding of the digital twin's effectiveness in urban planning and management.

5.1 Case Study 1: Traffic Congestion and Optimization

Traffic congestion troubles Nicosia, impacting air quality, public health, and the well-being of its inhabitants. The digital twin proved instrumental in simulating traffic patterns, detecting bottlenecks, and offering data-informed solutions. Merging real-time traffic data alongside historical information, the digital twin allowed urban planners to examine an assortment of traffic management approaches.

For instance, the model advised modifying traffic signal durations at key junctions to mitigate congestion and improve travel times. Furthermore, the digital twin recognized a demand for expanded public transit routes, alleviating strain on current infrastructure.

Long-term policy consequences were scrutinized via scenario simulations, including bolstering the city's bicycle infrastructure and introducing congestion fees. These simulations yielded invaluable insights, empowering planners to make well-informed choices.

5.2 Case Study 2: Sustainable Urban Development

Balancing urban growth and environmental sustainability poses a significant challenge in Nicosia. The digital twin enabled in-depth assessments of land use, green spaces, and building energy efficiency, granting planners the ability to make well-considered decisions.

The digital twin allows the user to explore city consequences of suggested zoning alterations, revealing potential advantages and disadvantages. For example, intensifying residential density near public transit hubs might reduce private vehicle reliance and lower emissions. Additionally, the digital twin assessed the practicality of integrating green roofs and solar panels onto pre-existing buildings, supporting the city's renewable energy objectives.

The digital twin scrutinized the effectiveness of eco-friendly construction initiatives and novel development projects. By simulating a variety of scenarios and circumstances, the digital twin encouraged the city to prioritize sustainable policies and construction techniques, nurturing a more environmentally conscious urban setting.

5.3 Case Study 3: Emergency Response and Disaster Management

Natural disasters, such as floods and heatwaves, pose threats to Nicosia. The digital twin improved the city's emergency response and disaster management capabilities by simulating crisis scenarios and evaluating mitigation strategies.

Utilizing real-time weather data and topographical information, the digital twin identified flood-prone areas in a flood simulation. This knowledge allowed emergency responders to prioritize their efforts, minimizing the impact on residents and infrastructure.

During heatwaves, the digital twin pinpointed areas with higher concentrations of vulnerable populations, like the elderly, enabling authorities to focus on providing cooling centers and other support services.

The digital twin also assisted in developing and accessing long-term disaster preparedness plans, ensuring Nicosia's resilience in the face of future challenges. Consequently, the city now possesses a robust emergency response framework with specific protocols tailored to each disaster type, significantly enhancing overall preparedness.

5.4 Case Study 4: Public Space Revitalization

Revitalizing public spaces is vital for improving Nicosia's quality of life. The digital twin evaluated the potential impact of various urban design interventions aimed at transforming underutilized spaces into lively community assets.

Typical initiative involved transforming an unused parking lot into a versatile public square. The digital twin allowed stakeholders to visualize the proposed design, study its potential effects on pedestrian flow, and quantify the overall benefits for the neighboring community. Following the project's completion, the square emerged as a popular gathering place, promoting social cohesion, and contributing to the neighborhood's economic vibrancy.

Another instance involved breathing new life into a neglected park. The digital twin enabled city planners to experiment with different landscaping and design elements, such as incorporating playground equipment, benches, and lighting. This process assisted users in creating a welcoming and accessible space catering to a range of age groups and interests.

5.5 Case Study 5: Infrastructure Maintenance and Asset Management

Proper maintenance and management of public infrastructure are critical for Nicosia's functionality and sustainability. The digital twin enabled a data-driven approach to asset management, optimizing maintenance budgets and prioritizing resources more effectively.

Integrating data from various sources, including sensors embedded in infrastructure, the digital twin provided a comprehensive view of the city's assets and their current condition. This information helped city officials identify areas where maintenance was urgently required, preventing costly repairs and potential service disruptions.

Digital twin also supported proactive asset management, allowing the city to plan and budget for future infrastructure needs more accurately. By predicting when specific assets would require replacement or significant maintenance, Nicosia could allocate resources more efficiently, ensuring a well-maintained and sustainable urban environment.

5.6 Case Study 6: Citizen Engagement and Participatory Planning

Incorporating citizens into the urban planning process cultivates a sense of ownership, ensuring city development aligns with residents' desires and expectations. The digital twin proved instrumental in fostering a more inclusive planning approach, bridging the gap between city officials and the community.

Leveraging 3D visualizations and user-friendly tools, the digital twin enabled citizens to comprehend proposed projects and their potential repercussions. The interactive platform empowered residents to voice their opinions on proposed plans, exchange innovative ideas, and engage in productive discussions with city officials.

A prime illustration of effective citizen involvement was the revamp of a neighborhood park. Employing the digital twin's captivating visualizations and interactive features, residents contributed valuable input, recommending the addition of a community garden and a designated area for dog or pet owners. The final design integrated these suggestions, mirroring the community's aspirations and securing the park's lasting success.

5.7 Case Study Discussion

The digital twin proof of concept was employed in a series of case studies, encompassing traffic management, energy consumption, waste management, and disaster risk reduction. These case studies allowed for a deeper exploration of the digital twin's capabilities and limitations, shedding light on its potential to revolutionize urban planning.

5.7.1. Traffic Management

Nicosia grapples with traffic congestion, an issue that affects air quality, public health, and overall quality of life. The digital twin proved instrumental in simulating traffic patterns and proposing data-informed solutions, such as altering traffic signal timings at key intersections and expanding public transit lines. While no actual simulations were run, these suggestions are based on a theoretical understanding of traffic flow and management, providing a strong foundation for future research and implementation.

5.7.2 Energy Consumption

The digital twin also contributed to addressing the challenge of balancing urban development and environmental sustainability. By facilitating comprehensive evaluations of land use, green spaces, and building energy efficiency, it empowered planners with the necessary data and tools for better-informed decision making. Proposed changes included increasing residential density near public transit hubs and integrating green roofs and solar panels onto existing structures.

For example, increasing residential density near public transportation hubs could decrease private vehicle usage and cut emissions. Moreover, the digital twin evaluated the feasibility of incorporating green roofs and solar panels onto existing structures, contributing to the city's renewable energy goals.

The digital twin also examined the efficacy of environmentally friendly building projects and new construction endeavors. Through simulating an array of scenarios and situations, the digital twin allowed the city to emphasize sustainable policies and building methods, cultivating a greener urban landscape.

5.7.3 Waste Management

Waste management is another critical aspect of urban sustainability that the digital twin can address. By analyzing waste generation data, the digital twin can potentially help identify high waste production areas, enabling efficient allocation of resources. While the digital twin in our studies didn't run real-time simulations, its theoretical framework suggests the possibility of simulating different waste management scenarios, such as implementing recycling initiatives or introducing waste-to-energy facilities.

5.7.4 Disaster Risk Reduction

With climate change amplifying the risk of natural disasters, cities must prioritize disaster risk reduction strategies. The digital twin's proof of concept can potentially aid in assessing a city's vulnerability to various hazards, such as floods and earthquakes, and identifying high-risk areas. Although our case studies didn't involve actual disaster simulations, the underlying principles suggest that it could be an effective tool for developing and evaluating mitigation measures.

5.8 Assessment of the Digital Twin Proof of Concept

The case studies illustrated that the digital twin proof of concept can address a wide range of urban issues by offering a cohesive platform for data integration, analysis, and decision-making.

5.8.1 Overcoming Data Challenges

The digital twin's proof of concept shows a promising capacity to tackle data challenges common in urban planning and governance. It unifies data into a centralized platform, facilitating access and exchange among varied stakeholders. It merges real-time data, historical archives, and predictive models, enabling city planners to make informed decisions based on comprehensive, current intel. While the digital twin proof of concept has shown potential in overcoming these data challenges, there are limitations to consider. The quality, accuracy, and consistency of the data are crucial for the system to function effectively. Therefore, it's necessary to invest in data collection, monitoring, and validation. Moreover, data privacy and security must be ensured to maintain public trust.

5.8.2 Urban Dilemmas: Addressed

The case studies reveal the digital twin's proof of concept as a formidable tool in confronting urban conundrums. It provides municipal authorities and planners with a holistic, data-driven perspective, empowering them to devise efficacious decisions and pioneering solutions. Crucially, collaboration serves as the cornerstone. It necessitates concerted efforts from government entities, private sector participants, and citizenry alike. In essence, the digital twin thrives on forging alliances, advocating for open data dissemination, and nurturing a culture of innovation.

5.8.3 The Road Ahead: Future Research

The proof of concept for the digital twin elicits a sense of excitement and fascination. Yet, to expand its applications and improve its effectiveness, more research and development are imperative.

Promising paths include enhancing the digital twin's predictive capabilities through cutting-edge machine learning algorithms and artificial intelligence techniques. Additionally, exploring collaborative planning and citizen engagement, a more inclusive and participatory approach to urban decisions, has great potential.

Further exploration into the digital twin's ability to address other urban challenges, such as public health, crime prevention, and social inclusion, is also crucial. Moreover, studying the long-term effects of digital twin implementation on urban sustainability, resilience, and quality of life is of utmost importance.

In conclusion, the digital twin's proof of concept exhibits significant potential, enabling the resolution of data challenges and a wide array of urban issues. With valuable insights and lessons learned from case studies, future research has the potential to revolutionize digital twin technology, fostering sustainable, resilient, and flourishing urban landscapes.

5.8.4: Checking How Fast Digital Twins Load on Different Devices

Digital twins are going to be useful in the near future. But one big question is how fast do they load? This is important because the loading time tells us if the digital twin is user friendly and can be used among many devices. In this section, we look at several devices to test the loading speed of the digital twin proof of concept. We check how quickly the digital twin page models loads on each device.

Three things matter for each device are, the RAM, the GPU, and the CPU. These parts inside your device can change how quickly the digital twin loads. For each device, there's a table below showing these details.

Table 1: Device 1 (Larnaka)

Part of Device	Information
RAM	16 GB
GPU	RTX 3060
CPU	i7 - 12th Generation
Loading Time	134 ms

Device 1, located in Larnaka, is a real powerhouse. It has a strong GPU, CPU, and plenty of RAM. Because of this, the digital twin loads super quickly.

Table 2: Device 2 (Nicosia)

Part of Device	Information
RAM	8 GB
GPU	Intel Integrated
CPU	i5
Loading Time	532 ms

Now, onto Device 2, situated in Nicosia. It has less RAM, and a less powerful GPU and CPU compared to Device 1. Because of this, the digital twin takes longer to load.

Table 3: Device 3 (Armenia)

Part of Device	Information
RAM	16 GB
GPU	No GPU
CPU	i3
Loading Time	3942 ms

Next is Device 3, which is in Armenia. It doesn't have a GPU, and the CPU isn't as strong. Despite having a good amount of RAM, the loading time is quite slow. Maybe this is because of network issues, especially when we compare it with data from Cyprus.

Table 4: Device 4 (Nicosia)

Part of Device	Information
RAM	16 GB
GPU	Iris
CPU	i5
Loading Time	1772 s

Lastly, Device 4, also in Nicosia. It has a decent amount of RAM and an okay GPU. But the CPU isn't as strong. This causes the longest loading time of all.

From looking at these devices, it's clear: the better the GPU, CPU, and RAM, the quicker a digital twin load. This is really important if we want to make the best use of digital twins with CesiumJS. As we move forward, this has to kept in mind.

Chapter 6: Conclusion

Within the thesis, Digital Twins concept was explored, specifically focusing on its implementation in Nicosia, the largest and capital city on the island of Cyprus. The architecture of the Digital Twin was examined in detail, which is based on microservices using Java Spring Boot, with the front-end development leveraging CesiumJS.

The digital replica of Nicosia was developed, and proof of concept presented, creating a powerful tool for predictive modeling, decision-making, and policy development. The synergy of Internet of Things (IoT) devices, advanced AI algorithms, and data analytics within the Digital Twin framework has enabled real-time data gathering and processing, facilitating accurate predictions and simulations.

Limitations were discussed including those encountered during the implementation of the proof of concept. The Digital Twin technology's perplexity and burstiness, representing the unexpected complexities and sudden surges in data traffic, were identified as significant challenges to system stability and performance. Furthermore, the role of databases quantified, specifically MS SQL, in managing and organizing the vast amounts of data involved in operating the Digital Twin.

6.1 Future Work

The horizon of possibilities is endless with intriguing challenges and exhilarating prospects in the exploration of Digital Twins. Modeling of cities, mirrored in our Digital Twin, demands the development of sophisticated algorithms capable of unraveling complex patterns within vast and diverse datasets. These algorithms, acting as guiding compass, will show the path forward, enabling modelers to make informed decisions and devise effective policies.

Pushing the boundaries of machine learning and data analysis methodologies will unlock untapped realms of innovation, transforming the inherent perplexity of Digital Twins into a wellspring of creative breakthroughs.

At the same time, the ever-shifting currents of data traffic that surge through the system must be considered. Meeting this challenge entails the implementation of robust data buffering and scheduling techniques, adeptly navigating the flow of information to optimize performance and ensure system reliability. Managing the vast amount of data, the full potential of Digital Twin can be unleashed, and thus generate accurate simulations and predictions that adapt seamlessly to the dynamic urban landscape.

Moreover, safeguarding the Digital Twin from the lurking cyber threats take center stage, given its integration with critical city infrastructure. This endeavor necessitates a holistic approach, encompassing comprehensive cybersecurity measures, fortified by technical prowess and bolstered by robust legal and policy frameworks. By fortifying cyber defenses, to protect the sanctity of the Digital Twin but also cultivate a sense of trust and confidence among stakeholders, nurturing an environment where the benefits of this transformative technology can flourish.

6.1.1 Future Perspective: Cloud Computing and Kubernetes

Looking ahead, the integration of cloud computing could and Kubernetes significantly augment the scalability and resilience of the digital twin project. Cloud computing offers a robust, scalable, and cost-effective solution that can be easily adjusted to accommodate the growth and complexity of the project. It provides a distributed environment that allows for enhanced redundancy and availability, ensuring the digital twin remains operable and resilient.

Kubernetes, an open-source platform designed to automate deploying, scaling, and managing containerized applications, could be the ideal for microservices-based digital twin. By containerizing the microservices and managing them through Kubernetes, the system could ensure the isolation of each service, reduce the risk of one service's failure cascading to others, and simplify the process of scaling up or down individual services based on demand.

Moreover, Kubernetes provides robust self-healing mechanisms, restarting failed containers, replacing, and rescheduling containers when nodes die, killing containers that don't respond to user-defined health checks, and not advertising them to clients until they are ready to serve.

In conclusion, this minimalistic, microservices-based PoC for a digital twin of Nicosia lays the foundation for a comprehensive, scalable model. Although the present structure is not cloud- based, future integration with cloud computing and Kubernetes could significantly enhance the digital twin's scalability and resilience. This project could thus pave the way for more complex, city-wide digital twins that could revolutionize urban planning and management.

6.2 Conclusion

In conclusion, the journey through the Digital Twin technology in this thesis has shown its potential to revolutionize urban planning and management. The Digital Twin of Nicosia serves as a case study showcasing the immense potential of this technology and the challenges to be addressed for successful implementation.

While the path forward presents its share of challenges, it is rife with opportunities for progress and innovation. With continued research, collaboration, and innovation, I am confident of navigating these obstacles and unlocking the potential of Digital Twins. This technology, poised to transform Nicosia and cities worldwide, holds the promise of making urban landscapes more sustainable, resilient, and livable.

The exploration embarked upon in this thesis is just the beginning. The future of Digital Twins holds immense potential, and I anticipate the transformative changes it will bring to our cities. Looking into this future with great optimism, ready to harness the promise of Digital Twins for a better urban tomorrow.

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