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Bachelor thesis

Building a Scalable Parking Management Solution for Multi-Community Deployment

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ABSTRACT

this is an abstract

Keywords: keyword1, keyword2, keyword3

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Thanks

AGRADECIMIENTOS

Gracias

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LIST OF ACROYNMS

AI	Artificial Intelligence.
AWS	Amazon Web Service.
CAGR	Compound Annual Growth Rate.
GDPR	General Data Protection Regulation.
IaaS	Infrastructure as a Service.
INCOSE	International Council on Systems Engineering.
IoT	Internet of Things.
KPI	Key Performance Indicators.
LPR	Licence Plate Recognition.
ML	Machine Learning.
NIS	Network and Information Systems.
PaaS	Platform as a Service.
PMS	Parking Management System.
PoE	Power over Ethernet.
RPO	Recovery Point Objectives.
RTO	Recovery Time Objectives.
SaaS	Software as a Service.

1. MOTIVATION

The rapid growth of urban populations and the corresponding increase in vehicle ownership have significantly intensified the challenges associated with parking management in cities worldwide. For instance, the dramatic rise in car usage in Madrid has substantially contributed to heightened levels of environmental pollution [1]. Despite the number of parking spaces in Spain remaining stable between 2014 and 2020 [2], the escalating demand for parking has resulted in higher costs, prolonged search times, increased traffic congestion, and elevated urban pollution levels.

The inadequacies of traditional, manual Parking Management Systems (PMSs) have further highlighted the need for innovative solutions in this domain. Studies highlight the importance of user-friendly, secure, and reliable systems, with these factors playing a crucial role in influencing parking behavior and preferences. This growing demand for smart parking solutions is reflected in the global market projections, which show remarkable growth from \$7.11 billion (US) in 2023 to an expected \$18.13 billion (US) by 2028, with a Compound Annual Growth Rate (CAGR) of 20.2% [3], see Figure 1.1.

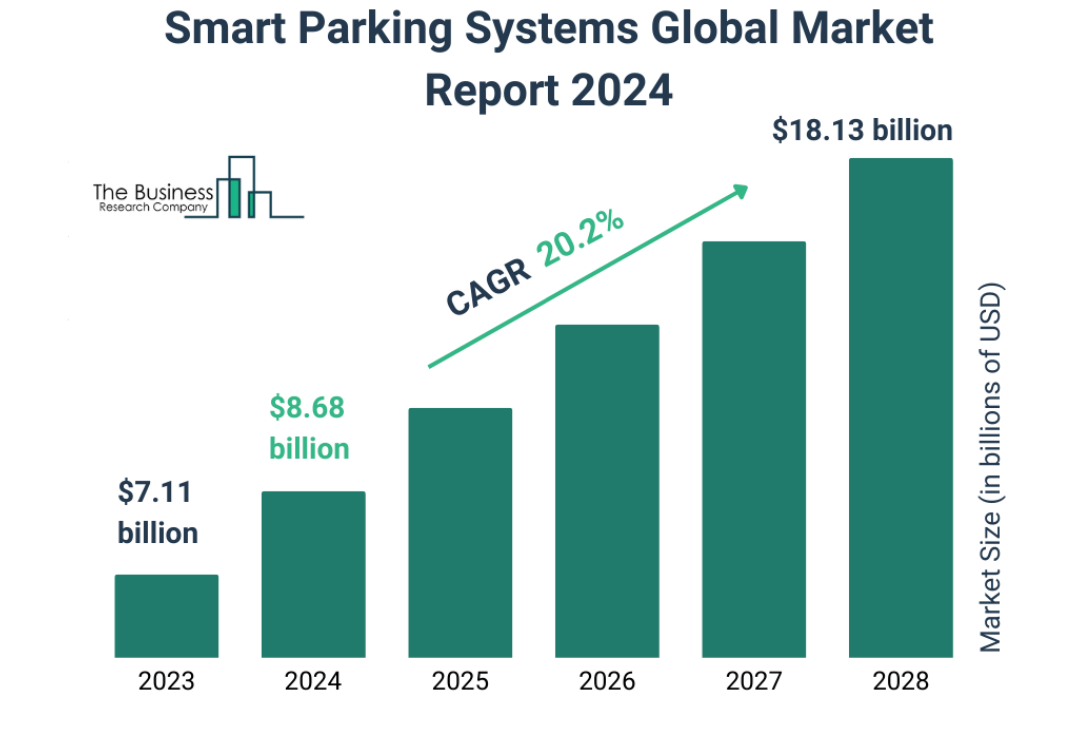


Figure 1.1. *Smart Parking System Market Report 2024* [3]

Advancements in technology provide new opportunities to address these challenges. The proliferation of internet-connected devices, growing by 20% annually [4], has catalyzed the emergence of Internet of Things (IoT)-based Parking Management Systems (PMSs). These systems aim to mitigate traffic congestion and reduce urban pollution while promoting sustainable and efficient urban mobility. By leveraging real-time data and automation, modern PMSs offer transformative potential for urban planning and management.

Integrating these advanced systems into urban environments offers multiple benefits, including decreased traffic congestion, reduced pollution, enhanced security, and an improved quality of life for residents. Additionally, PMSs enable automated parking space management, making them adaptable for a wide range of applications, including urban centers, residential communities, and commercial buildings.

Despite these advancements, the widespread adoption of PMSs in Spain has faced significant obstacles. Many existing systems rely heavily on human intervention, leading to delays, insufficient information dissemination, and limited control over parking space availability. This dependence on manual operations not only impairs system efficiency but also increases operational costs.

Emerging technologies have inspired the development of innovative PMSs, such as RFID-based systems [5], IoT-enabled solutions [6], and intelligent parking systems employing image processing techniques [7]. However, these systems frequently rely on centralized architectures, which are prone to scalability and reliability issues, particularly during service disruptions. Moreover, many current solutions lack the flexibility needed to accommodate the specific requirements of diverse user groups, limiting their broader applicability.

Addressing these limitations, the primary objective of this project is to design and implement a fully distributed and autonomous PMS that overcomes the challenges inherent in existing systems. This new approach emphasizes scalability, reliability, and adaptability, with a particular focus on meeting the demands of next-generation smart cities. Through this work, the project aims to contribute to the development of sustainable, efficient, and user-centric parking solutions for urban environments.

2. STATEMENT OF THE PROBLEM

The lack of efficient PMSs is a pervasive problem in modern cities, exacerbated by the growing number of vehicles and the resulting increase in urban population. Traditional manual PMSs have proven inadequate in addressing the complexities of modern urban parking, leading to higher costs, longer search times, traffic congestion, and elevated levels of urban pollution. The ongoing development of PMSs remains a crucial research area, as citizens favor systems that prioritize user-friendliness, security, and reliability [8] [9] [10] [11].

This project aims to address the gap by designing and implementing a fully distributed PMS tailored for the next generation of smart cities. The proposed system will focus on addressing the inefficiencies and challenges inherent in current PMSs through a distributed approach that leverages modern technologies.

Given the broad nature of this problem, the scope of this project will be narrowed to a specific environment and use case, as outlined below:

- **Environment:** The system will be designed for urban environments with high vehicle density and limited parking spaces. The case study will focus on a city center with a high volume of vehicles and limited parking availability, reflecting the challenges faced by many modern cities.
- **Atmospheric Conditions:** The system will be designed to operate under typical urban atmospheric conditions, with no specific constraints on temperature, pressure, or humidity. The system will be designed to function in a variety of weather conditions, including rain, heat, and cold.
- **Operational Parameters:** The system will be designed to manage parking spaces in a city center, with a focus on optimizing space utilization, reducing search times, and minimizing traffic congestion. The system will be scalable to accommodate a large number of parking spaces and users.
- **Hardware:** The system will be designed to leverage modern technologies such as IoT devices, sensors, and cloud computing to provide real-time monitoring and management of parking spaces. The system will be designed to be cost-effective, scalable, and user-friendly.

3. OBJECTIVES

The primary goal of this bachelor thesis is to design and implement a distributed parking management system to address the evolving needs of smart cities. The project aims to overcome the limitations of existing parking management solutions by utilizing scalable and IoT technologies. By doing so, it seeks to enhance performance, security, and user experience, contributing to the development of smart city solutions. The specific objectives of the project are outlined below:

- **Analyze Existing Systems:** Review current parking management systems, identifying inefficiencies and challenges. This includes assessing the limitations of centralized systems and understanding the needs of users (drivers and facility managers) to uncover areas for improvement using a distributed approach.
- **Evaluate Relevant Technologies:** Examine key technologies used in parking management systems, focusing on their suitability for a distributed architecture. This involves evaluating IoT devices, sensors, communication protocols, and data storage methods to determine the most scalable and secure technologies for the proposed system.
- **Design the System Architecture:** Develop the overall design of the distributed parking management system. This includes selecting IoT sensors, determining data storage solutions, and ensuring that the system can handle high data loads while integrating seamlessly with other smart city systems.
- **System Development:** Implement the system using an agile approach, following best practices in software engineering. This includes iterative planning, design, coding, testing, deployment, and maintenance, with an emphasis on modularity and extensibility to accommodate future updates and integration with emerging technologies (e.g., autonomous vehicles, AI-based traffic management).
- **Evaluate System Performance:** Assess the implemented system's performance based on Key Performance Indicatorss (KPIs) such as scalability, reliability, data accuracy, and real-time processing capabilities to ensure the system meets its design objectives.
- **Real-World Testing and Validation:** Deploy the system in a real-world urban environment with limited parking capacity. The goal is to validate the system's effectiveness in managing parking allocation, optimizing resource use, and reducing congestion while testing its robustness, scalability, and performance under actual conditions.

4. DOCUMENT STRUCTURE

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5. METHODOLOGICAL FRAMEWORK

To address the research objectives outlined in this thesis, a structured methodological framework is adopted to ensure a comprehensive and rigorous development process. This chapter presents the methodological approach employed in this research, which is grounded in the V-model as established by the International Council on Systems Engineering (INCOSE) [12]. The V-model provides a robust framework for project development, facilitating timely and budget-compliant completion through a comprehensive development process.

The methodological framework is composed of seven key stages, each addressing a distinct aspect of the project development process. The stages are designed to ensure clear validation and verification of initial requirements at every stage, guaranteeing that the proposed solution aligns with the project's objectives.

1. **User Requirement Identification:** This stage involves a detailed analysis of the problem statement to identify primary issues and potential solutions. User requirements are defined to ensure that the proposed solution aligns with the project's objectives. This stage is crucial in establishing a clear understanding of the project's scope and requirements.
2. **System Design and Architecture:** Based on the identified user requirements, the system architecture is developed, ensuring that the proposed solution is feasible and aligns with the project's objectives. This stage involves a high-level overview of the system components and their interconnections. Requirements are formulated to satisfy the previously defined solution requirements.
3. **Component Design and Development:** Building upon the high-level architecture of the solution, a more detailed approach is outlined for each component, taking into account their specific power and data transmission needs. This stage culminates in a comprehensive architecture of the solution, providing a detailed overview of the components, their selection rationale, and their interconnections.
4. **Implementation and Manufacturing:** The proposed solution is implemented and manufactured using available tools, integrating the necessary electrical components. This stage includes a detailed description of the implementation process, including the tools and materials used, as well as the integration of electrical components. The development of software and hardware components is also detailed.
5. **Component Testing and Verification:** The functionality of each component is verified in a standalone mode, with detailed information provided regarding the verification process. This stage ensures that each component functions as intended, paving the way for system integration.
6. **System Testing and Integration:** The methodology for conducting system tests and subsequent analyses is elaborated. System integration is performed by assessing communication between module pairs to ensure that data can be transmitted freely and utilized effectively.
7. **Acceptance Testing and Validation:** Validation of the initial requirements is conducted to confirm that all solution requirements have been met. This stage also in-

cludes preparations for potential future enhancements, ensuring the solution's scalability and adaptability.

A graphical representation of the V-model is provided in Figure 5.1 to illustrate the methodology's structure and relationship between the various stages.

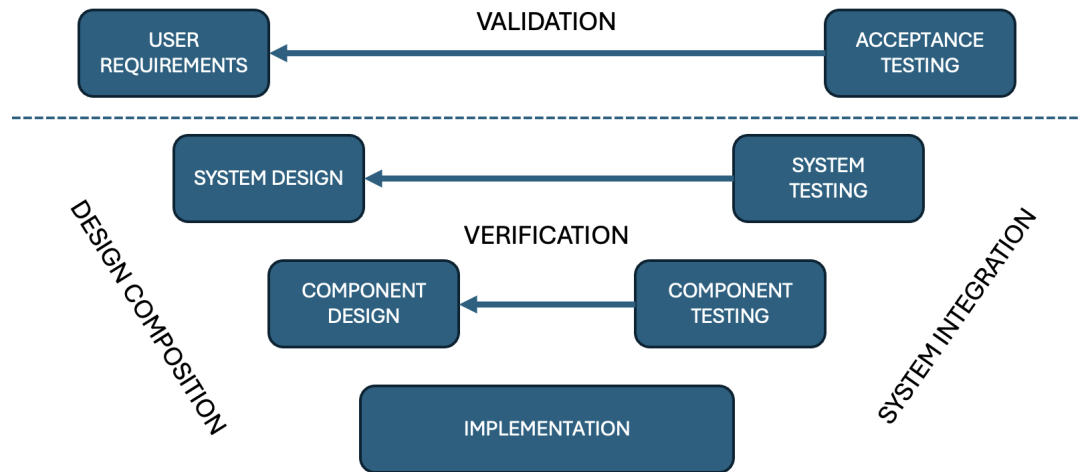


Figure 5.1. *Methodological framework based on the V-model from INCOSE with the different stages of the project development process*

The V-model provides a structured approach to project development, ensuring that all aspects of the project are considered and addressed. By following this methodological framework, this research aims to develop a comprehensive and effective solution for the design and implementation of a fully distributed parking management system tailored for the next generation of smart cities.

6. CLOUD COMPUTING

Cloud computing is a technological paradigm that enables the delivery of computing services, including servers, storage, databases, networking, software, and analytics, over the internet. This model shifts the management of physical infrastructure and resources from on-premises systems to remote data centers managed by cloud service providers. Cloud computing is fundamental to modern digital ecosystems, supporting a wide range of applications from personal use to large-scale enterprise operations.

6.1 Definition and Key Concepts

Cloud computing leverages a network of remote servers hosted on the internet to store, manage, and process data, rather than relying on local computers or private data centers. It offers resources on-demand, enabling users to scale operations according to their needs. The essential characteristics of cloud computing include:

- **On-Demand Self-Service:** Users can access computing resources as needed without requiring human interaction with service providers.
- **Broad Network Access:** Services are accessible over a network, typically the internet, using various devices such as smartphones, tablets, and laptops.
- **Resource Pooling:** Resources are pooled to serve multiple users, ensuring efficiency and scalability.
- **Rapid Elasticity:** Resources can be elastically provisioned and released, enabling scalability according to demand.
- **Measured Service:** Cloud systems automatically control and optimize resource use, charging users based on their consumption.

6.2 Advantages of Cloud Computing

The adoption of cloud computing offers several advantages that have contributed to its widespread popularity. One of the most significant benefits is its scalability and flexibility. Cloud computing enables organizations to adjust their resource usage dynamically based on real-time needs, eliminating the need for over-provisioning and supporting workloads of varying demands effectively. This adaptability ensures that resources are utilized efficiently, minimizing waste and optimizing performance.

Cost efficiency is another critical advantage. By using cloud services, organizations can avoid the significant capital expenditures associated with purchasing and maintaining hardware and software. Instead, they incur operational costs only for the resources they consume, making cloud computing an economically viable solution for businesses of all sizes. Additionally, cloud computing enhances accessibility and collaboration. Since cloud-based applications and services are accessible from anywhere with an internet connection, distributed teams can collaborate seamlessly, a feature that has become indispensable in today's increasingly globalized and remote work environments.

Reliability is also a key strength of cloud computing. Leading cloud providers ensure high levels of availability by deploying redundant systems across geographically dispersed data

centers, thereby minimizing downtime and enhancing disaster recovery capabilities. Furthermore, security is a paramount concern addressed by cloud providers. They invest significantly in advanced measures such as encryption, firewalls, and regular security audits, ensuring robust protection against cyber threats and unauthorized access. These combined advantages make cloud computing a transformative technology, supporting innovation and operational efficiency in diverse sectors.

6.3 Types of Cloud Computing

Cloud computing services are categorized into different types based on their deployment models and the services they provide. These distinctions allow organizations to select a cloud strategy that aligns with their specific requirements.

6.3.1 Deployment Models

- **Public Cloud:** A public cloud is owned and operated by third-party providers, delivering resources over the internet. Examples include Amazon Web Service (AWS), Microsoft Azure, and Google Cloud Platform. It offers cost-effectiveness and scalability but may pose data sovereignty concerns for certain organizations.
- **Private Cloud:** A private cloud is used exclusively by a single organization. It offers greater control over data and infrastructure, making it suitable for industries with strict regulatory requirements.
- **Hybrid Cloud:** A hybrid cloud combines public and private cloud environments, enabling organizations to benefit from both scalability and control. This model is particularly useful for balancing workloads and maintaining sensitive data on-premises while leveraging the public cloud for other operations.
- **Multi-Cloud:** A multi-cloud strategy involves using multiple cloud providers to mitigate risks associated with vendor lock-in and enhance reliability and performance.

6.3.2 Service Models

Cloud computing services are typically offered in the following models:

- **Infrastructure as a Service (IaaS):** Provides virtualized computing resources over the internet, including servers, storage, and networking. Users manage operating systems and applications while the provider handles the infrastructure.
- **Platform as a Service (PaaS):** Offers a platform that includes hardware, software, and development tools to build, test, and deploy applications. It abstracts the complexities of infrastructure management, enabling developers to focus on coding.
- **Software as a Service (SaaS):** Delivers software applications over the internet on a subscription basis. Users can access the software through a browser without worrying about installation or maintenance.

7. INTERNET OF THINGS

The IoT is a paradigm that establishes a network of interconnected devices equipped with sensors, software, and communication technologies. This enables seamless interaction between the physical and digital realms, facilitating the collection, transmission, and processing of data. Through its ability to deliver enhanced functionality and automation, the IoT has numerous applications, particularly in smart city infrastructure. These applications span healthcare, transportation, energy management, and urban planning.

The main point of IoT is its capacity for interconnectivity, enabling devices to autonomously communicate and share data. Advanced sensing technologies augment this connectivity, capturing real-world metrics such as temperature, motion, or occupancy. The processing of the data is achieved through edge computing, which provides localized analysis, or cloud computing for centralized processing, tailored to meet latency and scalability demands. This processed data is subsequently integrated with actuators, enabling automation of tasks such as the management of parking space access without requiring human intervention.

7.1 Architecture of IoT Systems

The architecture of IoT systems is structured across four principal layers. The perception layer constitutes sensors and actuators, which interface directly with the physical environment to gather data and execute specific actions. Data transmission occurs within the network layer, leveraging communication protocols such as Wi-Fi, Bluetooth, or cellular networks. The processing layer transforms raw data into actionable insights through edge or cloud computing methodologies. Finally, the application layer provides interfaces for end-users, ensuring an intuitive and accessible experience tailored to diverse functionalities.

7.2 Benefits of IoT

The adoption of IoT technologies confers significant advantages across multiple sectors, particularly in the realm of parking management systems. Real-time monitoring capabilities, enabled by sensors, deliver continuous updates on parking space availability, reducing search times and alleviating urban congestion. Automation, facilitated by actuators, streamlines operations such as access control and reservation management, minimizing human intervention. Moreover, IoT-driven data analytics empower urban planners with insights to optimize resource allocation and develop informed policies. The energy efficiency inherent in smart systems aligns with sustainability objectives by curbing unnecessary resource consumption.

7.3 Challenges and Limitations

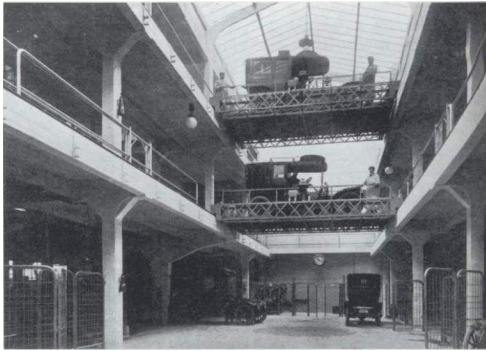
The deployment of IoT systems presents several challenges. Scalability remains a critical concern, particularly in large-scale implementations like city-wide parking systems. The management of sensitive information collected by IoT devices necessitates data security and privacy measures to mitigate risks. Interoperability challenges, stemming from

disparate manufacturer standards and communication protocols, complicate system integration.

8. HISTORICAL DEVELOPMENT

In the early 20th century, as urbanization accelerated and automobile ownership increased, the need for efficient parking solutions became apparent. The first significant step in this direction came in 1905 with the Garage Rue de Ponthieu [13] in Paris, designed by Auguste Perret. This multi-story concrete structure, see Figure 8.1a, featured internal elevators to transport cars between floors, where attendants would manually park them. While not fully automated, this innovation laid the foundation for future parking systems by maximizing vertical space utilization.

The 1920s marked the beginning of more advanced parking solutions, particularly in major U.S. cities. The Paternoster system [14], resembling a Ferris wheel for cars, refer to Figure 8.1b, could accommodate eight vehicles in the space typically used for two. This period also saw the introduction of Kent Automatic Garages in New York in 1928, which employed an electric "parker" to lift and move cars to available spaces. These early automated systems represented significant progress in addressing the growing demand for parking in densely populated urban areas.



(a) Garage Rue de Ponthieu in Paris, 1905 [13].



(b) Paternoster system, 1920s [14].

Figure 8.1. Historical developments in parking management systems.

The 1930s brought another crucial development with the introduction of parking meters, revolutionizing on-street parking management. This innovation allowed cities to better regulate parking durations and generate revenue from public parking spaces. The subsequent decades, particularly the 1940s and 1950s, witnessed a surge in the development of automated parking systems in the United States, with designs such as Bowser, Pigeon Hole, and Roto Park [15] gaining popularity.

While interest in automated parking systems temporarily waned in the U.S. during the 1960s to 1980s, development continued in Europe and Asia. Notable advancements included the Auto Stacker system in London in 1961 and Wohr's Electromechanical Parking System Type 100 [16] in Germany in 1962. During this period, Japan emerged as a leader in automated parking systems, with significant growth continuing into the 1990s.

The late 20th century marked the beginning of the digital revolution in parking management. The 1990s saw the introduction of parking guidance systems, which used sensors to monitor occupancy and provide real-time information to drivers. This technology significantly reduced the time and frustration associated with finding available parking spaces in large facilities.

The early 2000s ushered in a new era of smart parking solutions. In 2002, the first robotic parking garage in the United States opened in Hoboken, New Jersey [17], showcasing the potential of fully automated parking facilities. This period also saw the rapid development of technologies such as license plate recognition systems, mobile parking apps for finding and reserving spaces, and IoT-based parking management systems.

In recent years, parking management systems have continued to evolve, incorporating advanced technologies such as artificial intelligence and machine learning for predictive parking analytics. Cloud-based parking management platforms have become increasingly common, offering scalable and flexible solutions for parking operators. Furthermore, the integration of parking systems with broader smart city initiatives and connected vehicle technologies is paving the way for more efficient and sustainable urban mobility solutions.

The evolution of parking management systems reflects broader technological trends, moving from mechanical solutions to digital, interconnected systems. Today's parking management solutions prioritize efficiency, user experience, and environmental sustainability, addressing not only the immediate needs of drivers and parking operators but also contributing to the broader goals of smart urban planning and reduced environmental impact.

As cities continue to grow and evolve, parking management systems will undoubtedly play a crucial role in shaping the future of urban mobility. The ongoing development of these systems promises to further optimize space utilization, reduce traffic congestion, and enhance the overall urban experience for residents and visitors alike.

9. MODERN TRENDS

Automated parking management systems have evolved significantly to address the unique needs of residential communities. Currently, various types and technologies are employed in modern parking management solutions, focusing on their application in community settings. Sensor-based systems utilize advanced sensing technologies, such as ground sensors embedded in pavement and overhead sensors mounted above parking spaces, to monitor and manage parking spaces efficiently. These sensors provide real-time data on occupancy, enabling efficient space utilization and reducing search times for residents.

Licence Plate Recognition (LPR) systems have gained popularity in community parking management, offering advantages such as automated access control, visitor management, and enforcement of parking regulations. Radio-Frequency Identification (RFID) technology provides another efficient solution, particularly beneficial for large residential complexes with multiple parking areas. Mobile application-integrated systems offer residents a user-friendly interface to interact with the parking system, providing features like real-time availability information, digital permits, and reservation capabilities.

Cloud-based management platforms have revolutionized parking management by offering centralized, scalable solutions with real-time data analytics, remote management capabilities, and enhanced security. Smart gate systems, integrated with other parking management technologies, form a crucial component of modern community parking solutions, enhancing security and ensuring smooth traffic flow.

The choice of parking management system for a residential community depends on factors such as the size of the community, budget constraints, and specific parking challenges. Often, a combination of these technologies is employed to create a comprehensive, efficient, and user-friendly parking management solution tailored to the unique needs of each community. As urban populations continue to grow and vehicle ownership increases, these advanced parking management systems will play an increasingly important role in optimizing space utilization, improving resident satisfaction, and contributing to more sustainable urban environments.

10. REQUIREMENTS

The PMS for this project is designed to address the evolving needs of various users, including parking facility managers and drivers. The system's primary objective, detailed in Chapter 3, is to overcome the limitations of traditional parking management systems by improving scalability, reliability, and user adaptability, while aligning with the goals of smart city initiatives.

To achieve this, user and system requirements are identified. These requirements are essential for ensuring the system's effectiveness, efficiency, and alignment with the diverse needs of its users. The system's technical and functional specifications are also established to ensure its successful implementation.

10.1 User Requirements

The user requirements for the distributed PMS are determined through a thorough analysis of the needs and expectations of parking facility managers. These requirements are critical for designing a system that effectively addresses operational challenges, improves the efficiency of parking space utilization, and integrates seamlessly into existing urban mobility frameworks.

The primary users of the system, parking facility managers and drivers, have specific needs that the system is designed to meet. Their main objectives include improving parking management efficiency, ensuring the safety of the parking environment, and optimizing space utilization across multiple facilities. The system needs to enable them to monitor parking space availability in real-time, manage entry and exit of vehicles, and provide essential data for decision-making and reporting.

The requirements for the users can be broken down into the following key areas:

10.1.1 Real-Time Monitoring and Management

Parking facility managers need a system that provides real-time monitoring of parking spaces. This feature is essential for ensuring that parking spaces are used efficiently and that any underutilized spaces are identified and optimized. Real-time data to track the occupancy status of each parking spot, which is crucial for streamlining operations, reducing congestion, and improving the overall customer experience.

The system also allows parking facility managers to retrieve occupancy patterns and identify peak demand times, which helps adjust pricing strategies, optimize space allocation, and ensure parking spaces are available when needed.

10.1.2 Automation of Parking Access

Automation is another key requirement for the parking management system. Parking facility managers need a system that controls vehicle access to parking areas without requiring human intervention. Automated gates and barriers are essential for improving efficiency, reducing delays, and ensuring that vehicles can enter and exit parking facilities smoothly. These automated systems are integrated with real-time monitoring data to ensure that only authorized vehicles can access specific parking areas.

The system also provides tools for managing access rights based on specific criteria, such as license plate, membership status, or occupancy. Parking facility managers need to configure access control rules and monitor the effectiveness of these rules in real-time.

10.1.3 Security and Incident Management

Ensuring the security of parking facilities is a critical concern for parking facility managers. The system needs to incorporate security features to prevent unauthorized access to parking areas, detect potential security breaches, and provide timely alerts for incidents such as unauthorized parking or other violations. While surveillance systems are removed from the technical specifications, the cameras used for real-time monitoring still play a role in incident detection, as they capture images or video that can be reviewed in the event of an issue.

Real-time alerts are required for events such as access attempts by unauthorized vehicles, security breaches, or potential hazards. These alerts are sent to parking facility managers through the system's notification mechanisms, allowing them to respond quickly and effectively to incidents.

10.1.4 Data Analytics and Reporting

Parking facility managers need access to detailed reports and analytics on parking usage, including occupancy rates, peak demand times, revenue generation, and space utilization patterns. The system provides the ability to download the user data to perform reports, assisting in operational planning, resource allocation, and decision-making.

10.2 System Requirements

To meet the diverse user requirements, the distributed PMS is designed with several key system requirements in mind. These requirements focus on ensuring that the system is scalable, reliable, secure, and user-friendly, while also supporting the goals of smart city initiatives.

The main system requirements are as follows:

10.2.1 Real-Time Monitoring

The system needs to incorporate cameras for monitoring parking space occupancy in real-time. These cameras must be accurate, reliable, and capable of detecting vehicle presence or absence in parking spaces. The system must be able to process data from numerous cameras across multiple locations simultaneously, ensuring that the information provided to parking facility managers is accurate and timely.

Furthermore, the camera-based monitoring system must be robust enough to handle environmental factors such as weather conditions and lighting variations.

10.2.2 Automation and Access Control

Automated gate and barrier systems are a critical component of the system. These systems must be fully integrated with the parking management platform, allowing for real-time updates on space availability and enabling seamless access control. Vehicles must be able to enter and exit parking facilities autonomously based on the available space data, without the need for human intervention.

Access control mechanisms also need to ensure that only authorized vehicles can enter restricted areas. This can include integration with LPR systems, RFID-based solutions, or mobile applications that validate the identity of the vehicle and its access privileges.

10.2.3 Scalability and Flexibility

The system architecture needs to be scalable and flexible to accommodate a growing number of parking facilities, users, and devices. As demand for parking management grows, the system must be able to scale horizontally, adding additional cameras, sensors, or access control systems without impacting performance. Moreover, the system must be modular, allowing for easy updates or integration of new features.

10.2.4 Security and Availability

Given the importance of the system in managing urban mobility and infrastructure, security and availability are paramount. The system must be resilient to cyberattacks and other threats, with multiple layers of security in place to protect sensitive data and ensure continuous availability of services. Redundancy mechanisms, such as backup servers and data replication, are required to ensure high availability and minimize service interruptions. The system must be capable of maintaining operations even in the event of network outages or hardware failures. Interoperability is also a key consideration. The system must be designed to work seamlessly with existing infrastructure and technologies, both within the parking facilities and within the broader smart city ecosystem.

10.2.5 Physical System Requirements

In terms of hardware, the parking management system requires a robust and reliable physical infrastructure to support the real-time monitoring and automation functions. This infrastructure includes:

- **Cameras:** High-resolution cameras capable of detecting vehicle occupancy in parking spaces. These cameras must be weather-resistant, durable, and equipped with night vision or infrared capabilities to ensure reliable performance in various environmental conditions, such as low light or harsh weather.
- **Gate and Barrier Systems:** Automated gates and barriers for controlling vehicle access to parking areas. These systems must be seamlessly integrated with the overall parking management system to allow for real-time updates on space availability and facilitate the automated entry and exit of vehicles.
- **Network Infrastructure:** A robust communication system to transmit data from cameras, sensors, and access control devices to central servers. The network infrastructure must support high-speed data transfer and be resilient to failures.

The physical infrastructure must be designed for scalability and ease of maintenance, allowing for the expansion or upgrade of components as needed.

10.2.6 Data Privacy and Storage

Data privacy and security are paramount concerns in the design of the parking management system. The system must comply with relevant data protection laws, such as the General Data Protection Regulation (GDPR) [18], to safeguard personal information and prevent unauthorized access to sensitive data.

The data collected by the system, including parking history, vehicle entry and exit times, and payment details, must be encrypted both during transmission and while stored in the system's databases. Key data privacy and storage requirements include:

- **Secure Storage:** All personal and parking-related data should be stored in secure, encrypted databases with access restricted to authorized personnel only.
- **Data Retention:** The system must adhere to strict data retention policies, ensuring that data is stored only for the minimum time necessary to fulfill the purpose of the service, in accordance with relevant privacy regulations.
- **User Consent:** The system must obtain explicit consent from users for data collection, explaining the types of data collected and how it will be used, stored, and shared.
- **Access Control:** The system must include role-based access control mechanisms to ensure that only authorized personnel can access sensitive data, and it must provide audit logs to track data access and modifications.

In addition to ensuring compliance with privacy regulations, the system must include robust mechanisms for data breach detection and response, ensuring that any unauthorized access or data compromise is identified and addressed promptly.

11. DESIGN

The proposed parking management system employs a distributed architecture combining edge computing with cloud services, designed to meet the functional requirements outlined in 10. The solution adopts a distributed architecture that combines edge computing capabilities in local terminals with cloud-based interfaces, achieving an optimal balance between responsiveness and scalability.

11.1 System Architecture

The architecture of the system is divided into three main subsystems: the license plate recognition system, the back-end system, and the front-end system. Each subsystem plays a distinct role in ensuring the overall functionality and efficiency of the parking management solution.

The **license plate recognition system** is responsible for detecting vehicles and identifying their license plates. This subsystem utilizes advanced image processing techniques to extract license plate information from live video feeds. By processing this data locally at the edge, the system minimizes latency and ensures real-time responsiveness. The design emphasizes modularity to facilitate future upgrades or integration with other recognition technologies.

The **back-end system** serves as the central hub for data processing and logic management. It handles user authentication, license plate management, and communication with both the front-end interface and physical access control mechanisms. The back-end is also tasked with orchestrating requests from users, such as granting or denying access based on predefined rules. Additionally, it interfaces with community-specific terminals to control garage door operations securely and efficiently.

The **front-end system** provides an intuitive interface for end-users to interact with the parking management solution. Designed with usability in mind, it allows users to perform essential tasks such as registering new license plates, monitoring parking events, and remotely opening garage doors. The front-end is accessible via web browsers and mobile applications, ensuring seamless interaction across diverse platforms.

Each of these subsystems is described in more detail below to illustrate their roles within the overall architecture.

11.1.1 License Plate Recognition System

The license plate recognition system is a critical component of the parking management solution. Its primary function is to identify vehicles by analyzing video streams captured at entry and exit points. This subsystem consists of two main elements: a camera for capturing video footage and a computational unit for processing these images.

The camera continuously monitors designated areas near garage doors to detect approaching vehicles. Once a vehicle is detected, the computational unit processes the video feed to extract license plate information using machine learning algorithms optimized for accuracy and speed. The extracted data is then transmitted to the back-end system for further validation.

This design ensures that license plate detection operates independently within each community terminal, reducing reliance on external servers and enhancing fault tolerance.

11.1.2 Back-End System

The back-end system acts as the brain of the parking management solution. Its responsibilities include managing user accounts, storing license plate data securely, and processing requests from both users and community terminals.

A key feature of this subsystem is its ability to work autonomously without requiring any external services, in case of errors with the external services or connection interruptions. By adopting this architecture, it ensures that each community operates autonomously while still benefiting from centralized oversight when required.

The back-end also integrates with physical access control systems to enable automated garage door operations. For instance, upon receiving a valid access request from the Licence Plate Recognition System or user interface, it triggers the appropriate mechanism to open or close garage doors.

To ensure scalability and reliability, the back-end is deployed on each specific community terminal, allowing it to handle local requests efficiently. This distributed architecture minimizes latency and enhances system responsiveness, even under heavy loads.

11.1.3 Front-End System

The front-end system functions as the primary interface between users and the parking management solution, offering an intuitive and accessible platform for interaction. Its design emphasizes simplicity and usability, transforming complex operations into seamless workflows.

Through this interface, users can perform essential tasks such as registering or removing license plates, monitoring real-time parking availability, accessing detailed logs of parking events, and remotely controlling garage doors within authorized communities. The system is designed to be universally accessible, supporting both desktop browsers and mobile devices to ensure convenience across various platforms.

Security is a fundamental aspect of the front-end system, with all communications between the user interface and the back-end encrypted using industry-standard protocols. Additionally, role-based access controls are implemented to restrict sensitive operations to authorized personnel, further enhancing the system's security and reliability.

11.2 Hardware

The hardware section of this project focuses on the essential components required for the effective operation of the parking management system. The selected hardware includes terminals, cameras, and a server, each playing a critical role in ensuring the system's functionality and efficiency.

A comprehensive study was conducted to identify the most budget-friendly hardware options that still meet the necessary requirements for performance and reliability. This analysis took into account factors such as cost, durability, and compatibility with the overall system architecture. The goal was to strike a balance between affordability and capability,

ensuring that the chosen hardware would effectively support the project's objectives while remaining economically viable for deployment across multiple communities.

11.2.1 Terminals

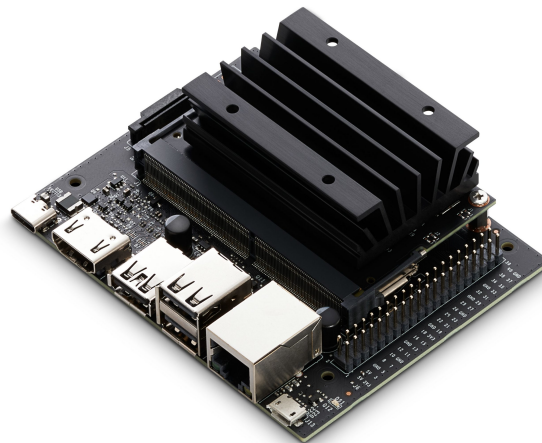
The terminals are the core part of the deployment and is where all the processing is done to manage each community. In order to provide the necessary capabilities for the community such as opening the garage doors and detecting the cars. For that, the requirements of the terminals are that it must support Linux operating system to be able to run the programs, and als it must be able to have the necessary computing capacity to run the programs to detect the licence plates. In order to select the correct computer, different alternatives are studied, shown in Table 11.1.

NVIDIA Jetson Orin Nano	
CPU	6-core Arm Cortex-A78AE
CPU Clock	1.5 GHz
GPU	1024-core NVIDIA Ampere
RAM	8GB LPDDR5
USB Ports	3x USB 3.2 Gen2, 3x USB 2.0
Ethernet	1x Gigabit Ethernet
Wi-Fi	Not specified
Bluetooth	Not specified
Power	7W - 15W
Price	600 €
NVIDIA Jetson Nano	
CPU	Quad-core Arm A57
CPU Clock	1.43 GHz
GPU	128-core Maxwell
RAM	4GB LPDDR4
USB Ports	4x USB 3.0, 1x USB 2.0
Ethernet	Gigabit Ethernet
Wi-Fi	802.11ac
Bluetooth	Bluetooth 5.0
Power	5W / 10W
Price	220 €
Raspberry Pi 4	
CPU	Quad-core Arm Cortex-A72
CPU Clock	1.5 GHz / 1.8 GHz
GPU	VideoCore VI
RAM	1GB/2GB/4GB/8GB LPDDR4
USB Ports	2x USB 3.0, 2x USB 2.0
Ethernet	Gigabit Ethernet
Wi-Fi	802.11ac (2.4 GHz and 5.0 GHz)
Bluetooth	Bluetooth 5.0
Power	5V DC via USB-C (3A)
Price	87 €
Raspberry Pi 5	
CPU	Quad-core Arm Cortex-A76
CPU Clock	2.4 GHz

GPU	VideoCore VII
RAM	4GB/8GB LPDDR4X
USB Ports	2x USB 3.0, 2x USB 2.0
Ethernet	Gigabit Ethernet
Wi-Fi	802.11ac (2.4 GHz and 5.0 GHz)
Bluetooth	Bluetooth 5.0
Power	5V/5A DC power (USB-C PD)
Price	125 €

Table 11.1. *Comparison of Single-Board Computers*

For this project, the NVIDIA Jetson Nano is used due to the advanced GPU and the relative cheap price-point compared to the NVIDIA Jetson Orin Nano. Moreover, the Jetson Nano is able to run the models with enough performance to be able to detect the licence plates and the cars in a relative short time-span. See Figure 11.1 for the image of the NVIDIA Jetson Nano.

Figure 11.1. *NVIDIA Jetson Nano*

11.2.2 Cameras

The selection of appropriate cameras is crucial for the effective operation of the parking management system. The primary requirements for these cameras include weather resistance to withstand heavy rain, the ability to transmit live video feeds to a central computer, and infrared detection capabilities for low-light conditions such as indoor garage parking or nighttime operations. Additionally, the cameras need to be capable of capturing high-quality images to facilitate accurate car detection and license plate identification.

To meet these requirements, several camera models were evaluated. Table 11.2 presents a comparison of the considered options:

After careful consideration, the Reolink RLC-811A, see Figure 11.2, was selected as the optimal choice for this project. This camera offers 4K resolution, providing exceptional image clarity for accurate vehicle and license plate detection. Its IP66 weather resistance

Specification	Reolink RLC-811A	Lorex Fusion 2K	Eufy Cam S350	Arlo Ultra 2
Resolution	4K (8MP)	2K (4MP)	4K (8MP)	4K (8MP)
Waterproof	IP66	IP66	Indoor only	IP65
Infrared	Yes	Yes	Yes	Yes
PoE	Yes	Yes	No	No
Price (€)	166	300	130	399

Table 11.2. *Comparison of Camera Options*

rating ensures durability in various outdoor conditions, including heavy rain. The camera's built-in infrared capabilities are sufficient for basic low-light operation and can be supplemented with additional infrared lighting when needed.

One of the key advantages of the Reolink RLC-811A is its support for Power over Ethernet (PoE). This feature allows for both power supply and data transmission through a single Ethernet cable, significantly simplifying installation and reducing wiring complexity. The camera's competitive price point of €166 also makes it an attractive option for large-scale deployments across multiple parking facilities.

While the Lorex Fusion 2K offers similar weather resistance and PoE capabilities, its lower 2K resolution may not provide the same level of detail required for accurate license plate recognition. However, it could be a viable alternative if budget constraints become more pressing, as it offers a good balance of features at a mid-range price point.

The Eufy Cam S350, despite its high 4K resolution and lower price, is not suitable for this project due to its lack of weather resistance and PoE capabilities. It is designed for indoor use only, which limits its application in outdoor parking environments.

The Arlo Ultra 2, while offering high-resolution 4K imaging and good weather resistance (IP65), lacks PoE support and comes at a significantly higher price point. Its wireless design, while potentially offering more flexible installation options, may not be ideal for a permanent, large-scale parking management system where consistent power and data connectivity are crucial.

Figure 11.2. *Reolink RLC-811A Camera*

11.2.3 Internet Connectivity

To provide connectivity from the on-board computer to the server, a networking connection needed to be established. As this deployment must be self-sufficient and not depend on the infrastructure of each community, a router with 4G connection is deployed. For this case, a simple 4G router was used, the TP-Link AC1200. This router offers 4G+ Cat6 connectivity and AC1200 wireless dual-band gigabit capabilities, making it suitable for

providing reliable internet access for the parking management system. Moreover, this router has a built-in switch to be able to connect the cameras with the terminal.

11.2.4 Server

The server is the point of contact to connect users with the different communities, facilitating user authentication and enabling connections to specific community resources. It is built on a scalable architecture deployed in AWS (Amazon Web Services), chosen for its rapid time-to-market capabilities and inherent scalability.

AWS provides a cloud-based solution that allows the system to efficiently manage varying loads and adapt to user demand, which is essential for a parking management system that may experience fluctuating traffic patterns. This flexibility ensures that the system can scale up or down seamlessly, accommodating an increasing number of users and devices without compromising performance.

Moreover, AWS offers robust testing environments that allow developers to validate system functionalities before full deployment. This capability is crucial for ensuring reliability and performance under real-world conditions, as it enables iterative testing and refinement of the system components. By leveraging AWS's extensive infrastructure, the project can ensure high availability and resilience, minimizing downtime and enhancing user experience.

In summary, the choice of AWS not only supports the immediate needs of scalability and rapid deployment but also provides a solid foundation for ongoing testing and development, essential for maintaining an effective and responsive parking management solution.

12. IMPLEMENTATION

Give the requirements and the design in the previous chapters, refer to Chapter 10 and Chapter 11, the different modules are implemented following the V-model established in Chapter 5.

12.1 Community deployment

In order to deploy a new system in a new community the following elements must be installed

TODO: add architecture

A terminal in charge of the processing of all the incoming data from the different elements and has the algorithm to open the gates when a allowed user enters or exists. The cameras already explained in the Chapter 11, and the networking system that provides connection to the central server and allows users and manager to connect to the specific community and administer it.

12.1.1 Terminals

As previously stated, the terminals are the ones in charge of the main functionality of the parking management system, storing the data, detecting the vehicles, and allowing the parking management managers administer the community. For this the following sub-systems are design, a database to store the data locally, a server to expose the service externally, and a detection algorithm to detect the vehicles. Moreover, other subsystems are also implemented, such as a backup system, and monitoring system.

TODO: add architecture of the terminals

database

In order to store the data of each community, a database is used. The options are between SQL or NoSQL database and a local database in the terminal or a centralized database in the cloud. For this case, a local SQL database based on SQLite **TODO:** add ref is used. The main reason behind it was due to the requirements of having the data inside the community for data privacy and security reasons.

Moreover, while it is true that using a centralized database would be easier for maintenance, backups, and upgradability, the requirement of high availability would requier to store a cache database portion in each terminal in order to make the database robust to internet connection losses. Using a local database we ensure that the systems keeps working even if internet connection losses occur. The drawback using a local database is that we have to ensure to backup the database periodically to meet Recovery Time Objectives (RTO) and Recovery Point Objectives (RPO) so no critical data is lost.

The schema used for the dataset is the following.

TODO: add schema image and explain

Terminal Server

To provide the capabilities for the server to communicate to the terminal, a local server is developed. This server will have all the require actions that a user can perform to administer and use the system. The server used is a ExpressJS **TODO: add ref** server and based on a RestAPI methodology. The reason to use this is that ExpressJS is a widely used framework with a wide adoptions and multiple libraries to perform different tasks such as database management and more.

The RestAPI methodology **TODO: explain**

The following different edpoints are used: **TODO: add endpoints**

Note that in order to authenticate the users, a custom JWT token is used that will be later explained in **TODO: add section explained**.

Detection Algorithm

In order to detect the different licence plates of the vehicles, a custom deep learning algorithm is used based on YOLO **TODO: add ref**. The implementation of this model is out of the scope of this project but more information can be found in the following paper <https://www.sciencedirect.com/science/article/pii/S0921889023002476?via>

In summary the system has two main steps, one step is to detect a licence plate in the image, it creates a bounding box of the licence plate that is later processed by a second algorithm to detect the characters of the licence plate.

TODO: add images

12.1.2 Door Opening

To control the door, a rele is used as previously explained. In order to allow the system to be able to open the door and also the detection algorithm, a small server is step up to listen for requests to open the door. When a request is sent to the server to open the door, a signal is sent throught the rele and the door opens successfully.

Other subsystems

The cameras are used to send the image captured in the different points of the community, usually places in the gate doors to the terminal. The terminal processes the data with the detection algorithm. The data is sent through an RTSP **TODO: add ref and gls** protocol and connected via Ethernet to the network.

In order to connect the cameras with the terminal and the terminal to the internet, the router with a switch is used. The specific router is a 4G router to povide connectivity to the terminal.

Finally, to ensure the correct functionality of them, a backup system that backups up the database every day to Amazon S3 **TODO: ref** encrypted, and also a monitoring system that sends metrics of the terminal to a centralized server in oder to keep track of the different terminals and detect if a specific terminal is malfunctioning.

TODO: add the infrared part for problems

TODO: add rele problems

12.2 Cloud deployment

To enable the access to the different communities, a web server is deployed in AWS. The main component is a NextJS server that holds the website that the users use to access the system and also the backend functionality to connect to each specific community.

12.2.1 Cloud Architecture

In order to deploy a scalable and robust application the following architecture is used.

add cloud architecture and explain

Note that this deployment is based on EC2 instances as the use of ZeroTier required to have virtualmachines installed as it cannot be install in containers. The main problem is that the Zerotier docker installation needs special network admin permissions <https://github.com/zyclonite/zerotier-docker>, which ECS **TODO: add ref** does not allow. Also a budget architecture was needed to keep the cost low.

Moreover, all the deployment was built and administer using Terraform **TODO: add ref**. The reason was to have a description of the deployment used and be able to make changes.

12.2.2 Website

The website was design to be responsive to be able to be used in mobile devices and computer devices. The website is built using the React framework **TODO: ref** to provide the functionality and responsive of a modern website. The website also uses TailwindCSS **TODO: ref** for a ascethic and mother look. Check out **TODO: add image**.

Moreover, the website is embeded in Progressive Web Apps in Android and iOS to allow users to download an application through the mobile store of choice and be able to use the website in their phones. **TODO: add image of mobiles**.

12.2.3 User Authentication

In order to authenitcate the users and be able for the users to sign in, the requirement was that a phone SMS based system was used to make it easier and more secure for the users to sign in. for this a Firebase Auth **TODO: add ref** was used. This allows the application to send sms to phone numbers of the users to authenticate. Also it sends a JWT token to the server that is later used by the terminal to authenticate the users and check the permissions.

12.3 Deployment

In order to perform updates to the system that is upgradeing and making software changed for the different terminals, an automatic deployment is design. This system is based on Github Actions, to build the NPM packages to be installed on the temrinals. This is done buy building github action workflows that build the package with the necesarry dependencies and are stored in GitHub packages for later used. It is worth to note that the creation of the package is done automatically when a new version is created using tags in the Git system.

Once the package is build, Ansible is used, **TODO: explain ansible**. This is done by creating a playbook and setting the required actions. Moreover a inventory is used, this holds all the terminals that Ansible will connect and update.

TODO: show the tasks done

It is worth noting that the migration of the database are done manually for the moment, as no straightforward way and a way that ensures the database integrity was design yet, but this is an area of current development.

TODO: extend, need to do it first

12.4 Monitoring

In order to monitor the different terminals in case of errors, The prometheus deployment is used to store the metrics. Custom scripts are done to send information to the system. Once the information is stored in prometheus, a aws managed grafana is used to view and send allerts

TODO: extend, need to do it first

13. TESTING

In order to test the system, first each different subsystem and components is tested individually as described in Chapter 5. For this, the database, terminal server are first tested individually. Then, the system is tested as a whole in a controlled environment to ensure the correct functionality and make sure that they system cover the requirements detailed in Chapter 10.

13.1 Individual Tests

13.1.1 Database

The database is a highly important part in the functionality of the system. A robust and properly designed database is needed to ensure the correct gathering of the data and relationships. For this in order to test the database, multiple custom SQL queries are designed to ensure that the edge cases are covered to store specific information. During this part, multiple iterations of the database are designed narrowing down the data categories and ensurin the different data entries have the correct data representation. For example, ensuring that boolean attribues can only allow for 0 and 1 or the number of cars a user is able to have in a specific parking is not negative. By doing this, we ensure that the data stored is correct and no unintended functionality is performed in the data layer.

13.1.2 Terminal

For the terminal, all API endpoints are tested to make sure that they function as expected. Insomnia **TODO: ref**, a tool to craft and perform API requests for testing, is used. This is done to ensure the correct functionality of the API and have an example for each API entries for documentation purposes.

TODO: add images

13.1.3 Server

For the server, two approches are used to ensure the correct functionality. First, the server is tested grafically and see that the website functions correctly. It is worth to note, that the website is tested to be responsive, that is to be adapted to mobile devices also. This is used using the Responsive Design Mode in the Inspector Tools of Firefox and Google Chrome **TODO: add ref**. Moreover, the server is tested in conjunction with the terminal to ensure the correct functinoality between both of them locally.

13.2 Controlled Environment Tests

In order to ensure that the system behaves correctly as a whole, tests are performed on controlled environments, that is a parking place where the system is used to managed add the problem with bad connection and trying different sims

14. CONCLUSIONS

TODO: write this chapter

15. FUTURE WORK

TODO: write this chapter

add that to change the db to a nosql for the users and keep the sql for the records

use prisma for the db

16. SOCIO-ECONOMIC ENVIRONMENT

The widespread adoption of automated parking management systems is transforming urban environments and the economy, offering significant benefits while also presenting challenges. This chapter examines the socio-economic factors influencing the deployment of these systems, particularly in residential communities. It explores the potential advantages, obstacles, and financial implications of integrating this technology across urban areas.

16.1 Social Impact

Automated parking management systems have gained popularity due to their efficiency and ability to optimize space utilization, revolutionizing urban planning and mobility. Their capacity to reduce traffic congestion and improve parking availability can greatly enhance urban living conditions. For example, sensor-based systems can guide drivers to available parking spots, reducing time spent searching and lowering emissions. The project demonstrated how these systems can provide real-time occupancy data, aiding both residents and visitors in finding parking more efficiently.

In densely populated urban areas, automated parking systems facilitate better use of limited space. This capability not only improves the quality of life for residents but also contributes to more sustainable urban development by maximizing the use of available land.

However, privacy and data security remain concerns. The extensive data collection by these systems raises issues of surveillance and personal data protection, underscoring the need for clear regulations and ethical guidelines, as discussed in the regulatory framework chapter.

16.2 Economic Impact

The economic benefits of adopting automated parking management systems are substantial, with the potential to boost urban efficiency and drive innovation. For property managers and urban planners, these systems enable more efficient use of space, potentially increasing property values and reducing operational costs associated with parking management.

Despite these advantages, the costs of implementing automated parking systems (e.g., installation, training, maintenance, and upgrades) remain significant barriers for some communities and smaller property management companies. Moreover, the need for technical expertise and the risk of system failures can increase operational expenses.

16.3 Environmental Impact

Automated parking management systems can positively impact the environment by reducing traffic congestion and associated emissions. By guiding drivers directly to available spots, these systems minimize the time vehicles spend idling or circling in search of parking, contributing to lower air pollution and fuel consumption in urban areas.

Nonetheless, the environmental costs of manufacturing and disposing of electronic components must be considered. The production of sensors, cameras, and other hardware components can be resource-intensive. Sustainable design practices and proper e-waste management are necessary to mitigate these effects.

16.4 Budget Analysis

The cost of implementing automated parking management systems is a significant consideration for many communities. The analysis includes a detailed assessment of hardware components, software, maintenance, and other relevant expenses.

Table 16.1 details manufacturing costs for terminals, cameras, and networking equipment costs and other expenses for each community. The total cost for these physical components is estimated at €621. However, it is worth noting that for this project, 10 different communities have been installed totaling to €6210 for the physical components. Moreover, in Table 16.2 the cost of the software components are included totaling to €30.

For this project, the total cost would amount to €6240, which includes the necessary hardware and software for a typical residential community. However, it's important to note that this does not account for installation and long-term maintenance costs or potential upgrades, which are essential for the system's longevity and effectiveness.

In conclusion, while automated parking management systems hold significant promise for urban areas and residential communities, careful consideration of social, economic, and environmental factors is essential. Addressing these challenges with appropriate regulations and sustainable practices will maximize their potential benefits in creating more livable and efficient urban spaces.

Item	Model	Quantity	Cost (€)
Edge Computer	NVIDIA Jetson Nano [21]	1	220
Cameras	Reolink RLC-811A [22]	2	166
Router	TP-Link AC1200 [23]	1	85
Reles		1	10
Ethernet Cables	Cat 6 30 meters	1	20
4G SIM Card	Orange Prepaid SIM Card (1 month)	1	10
Boxes, power supplies, etc.		1	100
Total			621

Table 16.1. *Manufacturing costs for the physical components for each community.*

Item	Model	Quantity	Cost (€)
Server	Amazon Web Services Deployment (1 month)	1	30
Total			30

Table 16.2. *Manufacturing costs for the software components and maintenance.*

17. REGULATORY FRAMEWORK

The regulatory framework governing smart cities in Europe is primarily based on the data protection provisions outlined in the GDPR. This is largely because these systems employ surveillance technologies such as cameras that monitor public spaces, and they handle sensitive personal data, including individuals' identification numbers and contact information. Additionally, the integration of technologies such as the IoT, Artificial Intelligence (AI), and data analytics has necessitated robust legal mechanisms to address privacy, security, and ethical considerations.

17.1 Applicable Legislation

The implementation and operation of smart city technologies in the European Union must adhere to a range of legislative measures that regulate data privacy, electronic communications, and emerging technologies. Chief among these is the GDPR, but other complementary regulations and directives are also critical in shaping the regulatory landscape.

17.1.1 General Data Protection Regulation (GDPR)

The GDPR [18], also known as the Regulation (EU) 2016/679 and enacted in 2016, provides a comprehensive framework for the protection of personal data within the European Union. Its principles of transparency, accountability, and data minimization serve as the cornerstone of privacy and data protection.

Under GDPR, smart city systems are required to obtain explicit consent from individuals before collecting or processing their personal data. Furthermore, data controllers must implement privacy-by-design and privacy-by-default principles, ensuring that data protection is an integral aspect of technological development. Smart cities must also conduct Data Protection Impact Assessments for projects involving high-risk data processing, such as large-scale surveillance or facial recognition.

17.1.2 Data Retention Policies

Smart city technologies often rely on continuous data collection through sensors, cameras, and connected devices. The GDPR mandates that data should only be retained for as long as necessary to fulfill its intended purpose. To comply, smart city operators must establish robust data retention and deletion policies. Automated systems are frequently employed to enforce these policies, ensuring that unnecessary data is securely deleted to minimize privacy risks and reduce storage costs.

17.1.3 ePrivacy Directive

The ePrivacy Directive (Directive 2002/58/EC) [24], commonly known as the "Cookie Law," governs the confidentiality of communications and the processing of electronic communications data. While initially designed for traditional telecommunications, its principles are increasingly relevant to smart city applications, such as real-time traffic monitoring and public Wi-Fi networks.

Under this directive, consent is required for the use of tracking technologies and location-based services, ensuring that users are aware of how their data is being utilized. The on-

going transition to the ePrivacy Regulation aims to enhance these protections and provide greater harmonization across member states.

17.1.4 Directive on Security of Network and Information Systems (NIS 2 Directive)

The Network and Information Systems (NIS) 2 Directive [25], adopted in 2016, focuses on the security of critical infrastructure and essential services, including those used in smart cities. It requires operators of essential services to implement risk management measures and report significant cybersecurity incidents to relevant authorities. For smart cities, this includes safeguarding critical systems such as transportation networks, energy grids, and communication systems against cyber threats.

17.1.5 Artificial Intelligence Act

The Artificial Intelligence Act [26], which came into force on 1 August 2024, establishes a common regulatory and legal framework for AI across the European Union. Its provisions will be implemented gradually over the following 6 to 36 months. The Act classifies AI systems into categories based on risk, ranging from minimal to unacceptable, and imposes specific requirements on high-risk AI applications.

For smart cities, the Act directly impacts technologies such as AI-driven surveillance systems, autonomous transportation, and automated decision-making tools. These applications must adhere to stringent requirements, including transparency, accountability, and mandatory human oversight. The Act ensures that AI technologies in smart cities are deployed ethically and align with EU values, particularly with respect to fundamental rights and safety.

17.2 Regulatory Challenges and Implications

The evolving nature of smart city technologies presents significant challenges for regulatory compliance. These challenges include the integration of multiple technologies such as IoT, AI, and data analytics, which often involve cross-border data flows and raise questions about jurisdiction and enforcement. Furthermore, the pace of technological innovation frequently outstrips the development of regulatory frameworks, creating gaps that may expose users to privacy and security risks.

Ensuring compliance with a wide array of legislative measures requires substantial investment in training and capacity-building for smart city administrators. Policymakers and industry stakeholders must collaborate to establish clear guidelines that address emerging issues while balancing innovation and the protection of fundamental rights.

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