uc3m | Universidad Carlos III de Madrid

University Degree in Data Science and Engineering and Telecommunication Technologies Engineering
2024 – 2025

Bachelor thesis

Building a Scalable and Decentralized Parking Management Solution for Multi-Community Deployment

---

Andrés Navarro Pedregal

Tutor
David Larrabeiti López

Leganés, 2025

ABSTRACT

this is an abstract

Keywords: keyword1, keyword2, keyword3

ACKNOWLEDGMENTS

Thanks

AGRADECIMIENTOS

Gracias

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACROYNMS

INCOSE	International Council on Systems Engineering.

Part I

Introduction

1. MOTIVATION

The exponential growth of urban populations and the resulting increase in the number of vehicles have exacerbated the challenges of parking management in cities worldwide. For example, the significant surge in car usage in Madrid has had a profound impact on environmental pollution levels [1]. Despite the stable number of parking spaces in Spain between 2014 and 2020 [2], the increased demand for parking has led to higher costs, longer search times, traffic congestion, and elevated levels of urban pollution.

The ongoing development of Parking Management Systems (PMSs) remains a crucial research area, as traditional manual PMSs have proven inadequate in addressing the complexities of modern urban parking. Research indicates that the type of PMS employed significantly influences parking choices, with citizens favoring systems that prioritize user-friendliness, security, and reliability [3].

Recent advancements in technology offer promising solutions to the limitations of traditional PMS. The proliferation of internet-connected devices, which has increased by 20% year-over-year [4], has facilitated the development of Internet of Things (IoT)-based PMSs. These systems aim to alleviate traffic congestion and reduce urban pollution, contributing to the implementation of sustainable and efficient urban mobility strategies.

The integration of modern PMS in urban settings provides numerous benefits, including the reduction of traffic congestion and pollution, enhancement of security, and improvement of the quality of life for residents. Furthermore, PMS offer the potential for automated parking space management, facilitating their application in diverse settings such as cities, communities, and buildings.

However, the widespread implementation of PMS in Spain is often hindered by the reliance on human intervention, resulting in issues such as delayed availability, inadequate information, and insufficient control of parking spaces. The continuous human presence required to maintain these systems results in increased operational costs.

Recent technological advancements have led to the development of innovative solutions, including RFID-based smart PMSs [5], IoT-based smart PMSs [6], and intelligent parking systems utilizing image processing [7]. Despite these advancements, challenges persist, with current PMSs often featuring centralized architectures that compromise scalability and reliability in the event of service interruptions. Furthermore, these systems often lack customization options, hindering their adaptability to user-specific needs.

In light of these limitations, the primary objective of this project is to design and implement a fully distributed PMS that addresses the shortcomings of current systems, focusing on enhancing scalability, reliability, and user adaptability, with a particular emphasis on the requirements of next-generation smart cities.

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 [3] [8] [9] [10].

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 objective of this bachelor thesis is to design and implement a fully distributed parking management system tailored for the next generation of smart cities. This project aims to address the inefficiencies and challenges inherent in current parking management systems through a distributed approach that leverages modern technologies. The objective of this project can be broken down into the following specific goals:

- Conduct a comprehensive study of existing parking management systems, identifying their main problems and inefficiencies. This involves understanding user requirements, analyzing the technologies employed, and evaluating system effectiveness.
- Analyze the technologies currently used in parking management systems to determine their suitability for a distributed architecture. This includes examining sensors, IoT devices, communication protocols, and data processing methods to identify the most suitable technologies for the proposed system.
- Design the overall infrastructure of the distributed parking management system. This encompasses defining the system architecture, selecting appropriate technologies, and developing detailed design specifications to ensure a scalable, secure, and user-friendly system.
- Develop the system by adhering to a structured methodology that includes phases of planning, design, implementation, testing, deployment, and maintenance. Each phase will follow best practices to ensure the system's robustness, efficiency, and reliability.
- Evaluate the implemented system based on various criteria such as performance, scalability, security, usability, reliability, availability, and cost. This comprehensive analysis will help in assessing the effectiveness of the system and identifying areas for improvement.

  and test the proposed system in a real-world scenario, such as a city center with high vehicle density and limited parking spaces, to validate its effectiveness and identify potential issues.

By achieving these objectives, the thesis aims to contribute to the advancement of smart city technologies by providing a scalable, secure, and user-friendly parking management solution. The distributed nature of the proposed system is expected to enhance its performance and reliability, making it a viable option for modern urban environments.

4. DOCUMENT STRUCTURE

TODO: Write this chapter when all the document is finished.

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) [11]. 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.

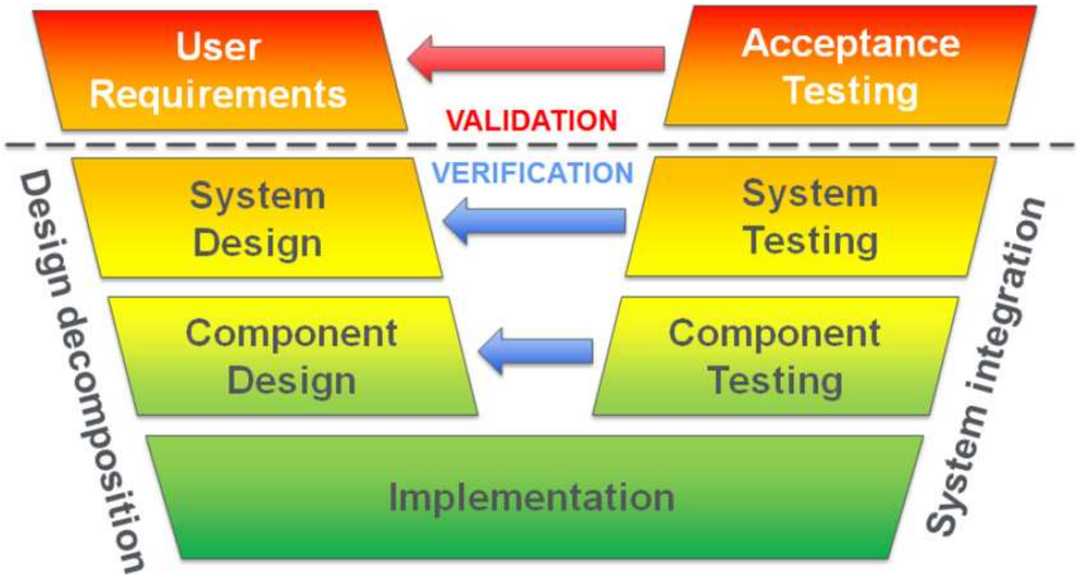

Figure 5.1. *Methodological framework based on the V-model from INCOSE with the different stages of the project development process[12]*

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.

Part II

Theoretical Background

6. DEEP LEARNING

Part III

State of the art

7. HISTORICAL DEVELOPMENT

TODO: Write this chapter

8. TYPES & TECHNOLOGIES

TODO: Write this chapter

9. MODERN TRENDS

TODO: write this chapter

Part IV

Methodology

10. REQUIREMENTS

TODO: Write this chapter

The parking management system developed for this project was designed to ensure that it met the needs of drivers, parking facility managers, and city administrators. The system was designed to address the limitations of current parking management systems, focusing on enhancing scalability, reliability, and user adaptability.

For this purpose, different user requirements were identified, and system requirements were defined to meet these needs. Furthermore, the system was designed to incorporate specific technical and functional specifications to ensure its effectiveness and efficiency.

10.1 User Requirements

The user requirements for the distributed parking management system were identified through a comprehensive analysis of the needs and preferences of drivers, parking facility managers, city administrators and users with disabilities. These requirements were essential to ensure that the system was user-friendly, efficient, and aligned with the objectives of smart city initiatives [13].

The requirements of the primary users were as follows:

For drivers, the system needed to provide real-time information about available parking spaces to minimize search time. This was crucial to reduce traffic congestion and pollution in urban areas. Moreover, drivers expected an easy-to-use interface for quick navigation and more importantly, automatic functionality of the system without the need for human intervention. That way, they did not have to worry about the availability of parking spaces and could focus on other tasks.

Parking facility managers required tools to monitor and manage their facilities efficiently, as well as access to detailed reports and analytics on parking usage patterns to optimize space utilization. A notification system for intrusions such as unauthorized parking or security breaches was also essential to ensure the safety of the parking facilities. Enhanced security measures, including surveillance and access control, were a must-have for them.

On the other hand, city administrators needed a system that could provide insights into parking demand and usage trends to inform urban planning decisions. The system should support the integration of parking data with other smart city initiatives to enhance overall urban mobility and sustainability. Moreover, city administrators required tools to monitor and minimize the environmental impact of parking facilities, such as reducing emissions and energy consumption. The system should also comply with local regulations and standards for data privacy and security such as GDPR [14].

Finally, users with disabilities needed accessibility features such as voice commands, screen readers, and other assistive technologies to ensure that they could use the system effectively. These features were essential to promote inclusivity and ensure that all users could benefit from the distributed parking management system. Moreover, the system should be designed to accommodate users with different needs and preferences, ensuring a seamless user experience for everyone.

10.2 System Requirements

For the distributed parking management system to meet the user requirements, it had to incorporate specific system requirements. These requirements were defined to ensure that the system was scalable, reliable, secure, and user-friendly, aligning with the objectives of smart city initiatives as well as the needs of drivers, parking facility managers, and city administrators. The system requirements were essential to guide the design and development of the distributed parking management system, ensuring that it met the expectations of all stakeholders and delivered the desired outcomes.

The main system requirements were as follows:

For the real-time monitoring of parking space availability, the system needed to incorporate sensors and IoT devices to detect vehicle presence and occupancy. These sensors had to be accurate, reliable, and cost-effective to provide up-to-date information on parking availability.

Reservation was another key requirement, allowing drivers to be assigned a specific number of parking spaces in advance to ensure that they could secure a spot when needed. The reservation system had to be integrated with the monitoring system to ensure that drivers could find available spaces.

The system also needed to be self-sufficient, with automated gate and barrier control to regulate access to parking facilities. It had to be capable of managing multiple parking facilities simultaneously, ensuring that drivers could access the system from different locations. And it had to be able to function without human intervention, reducing the need for manual oversight.

Moreover, the system had to be scalable and flexible, with a distributed architecture that could handle large volumes of data and a growing number of users. It had to support additional number of communities and parking facilities, ensuring that it could adapt to changing requirements. For the system to be effective, modularity was essential, allowing for easy updates and integration of new features as needed.

Security and availability were critical requirements for the system, ensuring that the system was robust and resilient against cyber threats and service interruptions. Interoperability was crucial to ensure compatibility with existing and future smart city infrastructure.

Finally, the user interface had to be intuitive and user-friendly, with mobile accessibility for drivers and web-based interfaces for facility managers and city administrators. And accessibility features were needed to support users with disabilities, ensuring that the system was inclusive and accessible to all.

11. DESIGN

TODO: Write this chapter

12. IMPLEMENTATION

TODO: Write this chapter

13. TESTING

TODO: write this chapter

Part V

Results

Part VI

Conclusions

14. CONCLUSIONS

TODO: write this chapter

15. FUTURE WORK

TODO: write this chapter

16. SOCIO-ECONOMIC ENVIRONMENT

TODO: write this chapter

17. REGULATORY FRAMEWORK

TODO: Write this chapter

BIBLIOGRAPHY

[1] Irene Lebrusán and Jamal Toutouh. "Assessing the Environmental Impact of Car Restrictions Policies: Madrid Central Case". In: *Smart Cities*. Ed. by Sergio Nesmachnow and Luis Hernández Callejo. Cham: Springer International Publishing, 2020, pp. 9–24. ISBN: 978-3-030-38889-8.

[2] Raquel Fernández-González et al. "Urban mobility trends and climate change: sustainability policies in the parking industry". In: *Environmental Science and Pollution Research* 30 (May 2023), pp. 1–14. DOI: 10.1007/s11356-023-26925-2.

[3] A. Ibeas et al. "Modelling parking choices considering user heterogeneity". In: *Transportation Research Part A: Policy and Practice* 70 (2014), pp. 41–49. ISSN: 0965-8564. DOI: https://doi.org/10.1016/j.tra.2014.10.001. URL: https://www.sciencedirect.com/science/article/pii/S0965856414002341.

[4] Fredrik Dahlqvist et al. "Growing opportunities in the Internet of Things". In: *McKinsey & Company* 22 (2019).

[5] Symeon Papavassiliou Eirini Eleni Tsiropoulou John S. Baras and Surbhit Sinha. "RFID-based smart parking management system". In: *Cyber-Physical Systems* 3.1-4 (2017), pp. 22–41. DOI: 10.1080/23335777.2017.1358765. eprint: https://doi.org/10.1080/23335777.2017.1358765. URL: https://doi.org/10.1080/23335777.2017.1358765.

[6] M. Venkata Sudhakar et al. "Development of smart parking management system". In: *Materials Today: Proceedings* 80 (2023). SI:5 NANO 2021, pp. 2794–2798. ISSN: 2214-7853. DOI: https://doi.org/10.1016/j.matpr.2021.07.040. URL: https://www.sciencedirect.com/science/article/pii/S2214785321048926.

[7] H. Al-Kharusi and I. Al-Bahadly. "Intelligent Parking Management System Based on Image Processing". In: *World Journal of Engineering and Technology* 2 (2014), pp. 55–67. DOI: 10.4236/wjet.2014.22006.

[8] Amira A. Elsonbaty and Mahmoud Shams. "The Smart Parking Management System". In: *International Journal of Computer Science and Information Technology* 12.4 (Aug. 2020), pp. 55–66. ISSN: 0975-4660. DOI: 10.5121/ijcsit.2020.12405. URL: http://dx.doi.org/10.5121/ijcsit.2020.12405.

[9] Adel Mounir Said, Ahmed E. Kamal, and Hossam Afifi. "An intelligent parking sharing system for green and smart cities based IoT". In: *Computer Communications* 172 (2021), pp. 10–18. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2021.02.017. URL: https://www.sciencedirect.com/science/article/pii/S0140366421000864.

[10] Paul Melnyk, Soufiene Djahel, and Farid Nait-Abdesselam. "Towards a Smart Parking Management System for Smart Cities". In: *2019 IEEE International Smart Cities Conference (ISC2)*. 2019, pp. 542–546. DOI: 10.1109/ISC246665.2019.9071740.

[11] International Council on Systems Engineering. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. 4th. Hoboken, NJ: Wiley, 2015. URL: https://www.incose.org/products-and-publications/se-handbook.

[12] Alastair Ruddle. *Simplified System Engineering 'V' Model*. https://www.researchgate.net/figure/Simplified-system-engineering-V-model_fig1_338672391. Accessed: 2024-10-15. 2020.

[13] Rui José and Helena Rodrigues. "A Review on Key Innovation Challenges for Smart City Initiatives". In: *Smart Cities* 7.1 (2024), pp. 141–162. ISSN: 2624-6511. DOI: 10.3390/smartcities7010006. URL: https://www.mdpi.com/2624-6511/7/1/6.

[14] General Data Protection Regulation GDPR. "General data protection regulation". In: *Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC* (2016).