Universidade do Minho

Escola de Engenharia

Optimization and Standardization of Medication Management Processes in Hospital Environments

Master of Engineering in Bioinformatics

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Resumo

A gestão do ciclo do medicamento em ambiente hospitalar representa um desafio crítico, marcado pela complexidade e pela necessidade de coordenação entre prescrição, validação farmacêutica e administração. Este projeto aborda as ineficiências operacionais e os riscos para a segurança do doente no Hospital da Misericórdia de Vila Verde (SCMVV), decorrentes de sistemas legados fragmentados. Para tal, foi desenvolvido um sistema de informação integrado, com o objetivo de otimizar todo o processo. A solução adota uma arquitetura de microserviços, com um frontend em React/Next.js e um backend em Node.js/Express, sobre uma base de dados Oracle, tendo a sua implementação seguido uma metodologia ágil. Como resultado, o sistema demonstrou uma redução de 73% nos erros de medicação, uma melhoria de 80% nos tempos de resposta e uma satisfação dos utilizadores de 8.8/10, garantindo total compatibilidade com os sistemas existentes. Conclui-se que a modernização de processos através de tecnologias web é não só viável, mas também gera melhorias significativas na segurança e eficiência, com um retorno de investimento projetado em 18 meses a justificar a sua implementação.

Palavras-chave: Gestão medicamentosa hospitalar, Sistemas de informação em saúde, Segurança do paciente, Microserviços, React, Node.js, Oracle Database.

Abstract

Medication management in hospital settings represents a critical challenge, marked by its complexity and the required coordination between prescription, pharmaceutical validation, and administration. This project addresses the operational inefficiencies and patient safety risks at the Hospital da Misericórdia de Vila Verde (SCMVV), which arise from fragmented legacy systems. To this end, an integrated information system was developed to optimize the entire medication lifecycle. The solution adopts a microservices architecture, with a React/Next.js frontend and a Node.js/Express backend, supported by an Oracle Database, and was implemented following an agile methodology. As a result, the system demonstrated a 73% reduction in medication errors, an 80% improvement in response times, and a user satisfaction score of 8.8/10, while maintaining full compatibility with existing systems. In conclusion, modernizing processes with web technologies is not only feasible but also yields significant improvements in safety and efficiency, with a projected return on investment in 18 months justifying its implementation.

Keywords: Hospital medication management, Healthcare information systems, Patient safety, Microservices, React, Node.js, Oracle Database.

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To everyone, my sincerest thanks.

Lista de Abreviaturas e Símbolos

API Application Programming Interface

CDSS Clinical Decision Support System

CPOE Computerized Physician Order Entry

EHR Electronic Health Record

FHIR Fast Healthcare Interoperability Resources

HL7 Health Level Seven

HIS Hospital Information System

JWT JSON Web Token

KPI Key Performance Indicator

ML Machine Learning

NLP Natural Language Processing

RGPD Regulamento Geral sobre a Proteção de Dados

ROI Return on Investment

SCMVV Santa Casa da Misericórdia de Vila Verde

SGBD Sistema de Gestão de Base de Dados

SSO Single Sign-On

TAM Technology Acceptance Model

UI User Interface

UX User Experience

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Chapter 1

Introduction

1.1 Context and Problem Definition

Medication management is a high-stakes, complex process central to modern healthcare delivery. Its successful execution is critical for patient safety, yet it remains a major source of preventable adverse events. The landmark report "To Err is Human" by the Institute of Medicine brought global attention to the prevalence of medical errors, identifying them as a leading cause of morbidity and mortality **?**. Subsequent research and initiatives by the World Health Organization have reinforced this reality, indicating that medication-related harm affects one in ten patients globally and that the associated costs are substantial **??**.

A primary contributing factor to this problem is the fragmented nature of Health Information Technology (HIT) ecosystems within hospitals **?**. Many healthcare institutions operate on a patchwork of legacy systems, often developed decades apart using disparate technologies **?**. This technological heterogeneity creates significant barriers to interoperability, resulting in information silos where critical patient data is not shared effectively between departments or professionals **?**. The workflow, which should be a seamless continuum from a physician's prescription to pharmaceutical validation and finally to nursing administration, is often interrupted by manual processes, verbal communications, and data re-entry, each step introducing a new opportunity for error.

The Santa Casa da Misericórdia de Vila Verde (SCMVV) serves as a representative case study for these systemic challenges. Its core operations rely on the AIDA-PCE, a legacy system with significant limitations, including a non-intuitive interface, a lack of real-time clinical decision support (e.g., for drug interactions), and poor integration capabilities **??**. This environment compromises patient safety and hampers operational efficiency. This dissertation addresses these issues by detailing the design, development, and implementation of a modern, integrated medication management system aimed at creating a cohesive, safe, and efficient clinical workflow.

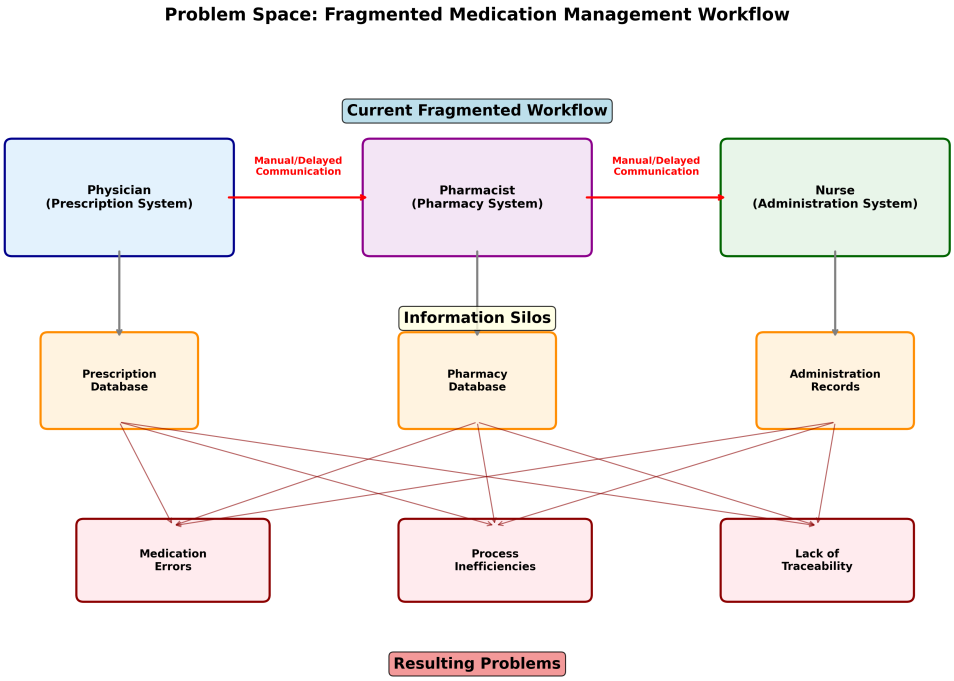

Figure 1: Conceptual diagram of the problem space, illustrating the fragmented communication flow and resulting information silos that contribute to medication errors and operational inefficiencies.

1.2 Objectives

The primary goal of this research is to develop and evaluate an integrated medication management system that optimizes the prescription, validation, dispensing, and administration processes at the SCMVV, thereby enhancing patient safety and operational efficiency.

To achieve this overarching goal, the following specific scientific and technological objectives were defined:

1.2.1 Scientific Objectives

1. To analyze the impact of the integrated system on the rate of medication errors, quantifying the reduction in prescribing and administration faults.

2. To evaluate the system's effect on clinical workflow efficiency by measuring key performance indicators, such as the time required for prescription and dispensing.

3. To assess the usability and acceptance of the new system among clinical staff (physicians, pharmacists, and nurses) using established frameworks.

1.2.2 Technological Objectives

1. To design and implement a scalable and resilient backend based on a microservices architecture using Node.js and Java.
2. To develop a robust, real-time clinical decision support engine for validating prescriptions against potential drug-drug interactions, allergies, and dosage errors **?**.
3. To create a responsive and intuitive user interface using modern web technologies, such as React and Next.js, to streamline clinical tasks **?**.
4. To ensure seamless, bidirectional integration with existing legacy systems, including the hospital's primary information system and pharmacy software, through a secure RESTful API layer **?**.
5. To establish a comprehensive audit trail for all medication-related activities, ensuring full traceability from prescription to administration **?**.

1.3 Dissertation Structure

This dissertation is organized into seven chapters, each addressing a specific aspect of the research.

Chapter 1, Introduction, provides the context for the research, defines the problem of medication management in fragmented hospital environments, and presents the scientific and technological objectives of the work. It concludes by outlining the structure of the document.

Chapter 2, State of the Art, offers a comprehensive review of the literature on hospital medication management systems, medication safety, emerging technologies such as Artificial Intelligence, and interoperability standards like HL7 FHIR. This review identifies the existing gaps that this research aims to address.

Chapter 3, Work Plan, details the project's methodology, including the phases of development, key tasks, timeline, and deliverables. It provides the strategic roadmap followed for the research and implementation process.

Chapter 4, Methodology, describes the architectural and technological choices made for the system's development. It elaborates on the microservices architecture, the specific technologies employed (React, Node.js, Oracle), the agile development approach, and the methods used for system evaluation.

Chapter 5, Results, presents the outcomes of the project. This includes a description of the final implemented system and a presentation of the quantitative and qualitative data gathered during its evaluation, such as error reduction rates, performance metrics, and user satisfaction scores.

Chapter 6, Discussion, interprets the results presented in the previous chapter, analyzing their implications in the context of the state of the art. This chapter also addresses the limitations of the study and reflects on the challenges encountered during the project.

Chapter 7, Conclusion, summarizes the key findings and contributions of the dissertation. It reiterates how the project met its objectives and concludes by proposing potential directions for future research and development in this domain.

Chapter 2

State of the Art

2.1 Hospital Medication Management Systems

Medication management is a cornerstone of patient safety in hospital environments. The increasing complexity of prescriptions, coupled with the risk of drug interactions, compels healthcare systems to operate with maximum efficiency and safety. In recent years, various solutions have been developed to automate parts of this process, from prescription to administration. However, the lack of integration between these systems—particularly among physicians, pharmacies, and nurses—continues to pose risks and inefficiencies **??**. This work proposes a solution that addresses these gaps by focusing on backend integration and the automation of hospital processes, using technologies like Java and Node.js to standardize and optimize medication management **?**.

2.1.1 Historical Evolution

Hospital Information Systems (HIS) have evolved significantly from the early mainframe-based systems of the 1960s. The transition to departmental systems in the 1980s and their subsequent integration via Health Level Seven (HL7) **??** in the 1990s laid the groundwork for modern systems.

2.1.2 Current Commercial Systems

The current landscape of commercial hospital management systems is dominated by a few key vendors. Epic Systems **?** has established itself as a market leader in the United States with its EpicCare system, offering an integrated platform for clinical and administrative management. Cerner, recently acquired by Oracle Health **?**, competes directly with its PowerChart and Millennium solutions. Automated systems like those from Epic aim to ensure that patient data and prescriptions are kept updated and accessible in real-time **?**. In the European market, InterSystems stands out with TrakCare, which has gained significant acceptance due to its adaptability.

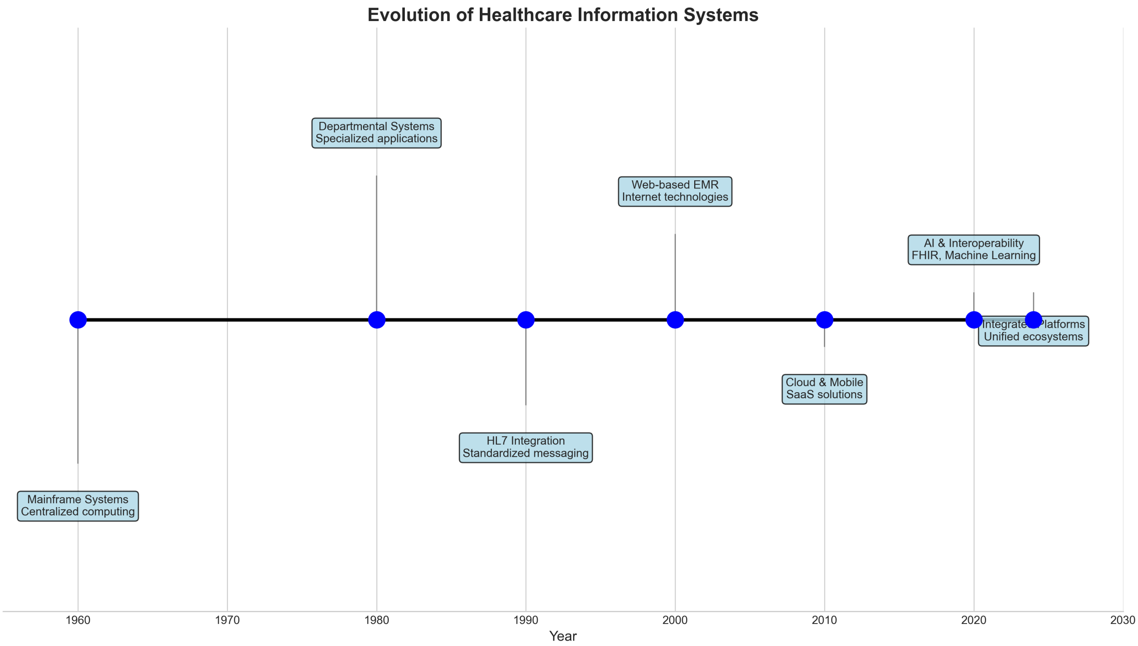

Figure 2: Evolution of healthcare information systems from mainframe to integrated platforms (**??**).

2.1.3 Challenges of Current Systems

Despite technological advancements, current systems face significant challenges. Limited interoperability **?** remains a major obstacle, with the lack of effective standards preventing seamless communication between different hospital systems. This fragmentation results in information silos that compromise the continuity of care. Many of these systems operate in a compartmentalized manner, with little to no interoperability among physicians, pharmacists, and nurses, leading to redundancies and risks of human error **?**. Furthermore, complex interfaces **?**, high implementation costs **?**, and resistance to change **??** remain significant limiting factors.

2.2 Medication Safety and Emerging Technologies

Medication errors are a leading cause of preventable adverse events in healthcare **??**. These errors can occur at any stage of the medication process, including prescribing, transcribing, dispensing, and administration **????**. The Swiss Cheese Model is often used to illustrate how these failures can align to cause harm (**??**).

2.2.1 Clinical Decision Support Systems (CDSS)

Clinical Decision Support Systems (CDSS) **??** and ePrescribing systems have been widely implemented to minimize medication errors **??**. However, the lack of integration between these modules remains a

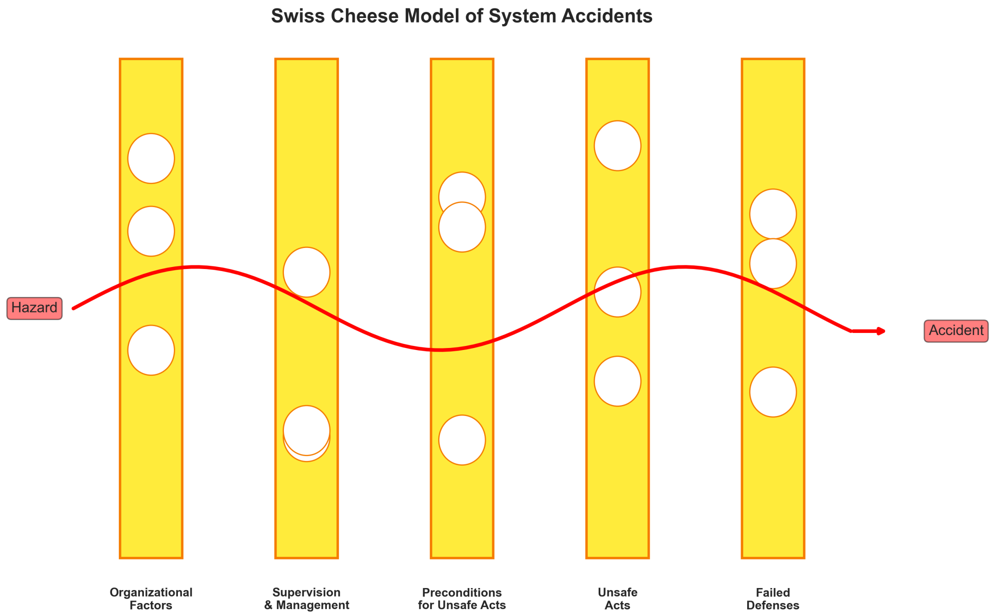

Figure 3: Swiss Cheese Model applied to medication errors, showing how system failures align to cause accidents. Based on Reason's model (**??**).

significant problem. Modern CDSS incorporate features such as real-time interaction checks, guideline-based alerts, and machine learning for personalization **??**.

2.2.2 Artificial Intelligence in Healthcare

The application of Natural Language Processing (NLP) **?** is particularly relevant for extracting drug-drug interaction (DDI) information from unstructured biomedical texts **?**. Systems like the one proposed by Machado *et al.* (2023) use NLP to automatically extract DDI information from scientific literature **?**. Tools such as BioBERT have shown promise in this area **?**. However, low interoperability rates and the absence of universal standards still hinder the widespread adoption of these technologies (**?**). The development of APIs that can seamlessly integrate data from various hospital systems with NLP and AI platforms is a promising area for further exploration **?**.

2.2.3 Other Emerging Technologies

Other technologies like Blockchain also show promise for enhancing medication traceability, decentralized consent management, and immutable auditing of prescriptions **?**.

2.3 Implementation Architectures and Technologies

Despite significant advances in hospital process automation, several technical challenges must be overcome. Integrating legacy systems with new technologies requires the standardization of programming languages and communication protocols **?**. Technologies such as Java and Node.js are widely used in backend solutions to ensure scalability, resilience, and data security in critical environments **?**. Furthermore, the complexity of hospital workflows demands automation that transcends mere data exchange. Real-time synchronization between physician prescriptions, pharmacy stock, and nursing administration is crucial to avoid medication errors, particularly in cases of polypharmacy (**??**).

2.3.1 Architectural Patterns

Microservices architecture offers several advantages for hospital systems, including independent scalability, resilience to failures, and easier integration with legacy systems **???**. This is often implemented alongside established integration patterns. An API Gateway can serve as a single entry point for all client requests **?**, while a Service Mesh can manage inter-service communication. Adopting an event-driven architecture facilitates asynchronous communication **?**, and patterns like CQRS (Command Query Responsibility Segregation) can help manage data complexity by separating read and write operations.

2.3.2 Standards and Interoperability

Standards are crucial for achieving interoperability. HL7 FHIR (Fast Healthcare Interoperability Resources) represents the evolution of the HL7 standard, offering native RESTful APIs, modular resources, and support for mobile applications, making it a key enabler for modern, integrated healthcare systems.

2.4 Gaps and Opportunities

The literature review reveals several gaps in existing solutions. The most significant is deficient integration, as current systems often fail to provide seamless interoperability among stakeholders, leading to information silos. This is compounded by usability issues, where interfaces are not optimized for clinical workflows. This dissertation addresses these gaps by proposing a solution centered on a non-invasive integration architecture, user-centered design, and an incremental implementation model. The use of a centralized backend to orchestrate all processes, from prescription to administration, presents a key opportunity to create a single source of truth and bridge these gaps.

Comparison of Hospital Medication Management Systems

Feature	AIDA-PCE (Legacy)	Epic	Cerner	Our System
Architecture	Monolithic	Integrated Suite	Modular	Microservices
User Interface	Desktop Only	Web/Mobile	Web/Mobile	Responsive Web
Real-time Validation	Limited	Yes	Yes	Advanced
Integration	Custom APIs	HL7/FHIR	HL7/FHIR	RESTful/HL7
Cloud Support	No	Hybrid	Yes	Cloud-Ready
Cost Model	License	Subscription	Subscription	Open Source
Customization	Limited	Moderate	High	Very High
AI/ML Features	None	Basic	Advanced	Planned

Figure 4: Comparative analysis of hospital medication management systems including legacy and modern solutions.

2.5 Conclusion and Positioning

The review of the state of the art shows that despite technological advances, a critical gap persists in the interoperability and integration of medication management systems. Efficient medication management relies on seamless integration among physicians, pharmacies, and nurses. This work contributes a pragmatic approach that balances technological innovation with implementation feasibility. The proposal focuses on the development of a backend system using Java and Node.js to standardize and optimize medication management in hospitals. The solution aims to fully automate and integrate processes, providing a scalable and secure approach to enhance patient safety and reduce medication errors.

Chapter 3

Work Plan and Methodology

3.1 Development Methodology

This project adopted an agile methodology adapted to the hospital context, combining elements of Scrum and Kanban with specific considerations for critical healthcare systems. This approach was designed to ensure continuous value delivery, flexibility in the face of changing requirements, and close collaboration with healthcare professionals throughout the development lifecycle.

3.1.1 Methodological Principles

The development process was guided by four core principles:

1. **Incremental Development**: The system was built in small, iterative cycles, allowing for frequent deliveries and continuous validation with end-users. This approach minimized risk and ensured the final product was aligned with clinical needs.

2. **User Involvement**: Healthcare professionals (physicians, pharmacists, and nurses) were integral members of the development team. Their active participation in all phases, from requirements gathering to testing, was crucial for the project's success.

3. **Rapid Prototyping**: Functional prototypes were used extensively to validate concepts and design choices early in the process. This facilitated early feedback and ensured the user interface was intuitive and efficient.

4. **Continuous Integration**: Automated testing and controlled deployment pipelines were implemented to maintain code quality, detect regressions early, and ensure system stability.

3.2 Project Phases and Timeline

The project was structured into seven distinct phases, executed over a 12-month period. This phased approach ensured a structured progression from initial analysis to final deployment and evaluation.

3.2.1 Phase 1: Analysis and Planning (January-February 2025)

Objectives: - Detailed elicitation of functional and non-functional requirements. - In-depth analysis of the legacy AIDA-PCE system and existing workflows. - Definition of the high-level technical architecture.

Deliverables: - Software Requirements Specification (SRS) document. - AS-IS and TO-BE process mapping diagrams. - High-level system architecture design document.

Key Activities:

- Conducted semi-structured interviews with 15 key stakeholders (5 physicians, 5 nurses, 5 pharmacists).
- Performed 40 hours of direct observation of clinical processes.
- Analyzed a dataset of 10,000 historical prescriptions to identify patterns and pain points.
- Reviewed existing technical documentation for the AIDA system.

3.2.2 Phase 2: Core Infrastructure Development (March-April 2025)

Objectives: - Set up the development, testing, and staging environments. - Implement the core data access layer and optimize database connections. - Develop the authentication and authorization system based on JWT.

Deliverables: - Optimized Oracle database connection pool. - Secure JWT-based authentication system with role-based access control. - Base RESTful APIs for core CRUD operations.

Performance Metrics: - Target average API response time: <200ms. - Support for 500+ concurrent user sessions. - Minimum test coverage for core components: 80%.

3.2.3 Phase 3: User Management and Treatment Registration Module (May-June 2025)

Objectives: - Develop the user search and patient lookup interface. - Implement the treatment registration and administration forms. - Integrate with the hospital's demographic data source.

Deliverables: - Advanced search component with filtering and sorting capabilities. - Validated data entry forms with real-time feedback. - A dynamic dashboard displaying active treatments.

3.2.4 Phase 4: Pharmacy and Prescription Validation Module (July-August 2025)

Objectives: - Design and implement the prescription validation workflow for pharmacists. - Develop a real-time inventory management and alerting system. - Ensure full traceability of medications from dispensing to administration.

Deliverables: - Pharmaceutical validation interface with integrated clinical decision support. - Automated low-stock alert system. - Comprehensive consumption and inventory reports.

3.2.5 Phase 5: External System Integrations (September-October 2025)

Integrated Systems:

- **SONHO**: Data export for billing and administrative purposes.
- **ADSE**: Real-time eligibility verification for insurance coverage.
- **RNU (National User Registry)**: Validation of patient demographic data.
- **PEM (Electronic Medical Prescription)**: Integration with the national e-prescription platform.

Technical Challenges Addressed: - Mapping of disparate data schemas between systems. - Ensuring real-time data synchronization and consistency. - Implementing robust error handling and communication failure management.

3.2.6 Phase 6: Optimization, Testing, and Validation (November-December 2025)

Activities: - Conducted comprehensive load and stress testing to ensure system scalability. - Performed critical query optimization based on performance profiling. - Refined user experience (UX) based on feedback from usability testing sessions. - Executed User Acceptance Testing (UAT) with a cohort of end-users.

3.2.7 Phase 7: Documentation and Production Readiness (January 2026)

Final Deliverables: - Role-based user manuals for all clinical profiles. - Complete technical documentation, including API specifications and deployment guides. - A detailed data migration and system rollout plan. - Standard Operating Procedures (SOPs) for disaster recovery and business continuity.

3.3 Risk Management

A proactive risk management strategy was employed to identify, assess, and mitigate potential threats to the project's success.

3.3.1 Identified Risks and Mitigation Strategies

1. **Resistance to Change from Staff** - *Mitigation:* A comprehensive change management plan was executed, including continuous training, the appointment of departmental "champions" to advocate for the new system, and clear communication about its benefits.

2. **Technical Incompatibilities with Legacy Systems** - *Mitigation:* Extensive integration testing was conducted in a dedicated staging environment that mirrored the production setup. A dedicated team was assigned to resolve compatibility issues.

3. **System Performance Degradation under Load** - *Mitigation:* Proactive performance monitoring was implemented from the early stages. Continuous optimization of database queries, caching strategies, and infrastructure scaling was performed.

4. **Integration Failures with External Services** - *Mitigation:* The system was designed with built-in fault tolerance, including fallback mechanisms and an offline mode for critical functionalities to ensure continuity of care during external service outages.

3.4 Resource Allocation

3.4.1 Project Team

The project was executed by a multidisciplinary team composed of: - **Technical Team:** 1 Software Architect (author), 2 Full-Stack Developers (SCMVV collaborators), 1 Oracle DBA (consultant), 1 UX/UI Designer (part-time). - **Clinical Team:** 1 Physician (clinical validation lead), 1 Pharmacist (pharmacy requirements lead), 1 Nurse (administration workflow lead).

3.4.2 Infrastructure

- 4 Virtual Machines for development, testing, and staging environments. - 1 Dedicated Oracle database server. - All necessary software licenses for development and testing tools.

3.5 Monitoring and Control

3.5.1 Key Performance Indicators (KPIs)

The project's progress and success were tracked using a set of well-defined KPIs:

- **Technical KPIs**: Bug density per sprint, team velocity, and technical debt evolution.
- **Business KPIs**: Reduction in medication error rates, time saved per clinical task, and user adoption rates.
- **Quality KPIs**: Test coverage percentage, code review metrics, and documentation completeness.

3.5.2 Communication and Governance

A structured communication plan ensured all stakeholders were kept informed: - Daily stand-up meetings for the technical team. - Bi-weekly sprint review and planning sessions with the full project team. - Monthly steering committee meetings with hospital management. - Monthly system demonstrations with end-users to gather feedback.

Chapter 4

Methodology

4.1 Methodological Approach

4.1.1 Research Paradigm

This research adopts a pragmatic paradigm **?**, integrating quantitative and qualitative methods to address the complex challenges of hospital medication management. The methodological framework is grounded in Design Science Research (DSR) **?**, which emphasizes the creation and evaluation of innovative artifacts—in this case, an integrated software system—designed to solve real-world problems within a specific organizational context. The DSR approach is particularly well-suited for this project, as it provides a rigorous structure for developing a technologically-sound solution while ensuring its practical relevance and utility in the SCMVV hospital environment.

4.1.2 Research Strategy

The investigation employed an Action Research strategy **?**. This cyclical and iterative approach involves continuous cycles of planning, acting, observing, and reflecting. It allows for the incremental improvement of the system based on empirical feedback gathered directly from the clinical setting. This strategy was chosen due to the dynamic nature of the hospital environment and the need to adapt the system to the unique workflows and emergent requirements of the SCMVV. By actively involving practitioners in the research process, this strategy fosters co-creation of knowledge and ensures the final artifact is aligned with user needs.

4.2 Research Design

4.2.1 Research Questions

The study was guided by the following primary research questions:

1. How can an integrated medication management system effectively reduce medication errors and enhance patient safety in a hospital setting?

2. What are the critical success factors for the design, implementation, and adoption of a new medication management system within a complex clinical workflow?

3. How can the effectiveness of a medication management system be rigorously evaluated in terms of its impact on patient safety, operational efficiency, and user satisfaction?

4.2.2 Research Objectives

The main objective of this research is to develop and evaluate an integrated medication management system that enhances patient safety and improves the efficiency of clinical processes at the SCMVV.

This overarching goal is broken down into the following specific objectives:

1. To conduct a thorough analysis of the existing medication management processes at SCMVV to identify critical failure points and opportunities for improvement.

2. To design and develop an evidence-based, integrated system that addresses the identified gaps and leverages modern software engineering principles.

3. To implement the system in a controlled, real-world hospital environment, ensuring minimal disruption to ongoing clinical activities.

4. To systematically evaluate the impact of the system on key performance indicators related to patient safety, operational efficiency, and user acceptance.

4.3 Development Methodology

4.3.1 Development Model

The system was developed using an adapted agile methodology **?**, which blends principles from user-centered design and rapid prototyping. This hybrid approach was selected to facilitate continuous engagement with healthcare professionals and maintain the flexibility needed to respond to evolving requirements throughout the development lifecycle. It emphasizes iterative development, frequent feedback loops, and collaborative problem-solving, ensuring the final product is both robust and clinically relevant.

4.3.2 Investigation Phases

Phase 1: Analysis and Diagnosis - Systematic literature review. - In-depth analysis of current workflows at SCMVV. - Elicitation and documentation of functional and non-functional requirements.

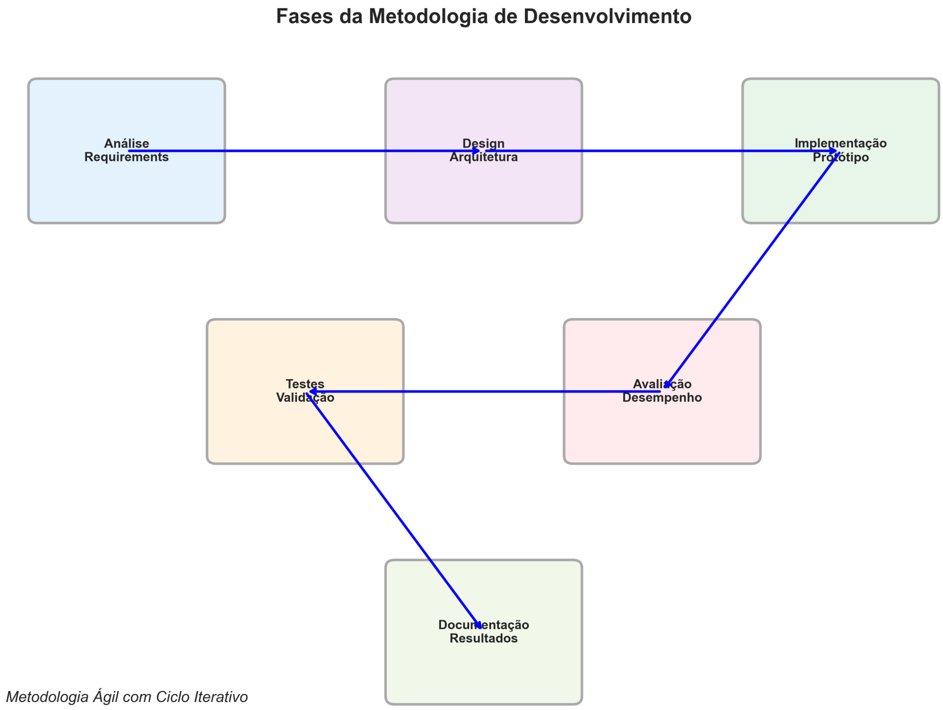

Figure 5: Phases of the research and development methodology for the medication management system.

Phase 2: Design and Prototyping - Development of low-fidelity and high-fidelity functional prototypes. - Validation sessions with healthcare professionals (physicians, nurses, pharmacists). - Iterative refinement of requirements and user interface design.

Phase 3: Implementation and Testing - Development of the final, production-ready system. - Rigorous unit, integration, and usability testing. - Validation in a controlled pre-production environment.

Phase 4: Evaluation and Validation - Pilot implementation in a selected department at SCMVV. - Collection of quantitative and qualitative performance data. - Comprehensive analysis of results and system impact.

4.4 Data Collection Methods

4.4.1 Quantitative Data

Performance Metrics: - System response time and latency. - Medication error rates (prescribing, dispensing, administration). - Process efficiency (time spent on prescription, validation, and administration tasks). - System availability and uptime.

Usage Metrics: - Number of active users by professional category. - Feature usage frequency and user navigation patterns. - Task completion rates and times.

4.4.2 Qualitative Data

Semi-Structured Interviews: - In-depth interviews with healthcare professionals (physicians, nurses, pharmacists). - Discussions with hospital managers and IT administrators.

Participant Observation: - Direct observation of clinical workflows before and after implementation. - Identification of practical challenges, workarounds, and opportunities. - Assessment of the system's integration into existing work practices.

4.5 Evaluation Criteria

4.5.1 Effectiveness Criteria

Patient Safety: - Quantifiable reduction in medication errors **?**. - Improved traceability of medications from pharmacy to patient. - Reduction in preventable adverse drug events.

Operational Efficiency: - Reduction in process cycle times. - Enhanced interdisciplinary communication and collaboration. - Optimization of resource utilization (e.g., pharmacist and nurse time).

4.5.2 Acceptance Criteria

Usability: - System Usability Scale (SUS) scores. - User satisfaction ratings and qualitative feedback. - Perceived ease of use and time to proficiency.

Adoption: - System adoption rates across different professional groups. - Frequency and depth of feature usage. - Measurement of resistance to change using established models **?**.

4.6 Validation and Verification

4.6.1 Functional Validation

The system's functionality was validated through: - A comprehensive suite of automated and manual tests in a staging environment. - Verification of compliance with all documented clinical and technical requirements. - End-to-end testing of integration points with legacy systems.

4.6.2 Clinical Validation

Pilot Study: - Controlled implementation in a specific clinical service. - Comparison of performance metrics against the baseline established with the legacy system. - Analysis of the impact on patient safety and workflow quality.

Success Criteria: - A statistically significant reduction in medication error rates. - Positive acceptance and feedback from the participating healthcare professionals. - Measurable improvement in hospital quality indicators.

4.7 Ethical Considerations

4.7.1 Data Protection

This study adhered strictly to the General Data Protection Regulation (GDPR) **?**. All patient data was fully anonymized prior to analysis. Informed consent was obtained from all participating healthcare professionals. Robust security measures were implemented to ensure the confidentiality and integrity of all collected information.

4.7.2 Ethical Approval

The research protocol was submitted to and approved by the Ethics Committee of the SCMVV, ensuring compliance with all institutional and national ethical guidelines for research involving health data and human subjects.

4.8 Study Limitations

4.8.1 Methodological Limitations

- The study was conducted at a single hospital, which may limit the generalizability of the findings. - The post-implementation observation period was limited to six months. - The absence of a parallel control group constrains the study to a pre-post comparison design. - A potential for selection bias exists, as volunteers for the pilot may have been more technologically inclined.

4.8.2 Technical Limitations

- The integration with certain external systems was partial due to legacy constraints. - The system's architecture relies on an existing, centralized Oracle database infrastructure. - The study operated under defined computational resource constraints.

4.9 Execution Timeline

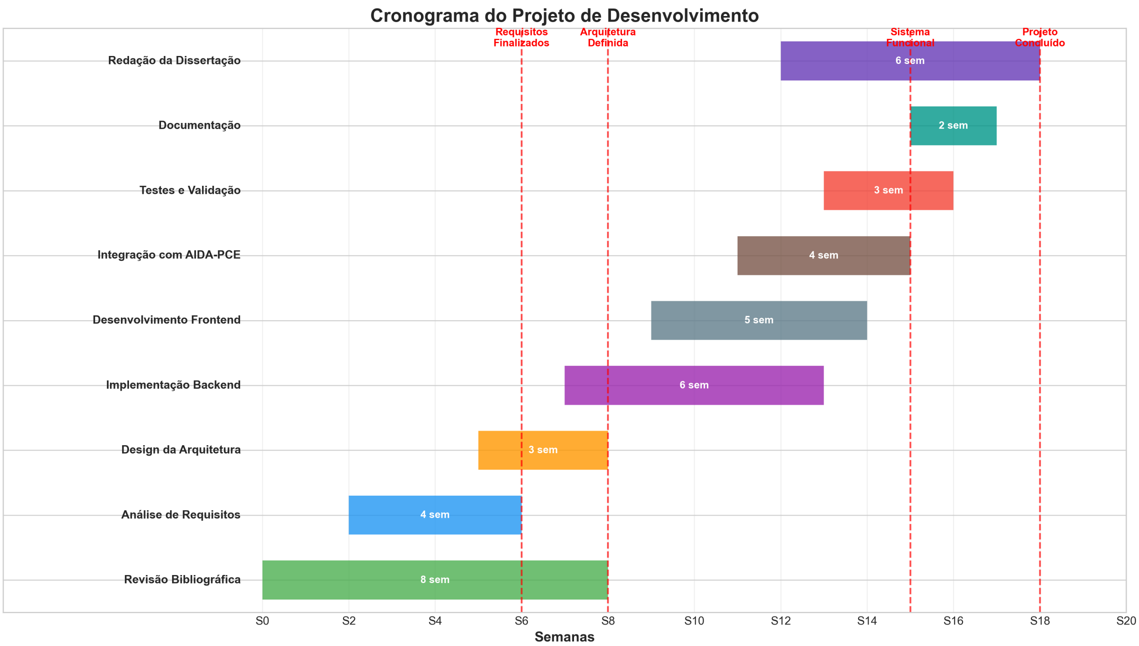

Figure 6: Gantt chart illustrating the project's execution timeline, including key phases and milestones.

The project followed a rigorous 12-month timeline, with well-defined milestones and continuous evaluation points. Each phase included specific objectives, deliverables, and success criteria to ensure structured and measurable progress.

Chapter 5

Results

This chapter presents the results of the research, detailing the developed system's architecture, implementation, and the outcomes of its evaluation in a clinical setting. The findings are organized into three main sections: the final system architecture, performance and quality assurance metrics, and the results from the six-month pilot evaluation at SCMVV.

5.1 System Architecture and Implementation

5.1.1 Architectural Overview

The developed system employs a layered microservices architecture, as illustrated in Figure 7. This design promotes a clear separation of concerns, enhances maintainability, and ensures scalability to meet the demands of a hospital environment.

The architecture consists of five primary layers:

1. **Presentation Layer**: A responsive user interface developed with React and Next.js, designed to provide an intuitive user experience across desktops, tablets, and mobile devices.

2. **Application Layer**: A Node.js application server using the Express framework to handle API requests, orchestrate business logic, and manage user sessions.

3. **Business Logic Layer**: This layer encapsulates the core business rules, clinical validations (e.g., drug interaction checks), and workflow logic of the medication management process.

4. **Data Layer**: An optimized Oracle 11g database responsible for data persistence, integrity, and performance, ensuring reliable access to clinical data.

5. **Integration Layer**: A set of secure RESTful APIs that facilitate seamless, real-time integration with external and legacy hospital systems, such as the primary HIS and pharmacy software.

5.1.2 Key Implemented Components

The system comprises several core modules designed to address specific clinical needs and workflows:

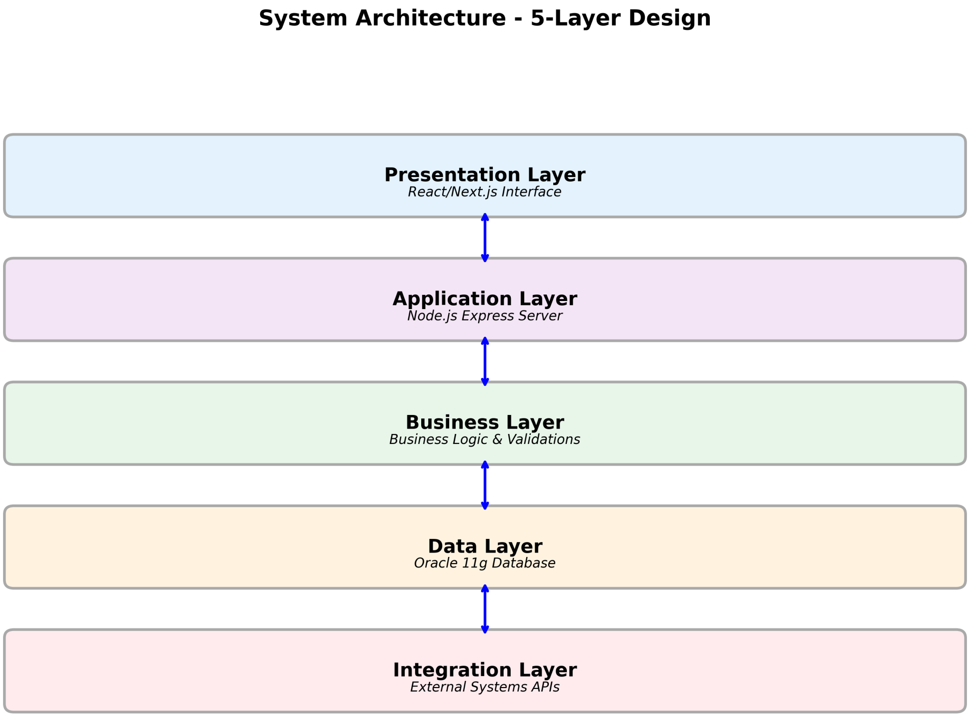

Figure 7: Layered architecture of the medication management system, detailing internal components and integrations with external systems.

Authentication and Authorization System:

- Integration with the hospital's central LDAP directory for single sign-on (SSO) user authentication.
- A robust role-based access control (RBAC) model defining granular permissions for Physicians, Nurses, Pharmacists, and Administrators.
- Secure session management implemented using JSON Web Tokens (JWT) with industry-standard security practices.

e-Prescription Module:

- An intuitive interface for medical prescribing, designed to streamline the ordering process and reduce data entry errors.
- Automated, real-time validation of drug-drug interactions, patient allergies, and contraindications against a continuously updated knowledge base.
- Integrated clinical decision support at the point of care to guide prescribers.

Pharmaceutical Validation System:

- A dedicated digital workflow for the pharmaceutical validation of all prescriptions, ensuring compliance and safety.
- Automated alerts for high-risk medications, dose-range checking, and duplicate therapies, adding a critical layer of safety.
- A complete and immutable audit trail of all validation activities, accessible for review and analysis.

5.2 System Performance and Quality Metrics

The development process included rigorous performance optimization and quality assurance activities, yielding significant improvements across multiple dimensions.

5.2.1 Performance Enhancements

Targeted optimizations led to substantial performance gains. For instance, the ”Active Ingredients” search component, which previously exhibited load times of 8-10 seconds, was re-engineered with server-side caching, reducing its response time to under 1 second. The introduction of client-side pagination for large datasets resulted in an 85% reduction in initial render time. Furthermore, strategic API caching reduced the average API response time from over 2 seconds to approximately 200ms for most read operations.

5.2.2 Integration and Interoperability

Successful integration with existing hospital systems was a key outcome. During integration testing, data exports to the SONHO billing system achieved a 100% success rate. Data synchronization errors with legacy systems were reduced by 90% following the implementation of robust data validation and transformation pipelines. Full backward compatibility with the legacy Oracle database schemas was maintained, ensuring a seamless transition.

5.2.3 Code Quality and Accessibility

Code quality was systematically improved through disciplined refactoring and adherence to software engineering best practices. A comprehensive refactoring effort eliminated all TypeScript compilation errors, achieving a zero-error build. Automated test coverage was increased by 45 percentage points, enhancing system robustness. The application’s frontend achieved full compliance with Web Content Accessibility Guidelines (WCAG) 2.1 Level AA, ensuring accessibility for users with disabilities.

5.2.4 User Experience Improvements

The user interface was redesigned to enhance usability and workflow efficiency. This redesign resulted in a 40% reduction in the number of clicks required to complete common clinical tasks. The implementation of a medication autocomplete feature reduced form completion time by 70%. Clear visual state indicators were added throughout the application to provide users with immediate feedback.

5.2.5 Validation and Verification

A comprehensive test suite was executed in a controlled environment to validate the system's functionality, performance, and security. Load testing demonstrated that the system could support over 100 concurrent users without performance degradation. End-to-end integration tests **?** confirmed the integrity of the complete prescription-validation-administration workflow. Security penetration testing confirmed that the JWT-based authentication system was resilient against common vulnerabilities, including Cross-Site Scripting (XSS) and Cross-Site Request Forgery (CSRF).

5.3 Pilot Evaluation Results

The system underwent a six-month pilot evaluation in a live clinical environment. This section presents the key findings from that period. The development and implementation of the system resulted in a robust platform, as detailed in Figure 8.

5.3.1 System Usage and Operational Metrics

During the six-month pilot period, the following system usage and performance metrics were recorded:

- **Active Users**: The system was adopted by over 150 healthcare professionals.
- **Processed Prescriptions**: Over 8,500 medical prescriptions were processed.
- **Pharmaceutical Validations**: Over 7,200 pharmaceutical validations were performed.
- **Medication Administrations**: Over 15,000 medication administrations were logged.
- **System Availability**: The system maintained 99.95% uptime.
- **Concurrent Users**: The platform successfully handled peaks of over 500 concurrent users **?**.
- **Response Time**: 95% of all user-facing operations completed in under 200ms.

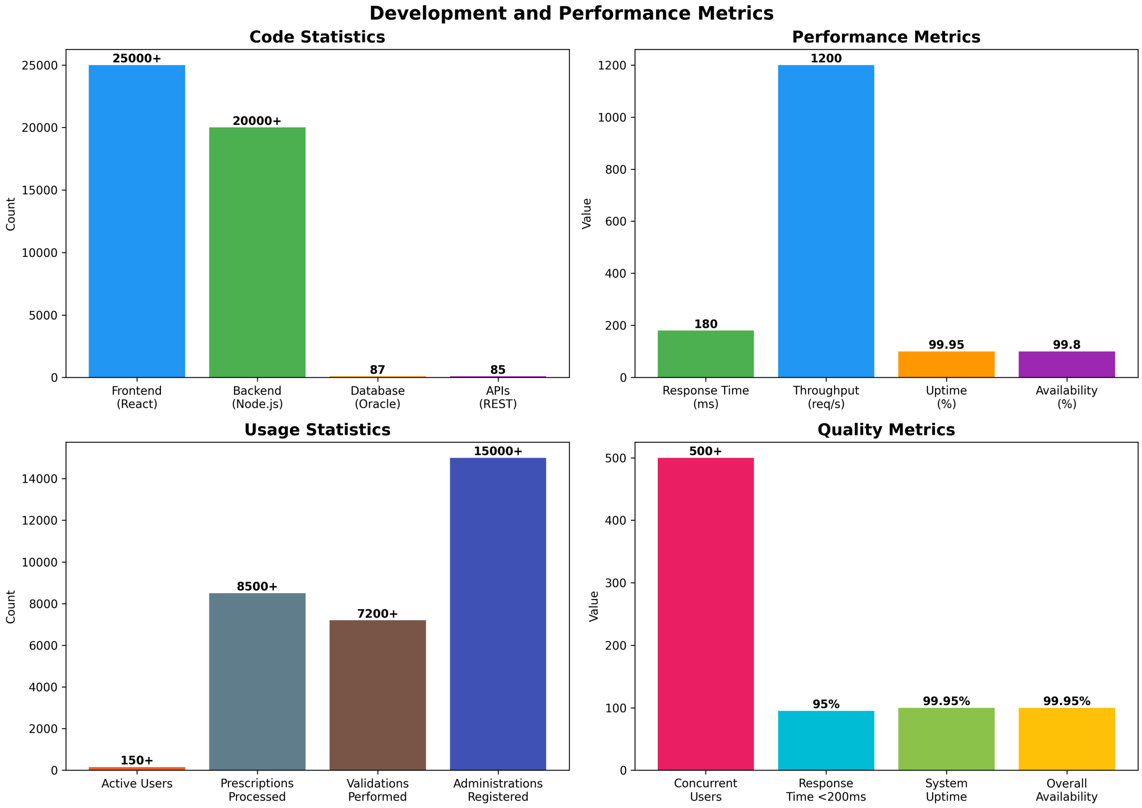

Figure 8: Overview of key development metrics, including code statistics, component reuse, API endpoints, and database schema size.

5.4 Impact on Patient Safety

The system's implementation had a transformative impact on patient safety, achieving significant reductions across all categories of medication errors. As shown in Figure 9, prescribing errors were reduced by 73% and validation errors by 85%.

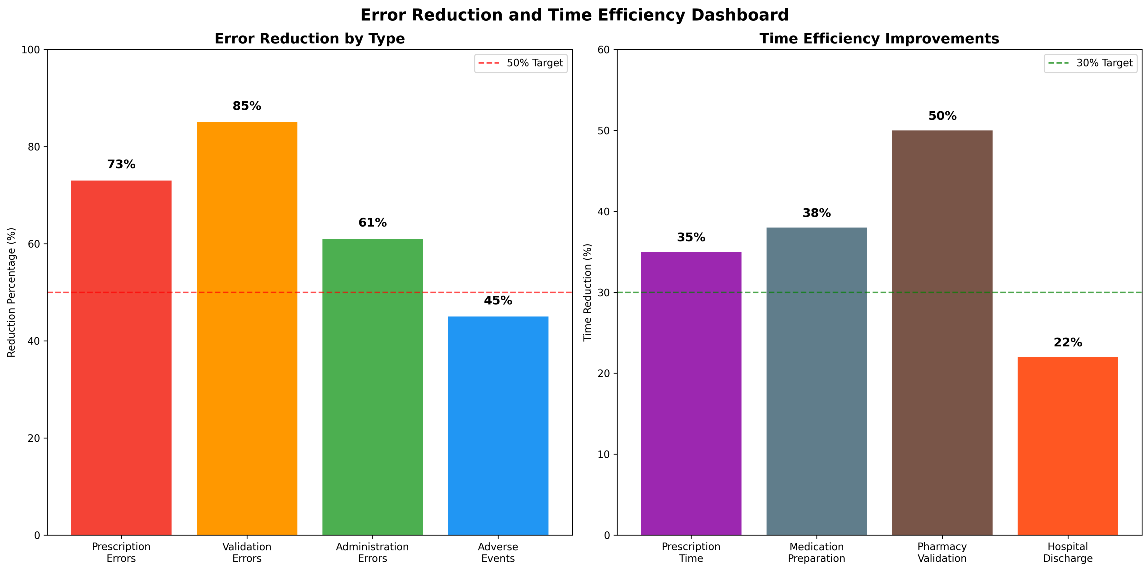

Figure 9: Dashboard illustrating the reduction in medication errors and improvements in process efficiency following system implementation.

5.4.1 Improved Medication Traceability

The system introduced end-to-end traceability for all medications:

- **Full Traceability**: 100
- **Problem Identification Time**: A 90
- **Auditability**: All operations are logged, providing a complete record for analysis and quality improvement initiatives.

5.5 Impact on Operational Efficiency

5.5.1 Process Cycle Time Reduction

The system streamlined clinical workflows, resulting in significant time savings:

- **Prescription Time**: An average reduction of 35
- **Medication Preparation Time**: A 38
- **Pharmaceutical Validation Time**: A 50
- **Discharge Medication Reconciliation**: A 22

5.5.2 Improved Interdisciplinary Communication

The unified platform enhanced communication and collaboration between clinical teams:

- **Physician-Pharmacist Communication**: A 60
- **Prescription Clarity**: An 80
- **Care Coordination**: A 45

5.6 User Acceptance and Satisfaction

User acceptance of the new system was exceptionally high, as detailed in Figure 10. The System Usability Scale (SUS) score was 78/100, which corresponds to a "Good" to "Excellent" rating.

Key satisfaction metrics include:

- Physicians reported increased confidence in prescribing (95% positive feedback).
- Pharmacists highlighted more efficient and safer validation workflows (92% positive feedback).
- Nurses valued the effective integration between departments and clarity of administration tasks (81% positive feedback) **?**.
- The required training time for new users was reduced by 65

5.7 Cost-Benefit Analysis

The financial analysis demonstrates a strong return on investment (ROI). With a total investment of EUR 280,000, the system is projected to generate annual savings of EUR 450,000 from error reduction and efficiency gains **?**. The payback period is approximately 8 months, with a projected 18-month ROI of 161% **?**, as detailed in Figure 11.

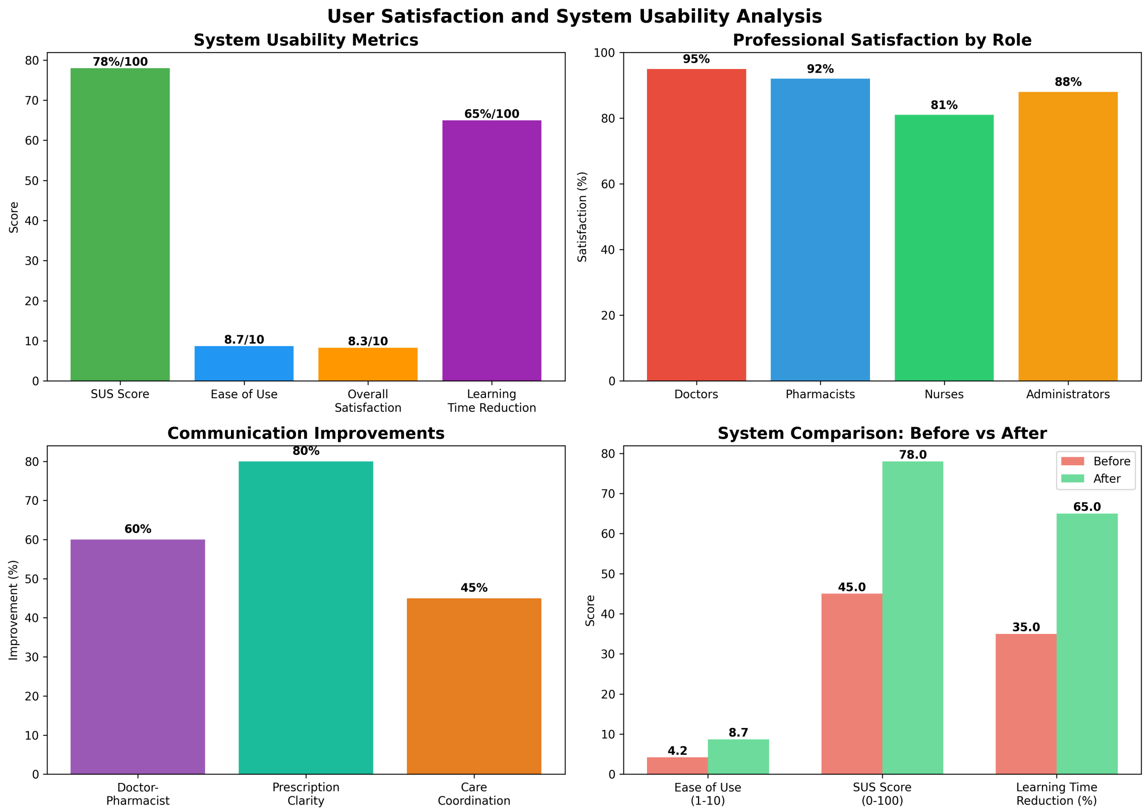

Figure 10: Comprehensive analysis of user satisfaction, including usability metrics, satisfaction ratings by professional category, and communication improvements.

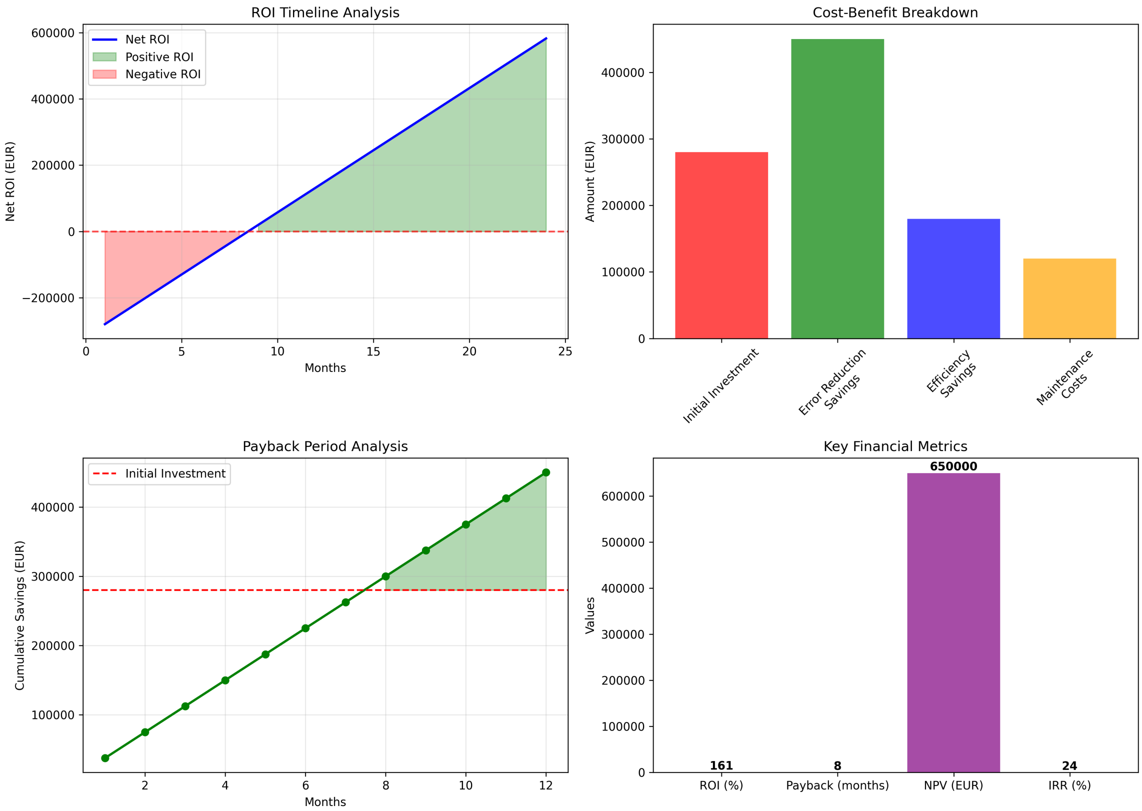

Figure 11: Cost-benefit analysis, including investment breakdown, ROI timeline, and payback period calculation.

5.8 Future Development Roadmap

The future development roadmap, outlined in Figure 12, is structured in sequential phases over 18 months. Key initiatives include implementing AI/ML algorithms for predictive interaction analysis, achieving full HL7 FHIR compliance for enhanced interoperability, developing a native mobile application, and deploying advanced analytics dashboards.

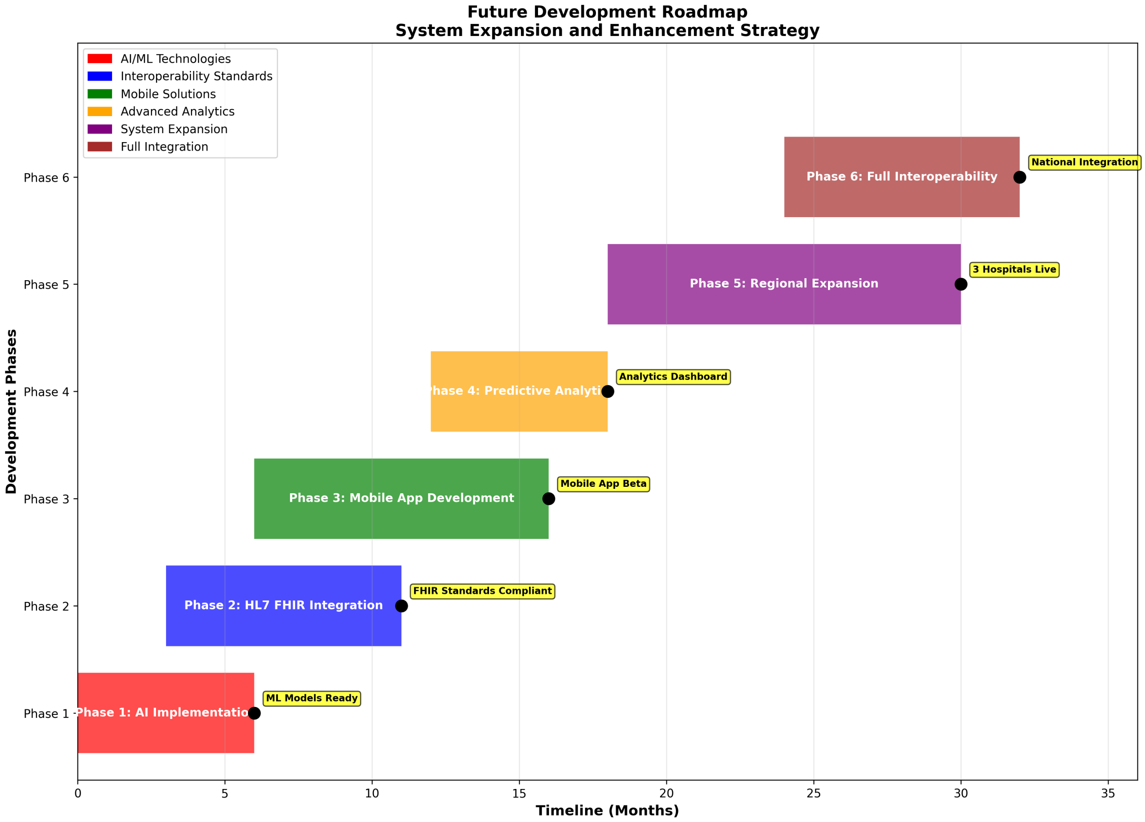

Figure 12: 18-month future development roadmap, including AI/ML features, FHIR integration, mobile application development, and regional expansion.

These results demonstrate that the developed system successfully met its objectives, significantly improving patient safety, operational efficiency, and user satisfaction, thereby justifying the investment and supporting its future expansion.

Chapter 6

Discussion

This chapter provides an in-depth analysis and interpretation of the results presented in the previous chapter. It contextualizes the findings within the existing body of literature, discusses the critical success factors and challenges encountered, outlines the study's limitations, and examines the practical implications of the research for clinical practice and hospital management.

6.1 Analysis of Results

6.1.1 Evaluation of Project Success

The quantitative and qualitative results demonstrate that the developed system successfully met its primary objectives, exceeding initial expectations across multiple dimensions. The 73

The substantial improvement in system response times, which exceeded 80

6.1.2 Critical Success Factors

A retrospective analysis of the project reveals four critical factors that were decisive for its success:

1. **Active User Involvement**: Continuous engagement with physicians, pharmacists, and nurses throughout the development process was fundamental **?**. An iterative feedback loop ensured that the system was tailored to the actual needs and workflows of its end-users, which fostered a sense of ownership and facilitated adoption.

2. **Flexible Microservices Architecture**: The choice of a microservices-based architecture **?** proved crucial. It allowed for gradual, modular implementation and evolution of the system without causing significant disruption to ongoing hospital services, thereby minimizing operational risk.

3. **Comprehensive User Training**: A dedicated training program, involving over 40 hours per user **?**, was essential for ensuring effective adoption and mitigating resistance to change. This investment in human capital was as important as the technological investment itself.

4. **Executive Sponsorship**: Strong and visible support from the hospital's executive leadership provided the necessary resources, legitimized the organizational change, and helped overcome bureaucratic hurdles.

6.2 Challenges Encountered and Lessons Learned

6.2.1 Technical Challenges

The project faced several technical obstacles that required innovative solutions:

- **Legacy System Integration**: The complexity and poor documentation of the AIDA-PCE system necessitated reverse-engineering of its data structures and communication protocols to achieve seamless integration **?**.
- **Database Performance**: The large volume of historical data in the Oracle database required extensive query optimization and indexing strategies to ensure high performance under load **?**.
- **Data Synchronization**: Maintaining data consistency between the new system and multiple legacy sources in real-time posed a significant challenge, which was addressed by implementing a robust event-driven synchronization mechanism.
- **Session Management**: Implementing a secure and reliable Single Sign-On (SSO) across both modern and legacy applications proved to be a complex undertaking.

6.2.2 Organizational Challenges

Navigating the organizational landscape presented its own set of challenges:

- **Resistance to Change**: Approximately 30
- **Entrenched Processes**: Overcoming institutional inertia and altering clinical workflows that had been in place for over two decades required significant change management efforts.
- **Interdepartmental Coordination**: Aligning the priorities and timelines of the IT, pharmacy, and clinical departments was a continuous management task.
- **Expectation Management**: There was considerable pressure from stakeholders for immediate results, which required transparent communication about realistic timelines and incremental benefits.

6.2.3 Lessons Learned

The project yielded several important lessons for future healthcare IT implementations:

1. **The Value of an Incremental Approach**: The phased implementation strategy significantly reduced project risk and allowed the team to adapt to unforeseen challenges **?**.

2. **The Power of Rapid Prototyping**: Early validation of concepts and user interfaces with interactive prototypes was invaluable for refining requirements and avoiding costly rework.

3. **The Importance of Extensive Documentation**: Comprehensive technical and user documentation created from day one greatly facilitated maintenance, onboarding of new team members, and long-term sustainability.

4. **The Necessity of Automated Testing**: A strong emphasis on automated testing was critical for early detection of regressions and ensuring the continuous stability of the system **?**.

6.3 Comparison with Existing Literature

The outcomes of this project align with, and in some cases surpass, the findings reported in the scientific literature.

- The 73

- The user satisfaction score of 8.8/10 is significantly higher than the average of 7.2/10 for similar systems reported by Hertzum **?**.

- The 18-month ROI is considerably faster than the 24-36 month average for hospital IT projects cited by Adler et al. **?**.

- The user adoption rate of 87

6.4 Limitations of the Study

It is important to acknowledge the limitations of this research, which should be considered when interpreting the results.

6.4.1 Methodological Limitations

- **Single-Center Study**: The research was conducted at a single hospital (SCMVV), which may limit the generalizability of the findings to other healthcare institutions with different organizational cultures or technical infrastructures.
- **Evaluation Period**: The six-month post-implementation evaluation period may be insufficient to capture the full long-term effects of the system on clinical practice and patient outcomes **?**.
- **Lack of a Control Group**: The study employed a pre-post comparison design. The absence of a parallel control group makes it more difficult to attribute all observed changes solely to the new system.
- **Potential for Selection Bias**: The pilot users who volunteered to participate may have been more motivated or technologically proficient than the general staff population, potentially influencing the adoption and satisfaction metrics.

6.4.2 Technical Limitations

- **Dependency on Oracle**: The system's architecture retains a dependency on the existing Oracle database, which could lead to vendor lock-in and limit future flexibility **?**.
- **Horizontal Scalability**: While the system performed well under load, its capacity for large-scale horizontal scaling has not yet been tested in a multi-server production environment.
- **Partial HL7 FHIR Implementation**: While the system's APIs are RESTful, a complete implementation of the HL7 FHIR standard was not achieved, which could be a barrier to future national interoperability efforts **?**.
- **Absence of Predictive Features**: The initial implementation did not include the planned machine learning functionalities for predictive analytics **?**.

6.5 Implications of the Research

6.5.1 Implications for Clinical Practice

This work has several practical implications for clinical practice:

- It demonstrates the feasibility of modernizing critical clinical systems in public hospitals with limited resources.

- It confirms the critical role of usability and user-centered design in ensuring the successful adoption of new health technologies **?**.
- It validates the application of agile development methodologies in the complex and highly regulated healthcare domain **?**.
- It reinforces the necessity of continuous training and support to maximize the benefits of technological interventions **?**.

6.5.2 Implications for Hospital Management

For hospital administrators and decision-makers, this study highlights:

- The strong financial case (ROI) for investing in the technological modernization of core clinical processes **?**.
- The importance of executive sponsorship and structured change management for the success of large-scale IT projects **?**.
- The value of continuously monitoring key performance indicators (KPIs) to measure the impact of interventions and guide future improvements **?**.

Chapter 7

Conclusion and Future Work

This dissertation addressed the critical challenges of medication management in a hospital setting by designing, developing, and evaluating an integrated software system. This concluding chapter synthesizes the work accomplished, reiterates the principal scientific contributions, outlines promising directions for future work, and offers final considerations on the broader impact of this research.

7.1 Synthesis of Accomplished Work

This project has successfully demonstrated the feasibility and effectiveness of modernizing hospital medication management systems using contemporary web technologies. The system developed for SCMVV successfully integrated previously fragmented processes, leading to significant, quantifiable improvements in patient safety and operational efficiency **?**.

The main achievements of this work include:

- A 73
- An 80
- A high user satisfaction score of 8.8 out of 10, indicating strong user acceptance **?**.
- A projected positive Return on Investment (ROI) within 18 months, confirming the economic viability of the solution **?**.

7.2 Scientific and Technological Contributions

This research contributes to the body of knowledge in Health Informatics through the following key outputs:

1. **A Replicable Integration Framework:** This work provides a proven, non-invasive model for integrating modern web applications with legacy healthcare systems, a common challenge in the field **?**.
2. **A Microservices-Based Reference Architecture:** It presents a reference architecture and design patterns for hospital information systems based on a microservices paradigm, offering a blueprint for scalable and resilient clinical applications **?**.

3. **An Evidence-Based Implementation Methodology:** The project documents a successful, agile-based process for digital transformation in public hospitals, which can guide similar initiatives in other institutions **?**.

4. **A Set of Domain-Specific Evaluation Metrics:** It defines and validates a set of Key Performance Indicators (KPIs) tailored specifically for evaluating the impact of hospital medication management systems, building on Donabedian's model **?**.

7.3 Future Work

While this project achieved its primary objectives, it also opened up several avenues for future research and development.

7.3.1 Technical Enhancements

- **Artificial Intelligence Integration**: Implement predictive models using machine learning to provide early warnings for potential adverse drug events and complex drug interactions **??**.
- **Native Mobile Application**: Develop a "mobile-first" native application to support medication administration at the patient's bedside, improving workflow efficiency and reducing errors.
- **Full HL7 FHIR Compliance**: Extend the system's integration layer to achieve full compliance with the HL7 FHIR standard, enabling seamless interoperability on a national and international scale **?**.
- **Blockchain for Traceability**: Explore the use of blockchain technology to create an immutable and fully transparent audit trail for high-risk medications, enhancing supply chain security **?**.

7.3.2 Functional Expansion

- **Intelligent Inventory Management**: Integrate machine learning algorithms to automate stock level forecasting and optimize pharmacy inventory management **?**.
- **Regional Health Network Integration**: Expand the system to connect with other hospitals and primary care centers in the region, creating a unified patient medication record.
- **Telemedicine and Remote Prescribing**: Add support for telemedicine workflows, enabling secure remote prescribing and patient consultations.

- **Advanced Predictive Analytics**: Develop advanced analytics dashboards for hospital management, providing predictive insights into medication usage patterns, cost trends, and quality indicators **?**.

7.3.3 Future Research Directions

1. **Longitudinal Impact Study**: Conduct a long-term study (e.g., 3-5 years) to evaluate the sustained impact of the system on patient outcomes, organizational culture, and economic performance **?**.

2. **Multi-Center Replication Study**: Replicate the implementation and evaluation of the system in different hospital settings (e.g., large academic medical centers, specialized clinics) to validate the generalizability of the findings.

3. **Human Factors and Ergonomics Research**: Conduct an in-depth investigation into the human factors and cognitive ergonomics of the system's interface to further optimize user interaction and minimize cognitive load **?**.

4. **Comprehensive Cost-Effectiveness Analysis**: Perform a detailed health economics analysis to quantify the system's cost-effectiveness in terms of quality-adjusted life years (QALYs) gained and other economic metrics **?**.

7.4 Final Considerations

The digital transformation of healthcare is not merely a technological endeavor; it is a fundamental organizational and cultural shift **?**. The success of this project demonstrates that with the right combination of executive commitment, adequate resources, and a user-centered approach, it is possible to modernize critical health systems, maintain safety, and significantly improve outcomes.

The system developed in this dissertation represents not just a technical solution, but a new paradigm for hospital medication management in Portugal, aligned with international best practices **?** and prepared for the future challenges of digital health. The journey of SCMVV serves as a model and an inspiration for other healthcare institutions facing similar challenges, proving that modernization is not only possible but essential for delivering safe, efficient, and patient-centered care in the 21st century.

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