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A Context-Aware Information Systems Architecture for Sustainable E-Health Implementation in the Democratic Republic of Congo

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Background and Purpose: The digital transformation of healthcare systems through e-health technologies has become a strategic priority for improving healthcare accessibility, efficiency, and quality, particularly in developing countries. However, successful implementation requires not only user adoption but also robust, interoperable, and secure information systems architectures adapted to local contexts. This study aims to propose a context-aware information systems architecture to support sustainable e-health implementation in the healthcare sector of the Democratic Republic of Congo (DRC), where infrastructural constraints and institutional challenges remain significant barriers
Methods: The study builds upon an empirically validated e-health adoption model derived from integrated Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT) constructs. Key technological, organizational, and institutional requirements were identified and translated into architectural design specifications. A layered architecture approach was adopted, incorporating interoperability standards, data security mechanisms, privacy protection, and modular components to ensure compatibility with existing health information systems and adaptability to resource-constrained environments.
Results: The proposed architecture comprises five interrelated layers: infrastructure, application, data management, interoperability, and security governance. The framework addresses contextual challenges such as limited ICT infrastructure, intermittent connectivity, and varying levels of digital literacy among healthcare professionals. It supports essential digital health services, including electronic health records, telemedicine, health information exchange, and mobile health applications. The architecture demonstrates scalability, flexibility, and resilience, enabling phased implementation and long-term sustainability.
Conclusions: By aligning technological design with empirically identified adoption determinants and policy requirements, the proposed framework contributes to both digital health implementation practice and information systems architecture research in resource-constrained settings. The study provides practical guidance for policymakers, healthcare institutions, and system designers seeking to deploy sustainable e-health solutions in the DRC and similar developing healthcare systems.

Keywords: E-Health, Information Systems Architecture, Digital Health, Health Informatics, Interoperability, Developing Countries, Democratic Republic of Congo Introduction

1 Introduction

The digital transformation of healthcare systems has emerged as a global priority aimed at improving the accessibility, efficiency, and quality of healthcare services. Advances in information and communication technologies have enabled the development of various digital health solutions, including electronic health records, telemedicine platforms, mobile health applications, and health information exchange systems [1]. These technologies have the potential to enhance clinical decision-making, streamline health service delivery, and improve patient outcomes [2]. In recent years, governments and international organizations have increasingly recognized the strategic importance of digital health in strengthening healthcare systems and achieving universal health coverage [3]. E-health systems enable better management of medical

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information, facilitate communication between healthcare providers, and support data-driven healthcare policies. As a result, digital health has become a key component of healthcare modernization strategies worldwide [4].

Despite these opportunities, the implementation of e-health systems requires more than the simple deployment of digital technologies. Successful digital health initiatives depend on the existence of robust information systems architectures capable of supporting interoperability, data security, system scalability, and integration with existing healthcare infrastructures [5]. Although digital health technologies offer significant benefits, their implementation remains particularly challenging in developing countries. Many healthcare systems in low- and middle-income countries face structural constraints such as limited ICT infrastructure, unreliable internet connectivity, insufficient technical expertise, and inadequate financial resources [6]. These limitations often hinder the effective deployment and sustainability of digital health initiatives.

In addition to technological barriers, institutional and organizational challenges may also affect the adoption and implementation of e-health systems [7]. Healthcare institutions may lack the necessary governance structures, regulatory frameworks, and technical support mechanisms required to manage complex digital infrastructures. Furthermore, varying levels of digital literacy among healthcare professionals may limit the effective use of digital health technologies in clinical practice [8].

In fragile healthcare systems such as that of the Democratic Republic of Congo, these challenges are further amplified by broader socio-economic constraints and infrastructural limitations. system interoperability, data integration, security management, and long-term sustainability [9]. In many cases, digital health solutions are implemented as isolated systems that lack the ability to communicate effectively with other healthcare information systems.

In the Democratic Republic of Congo, the healthcare sector has witnessed increasing interest in the adoption of digital health technologies aimed at improving health information management and service delivery [10].However, the absence of a comprehensive and context-aware information systems architecture has limited the effective integration of digital health solutions across healthcare institutions [3].As a result, many digital health initiatives struggle to achieve long-term sustainability due to the absence of integrated and context-adapted information systems architectures [4].

While numerous digital health initiatives have been introduced in developing countries, many of these projects face difficulties related to existing digital health systems often operate independently, resulting in fragmented data management, limited interoperability, and challenges in ensuring data security and privacy [4]. These limitations highlight the need for a structured and context-sensitive information systems architecture capable of supporting sustainable e-health implementation in the Congolese healthcare environment.

The main objective of this study is to propose a context-aware information systems architecture that can support the sustainable implementation of e-health systems in the healthcare sector of the Democratic Republic of Congo.

This study contributes to both the digital health and information systems architecture literature in several ways.

First, the research proposes a context-aware architectural framework specifically designed for healthcare systems operating in resource-constrained environments. Unlike conventional information systems architectures developed for technologically advanced settings, the proposed framework considers the infrastructural and institutional realities of developing healthcare systems.

Second, the study integrates insights from an empirically validated e-health adoption model with information systems architecture design principles. By linking technology adoption determinants with system architecture requirements, the research provides a more holistic perspective on digital health implementation.

Third, the proposed architecture introduces a layered design framework that incorporates infrastructure, applications, data management, interoperability mechanisms, and security governance components. This structure facilitates the development of scalable and interoperable digital health systems capable of supporting various healthcare services, including electronic health records, telemedicine, and mobile health applications.

Finally, the study provides practical guidance for policymakers and system designers seeking to implement sustainable e-health solutions in the Democratic Republic of Congo and similar developing healthcare environments.

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2 Literature Review

2.1 Digital Health Architecture

Digital health architecture refers to the structured design of technological components, standards, and processes that support the development, deployment, and integration of digital health solutions [11]. It provides the foundation for implementing electronic health records, telemedicine platforms, mobile health applications, and health information exchange systems within healthcare environments [12].

Modern digital health architectures increasingly adopt layered and service-oriented approaches to ensure flexibility, scalability, and interoperability [13]. These architectures typically include infrastructure components, application services, data management systems, communication networks, and governance mechanisms. Cloud computing, mobile technologies, and distributed data platforms have further transformed digital health architecture by enabling remote access to healthcare services and facilitating data sharing across geographical boundaries [13].

However, the design of digital health architectures must account for contextual constraints, particularly in developing countries. Conventional architectures developed for technologically advanced environments may not be suitable for healthcare systems with limited infrastructure, intermittent connectivity, and constrained technical capacity [14]. As a result, researchers increasingly emphasize the need for context-aware architectures that adapt technological design to local conditions, resource availability, and institutional capabilities.

Furthermore, digital health architectures must address critical issues such as system reliability, data security, privacy protection, and long-term sustainability. Failure to incorporate these considerations may lead to fragmented systems, data silos, and ineffective healthcare service delivery.

2.2 Information Systems Architecture in Healthcare

Health Information Systems (HIS) architecture refers to the structural organization of information technologies used to collect, process, store, and exchange health-related data[61]. A well-designed HIS architecture enables healthcare institutions to manage clinical information efficiently, support decision-making processes, and coordinate healthcare services across different levels of the health system.

Traditional HIS architectures often consisted of isolated applications developed for specific functions, such as patient registration, laboratory management, or billing. While these systems improved operational efficiency within individual departments, they frequently lacked integration capabilities, resulting in fragmented information flows and duplicated data[57].

Contemporary HIS architecture emphasizes integrated platforms capable of supporting comprehensive healthcare information management. Enterprise architecture frameworks are increasingly applied to healthcare systems to align technological solutions with organizational goals and operational processes. Such approaches facilitate interoperability, standardization, and scalability while enabling the integration of legacy systems with new digital applications [15].

In developing healthcare environments, the absence of coordinated architectural frameworks often leads to the proliferation of independent digital solutions implemented by different stakeholders. This fragmentation reduces the effectiveness of health information systems and complicates efforts to establish national health information infrastructures. Therefore, the development of coherent and adaptable HIS architectures is essential for supporting sustainable digital health transformation [16].

2.3 Interoperability in Health Information Systems

Interoperability is widely recognized as a fundamental requirement for effective digital health implementation. It refers to the ability of different information systems, devices, and applications to exchange data and interpret shared information in a meaningful way. Interoperability enables seamless communication between healthcare providers, institutions, and information platforms, thereby supporting coordinated patient care and efficient health service delivery [17].

Interoperability can be categorized into several levels, including technical interoperability (data exchange), semantic interoperability (shared meaning of data), and organizational interoperability

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(alignment of policies and processes). Achieving these levels requires the adoption of standardized data formats, communication protocols, and governance frameworks.

Lack of interoperability remains one of the most significant barriers to digital health implementation worldwide. Fragmented systems prevent the effective sharing of patient information, hinder clinical decision-making, and limit the potential benefits of digital health technologies. In resource-constrained healthcare environments, interoperability challenges are often exacerbated by inconsistent standards, limited technical expertise, and insufficient coordination among stakeholders [18].

Interoperability is particularly critical for national health information exchange systems, which aim to integrate data from multiple sources, including hospitals, clinics, laboratories, and public health agencies. Without interoperable architectures, healthcare systems risk becoming collections of isolated digital tools rather than integrated platforms capable of supporting comprehensive healthcare management [19].

2.4 E-Health Implementation in Developing Countries

The implementation of e-health systems in developing countries presents unique challenges that extend beyond technological considerations. While digital health initiatives have the potential to improve healthcare accessibility and efficiency, their success depends on a complex interplay of infrastructural, organizational, financial, and socio-cultural factors [20].

Many developing countries face significant barriers, including limited ICT infrastructure, unreliable electricity supply, inadequate funding, and shortages of skilled personnel. These constraints often lead to the partial or unsuccessful implementation of digital health projects. Additionally, weak regulatory frameworks and governance structures may complicate issues related to data protection, privacy, and system accountability [4].

Another critical challenge is the sustainability of e-health initiatives. Projects implemented with external funding or pilot programs may fail to scale up or continue after initial support ends. Sustainable implementation requires long-term planning, local capacity building, and alignment with national health strategies [21].

Despite these challenges, developing countries also present opportunities for innovative digital health solutions tailored to local contexts. Mobile health technologies, for example, have shown significant potential in regions where mobile phone penetration exceeds access to traditional healthcare infrastructure. However, the effectiveness of such solutions depends on their integration into broader health information systems architectures [22].

In the case of the Democratic Republic of Congo, the healthcare system faces multiple structural constraints, including geographical barriers, limited infrastructure, and resource shortages. These conditions underscore the need for a context-aware architectural framework capable of supporting scalable, interoperable, and secure digital health systems adapted to local realities [4].

2.5 Research Gap

Although extensive research has been conducted on digital health technologies, health information systems, and interoperability, relatively few studies have focused on the development of context-aware information systems architectures tailored to fragile healthcare environments. Existing frameworks often assume the availability of stable infrastructure, advanced technical capacity, and strong institutional support conditions that may not exist in many developing countries.

Moreover, many digital health initiatives prioritize technology deployment without adequately addressing architectural integration and long-term sustainability. This gap highlights the need for comprehensive frameworks that align technological design with contextual constraints, adoption determinants, and policy requirements.

Therefore, this study seeks to address this gap by proposing a context-aware information systems architecture specifically designed to support sustainable e-health implementation in the Democratic Republic of Congo.

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3 Research Context: Healthcare System in the DRC

3.1 Overview of the Healthcare System in the DRC

The healthcare system of the Democratic Republic of Congo (DRC) is characterized by a multi-tiered structure designed to deliver services at primary, secondary, and tertiary levels. The system is organized around health zones, which serve as the fundamental administrative and operational units responsible for delivering primary healthcare services to defined populations [23]. Each health zone typically includes a network of health centers supported by a referral hospital that provides more specialized medical services [24].

Despite this structured organization, the healthcare system faces significant challenges related to resource constraints, workforce shortages, and uneven distribution of healthcare facilities. Rural and remote areas often experience limited access to qualified medical personnel and essential health services, contributing to disparities in healthcare delivery across the country. In addition, healthcare financing relies heavily on out-of-pocket payments, which can limit access to care for vulnerable populations [25].

Public, private, and faith-based organizations all play important roles in service provision, resulting in a heterogeneous healthcare landscape. While this pluralistic system expands service availability, it also creates coordination challenges and inconsistencies in service quality and data management practices [26].

3.2 Current State of Digital Health Infrastructure

Digital health infrastructure in the DRC remains at an early stage of development. Although several initiatives have been introduced to modernize health information management, the adoption of digital technologies across healthcare institutions is uneven and fragmented. Many facilities continue to rely on paper-based record systems, which limit the efficiency of data collection, storage, and retrieval [20].

Where digital systems exist, they are often implemented as standalone applications designed for specific functions, such as disease surveillance, patient registration, or reporting to national health authorities. These systems frequently lack interoperability, preventing seamless data exchange between healthcare institutions and administrative levels [27].

Access to reliable ICT infrastructure remains a major constraint. Internet connectivity is inconsistent, particularly in rural areas, and electricity supply is often unstable. Healthcare facilities may lack sufficient computing equipment, secure data storage solutions, and technical support personnel. Consequently, the functionality of digital health systems is frequently constrained by infrastructural limitations [3].

Mobile technologies have shown potential for expanding digital health services, given the relatively high penetration of mobile phones compared to fixed internet infrastructure. However, the integration of mobile health applications into broader health information systems remains limited.

3.3 Challenges for E-Health Implementation

The implementation of e-health systems in the DRC is hindered by a complex combination of technological, organizational, and institutional challenges [28].

From a technological perspective, limited ICT infrastructure, intermittent connectivity, and unreliable electricity supply significantly restrict the deployment and operation of digital health systems [1].These constraints affect system availability, data synchronization, and real-time communication capabilities [46].

Organizational challenges include insufficient technical capacity within healthcare institutions, limited training opportunities for healthcare professionals, and resistance to technological change [29]. Many healthcare workers may lack the digital skills necessary to effectively use advanced information systems, which can reduce adoption rates and system utilization [10] [30].

Institutional factors also play a critical role. The absence of comprehensive national standards for health information systems, interoperability frameworks, and data governance policies complicates the integration of digital solutions across the healthcare sector. In addition, funding limitations may impede the procurement of equipment, system maintenance, and long-term sustainability of digital health initiatives [4] [55].

Socio-cultural factors, such as trust in digital technologies and concerns about data privacy, may further influence the acceptance of e-health systems among both healthcare professionals and patients [10].

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Taken together, these challenges highlight the need for a context-aware information systems architecture specifically designed to address the realities of healthcare delivery in the DRC. Such an architecture must be robust, scalable, interoperable, and adaptable to environments with constrained resources while ensuring data security and system reliability.

4 Methodological Approach

4.1 Research Design

This study adopts a design science research approach to develop a context-aware information systems architecture for sustainable e-health implementation in the Democratic Republic of Congo. Design science is particularly appropriate for research aimed at creating and evaluating technological artifacts intended to solve real-world problems. In this context, the artifact consists of a conceptual architecture tailored to the needs and constraints of a resource-constrained healthcare environment [31].

The research combines empirical evidence derived from healthcare professionals with theoretical insights from digital health, information systems architecture, and technology adoption literature. Rather than focusing solely on user behavior or technical specifications, the study integrates both perspectives to ensure that the proposed architecture aligns with practical requirements and contextual realities.

The research process follows an iterative approach involving problem identification, requirement analysis, architectural design, and conceptual validation. This process ensures that the resulting framework addresses the key challenges identified in the healthcare system while remaining adaptable to evolving technological conditions.

4.2 Data Sources and System Requirements

The architectural design is informed by multiple data sources to ensure its relevance and applicability to the healthcare context of the Democratic Republic of Congo.

Secondary data sources include policy documents, national health strategies, reports from international organizations, and existing literature on digital health implementation in developing countries. These sources contributed to the identification of institutional, regulatory, and infrastructural requirements that must be considered in architectural design.

Based on these inputs, both functional and non-functional requirements were defined. Functional requirements include support for electronic health records, telemedicine services, health information exchange, and reporting systems. Non-functional requirements encompass system scalability, interoperability, reliability, security, privacy protection, and resilience to infrastructural disruptions such as power outages or connectivity failures.

4.3 Analytical Framework for Architecture Design

The architecture is developed using a layered analytical framework that integrates principles from enterprise architecture, health information systems design, and digital health implementation models. This framework ensures that the proposed system addresses technical, organizational, and governance dimensions simultaneously [32].

The analytical process begins with mapping the identified requirements to architectural components. Infrastructure constraints, such as limited connectivity and hardware availability, inform the design of the infrastructure layer. User needs and clinical workflows guide the application layer, while data management requirements shape the structure of the data layer [33].

Interoperability considerations are addressed through the incorporation of standardized communication protocols and data exchange mechanisms, enabling integration with existing health information systems and external platforms. Security and privacy requirements are embedded across all layers through governance mechanisms, access control policies, and data protection strategies.

The framework emphasizes modularity and scalability, allowing the architecture to evolve as technological capacity improves. It also prioritizes resilience, ensuring that core system functions remain operational even under constrained conditions.

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By combining empirical evidence, theoretical principles, and contextual analysis, the methodological approach supports the development of a comprehensive architecture capable of facilitating sustainable e-health implementation in the Democratic Republic of Congo

5 Proposed E-Health Information Systems Architecture

5.1 Architectural Design Principles

This section presents the proposed e-health information systems architecture designed to support secure, interoperable, scalable, and context-appropriate digital health services in the Democratic Republic of Congo (DRC). The architecture addresses the technical challenges identified in earlier chapters and aligns with the functional and non-functional requirements of e-health systems in low-resource and fragile settings such as North Kivu. It adopts a layered and modular approach to ensure flexibility, maintainability, and sustainability.

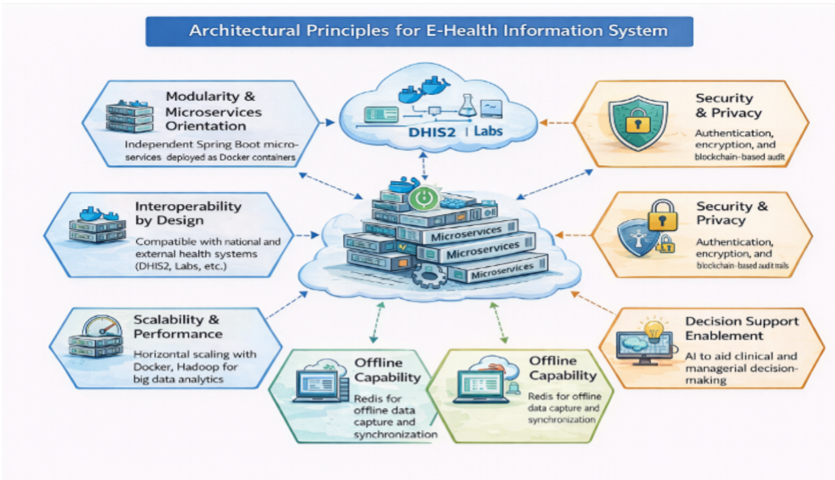

Fig. 1. Architectural Principles for E-Health System

The proposed e-health architecture is built upon several foundational principles designed to ensure flexibility, resilience, and effectiveness within the complex healthcare landscape. Central to this design is a Modularity and Microservices Orientation, which utilizes the Spring Boot framework to decouple functional components. This approach ensures that each service can be developed, deployed, and scaled independently, thereby preventing system-wide failures during updates [34].

Furthermore, the framework prioritizes Interoperability by Design to facilitate seamless communication with existing national and external health systems, such as DHIS2 and various laboratory platforms. By implementing standardized RESTful APIs and adhering to global health data standards, the architecture effectively eliminates data silos and enables a unified view of patient information [35]. To safeguard this information, Security and Privacy measures are integrated into every layer of the system. This defense-in-depth strategy employs advanced authentication, authorization, and encryption protocols, complemented by blockchain-based audit mechanisms that ensure the integrity and traceability of sensitive health records [36].

To meet the high-performance demands of modern medicine, the architecture emphasizes Scalability and Performance. Through the use of Docker containers for horizontal scaling and the integration of big data technologies like Hadoop, the system is capable of processing and analyzing vast quantities of healthcare data efficiently [37]. Additionally, the architecture includes a robust Offline Capability specifically designed for remote areas with unstable internet connectivity. By leveraging Redis and local storage for data capture and subsequent synchronization, the system ensures that healthcare delivery remains uninterrupted regardless of network status [38].

Finally, the system is enhanced through Decision Support Enablement, where artificial intelligence (AI) components are directly integrated into the workflow. These tools assist both clinicians and managers by

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providing data-driven insights, which significantly improve diagnostic accuracy and institutional resource management [39].

5.2 Logical Architecture

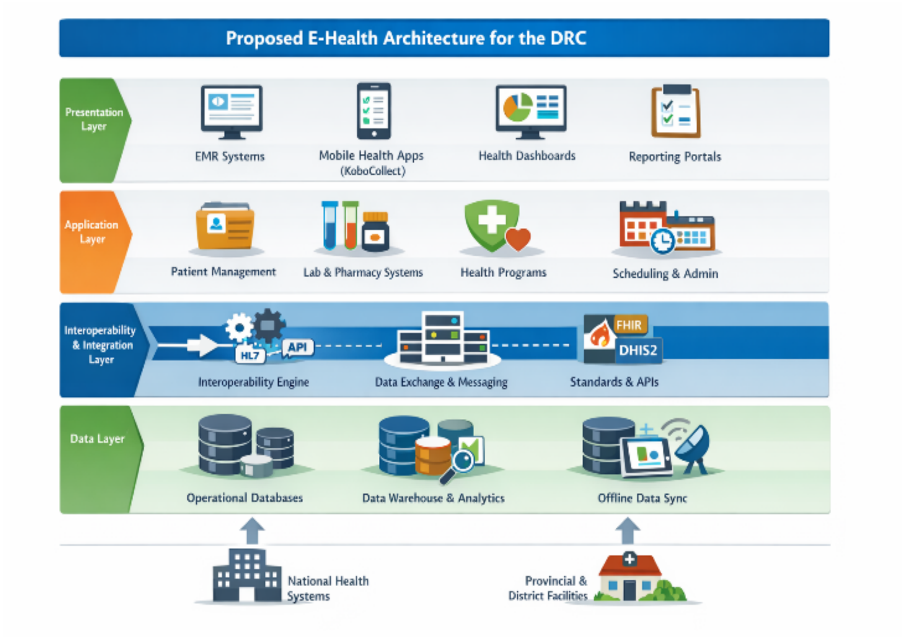

Fig. 2 Proposed E-Health Architecture for the DRC

The proposed e-health architecture for the Democratic Republic of Congo is conceived as a layered, modular, and interoperable information system designed to support healthcare service delivery, data management, and decision-making across different levels of the health system. The architecture aims to address the technical, organizational, and contextual challenges identified in the Congolese healthcare sector, particularly in provinces such as North Kivu, while remaining adaptable to future expansion and technological evolution.

At a high level, the architecture is organized into four main layers: the presentation layer, the application layer, the interoperability and integration layer, and the data layer. Each layer performs a specific function while interacting seamlessly with the others to ensure efficient data flow and system coordination.

The presentation layer represents the user interface through which healthcare professionals and administrators interact with e-health systems [40]. This layer includes web-based and mobile applications such as electronic medical records (EMR), health management dashboards, mobile data collection tools, and reporting interfaces. The design of this layer emphasizes usability, accessibility, and support for low-bandwidth environments, recognizing the diverse technological capabilities of health facilities in the DRC.

The application layer consists of core health information system components that support clinical, administrative, and public health functions. These include systems for patient registration, clinical documentation, laboratory and pharmacy management, appointment scheduling, and health program monitoring. Each application module operates independently while adhering to shared standards that enable integration across the architecture.

The interoperability and integration layer serves as the backbone of the proposed architecture. It enables communication and data exchange between disparate applications and systems through standardized interfaces, APIs, and messaging services. This layer ensures that information generated at facility level can be aggregated, shared, and reused at district, provincial, and national levels, thereby reducing data silos and improving coordination across the health system [41].

The data layer provides centralized and decentralized data storage, management, and analytics capabilities. It includes operational databases for transactional data, data warehouses for aggregated reporting, and analytics tools to support monitoring, evaluation, and decision-making. Mechanisms for data

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synchronization are incorporated to support offline data capture and delayed transmission in areas with limited connectivity [42].

Overall, the proposed e-health architecture is designed to be flexible, scalable, and context-aware, allowing gradual implementation and integration with existing health information systems in the DRC. By combining technical robustness with user-centered considerations, the architecture seeks to support effective e-health adoption while enhancing the quality, accessibility, and reliability of health information across the healthcare system.

5.3 Physical Architecture

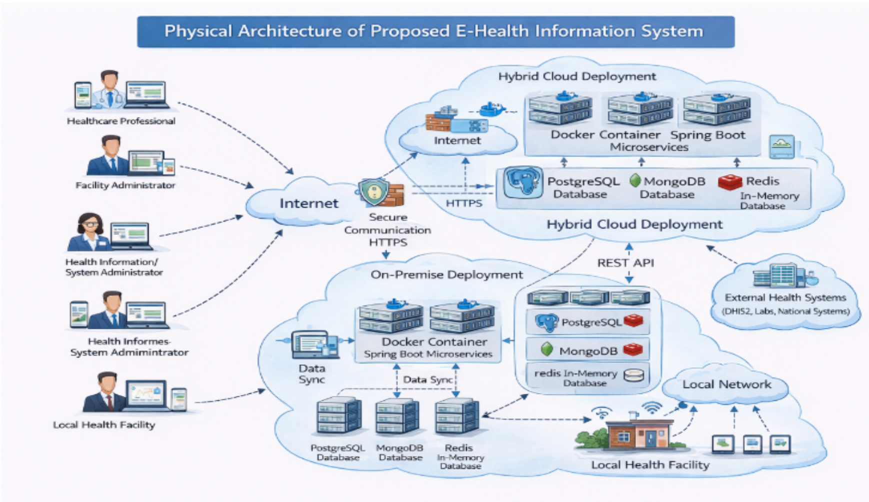

Fig. 3. Physical Architectural of Proposed E-Health Info. System

The physical architecture of the system defines the strategic deployment of components across infrastructure resources to ensure high availability and operational consistency. At the foundation of the Server Environment, all backend services are encapsulated within Docker containers. This containerization strategy enables a uniform deployment pipeline across development, testing, and production environments, effectively mitigating the "it works on my machine" syndrome and simplifying the management of complex dependencies [43].

To address the diverse geographical and technological landscape of the DRC, the system utilizes a Cloud and On-Premise Hybrid Deployment model [1]. This flexible approach allows the architecture to accommodate local health facilities that may have limited or intermittent internet connectivity by hosting critical services on-site, while simultaneously synchronizing with national-level data centers for centralized management and data aggregation [44]. The integrity of this distributed network is maintained through rigorous Network Security protocols. Secure communication across all nodes is mandated via HTTPS, while the infrastructure is further protected by advanced firewalls and strategic network segmentation to prevent lateral movement in the event of a security breach [45].

Finally, the architecture leverages Distributed Storage and Processing to manage the vast influx of medical information. By utilizing Hadoop clusters, the system provides a scalable environment for large-scale data storage and complex analytics. This distributed capability is essential for supporting population health analysis and long-term policy planning, allowing health authorities to derive actionable insights from regional and national data patterns [46].

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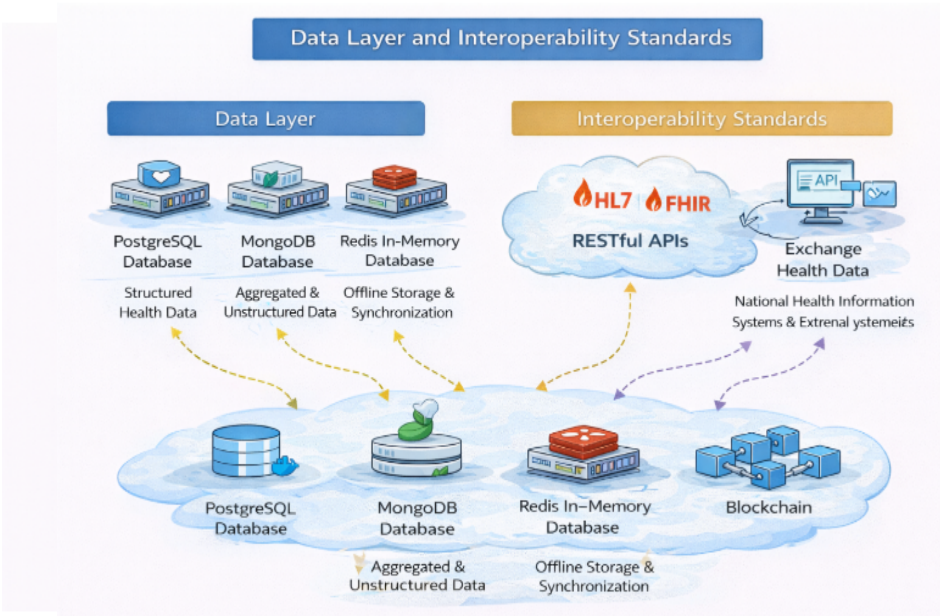
5.4 Application Layer Architecture

Fig. 4. Application Layer Architecture



The application layer of the proposed system is engineered using a microservices-based architecture built on the Spring Boot framework. This design begins with the Patient and Clinical Management Services, which function as the core of the clinical workflow. These services are responsible for managing patient registration, maintaining comprehensive electronic medical records, and facilitating the capture and retrieval of patient history. By isolating these functions, the system ensures that sensitive clinical data remains accessible and organized for frontline healthcare providers [47].

Complementing the clinical services are the Facility Management Services, which streamline the operational aspects of healthcare institutions. This module supports the management of appointments and integrates laboratory and pharmacy data to ensure a cohesive supply chain and service flow. Furthermore, these services automate facility-level reporting, which is essential for tracking institutional performance and resource utilization [48]. To add a layer of intelligence to these operations, Decision Support Services are integrated directly into the application layer. These AI-driven modules perform real-time analysis of clinical and operational data to generate proactive alerts, clinical recommendations, and predictive insights, thereby enhancing the precision of medical interventions [49].

The security and governance of the application are maintained through User and Access Management Services. This component is dedicated to managing user profiles, defining complex roles and permissions, and overseeing the authentication processes required to protect system integrity. This ensures that only authorized personnel can access specific tiers of sensitive health information [50]. Finally, the Interoperability Services act as the gateway for external communication. By utilizing standardized REST APIs and universal data formats, these services enable the seamless exchange of information with external health platforms and national databases, ensuring that the system remains an integrated part of the broader digital health ecosystem [51].

5.5 Data Layer and Interoperability Standards

Fig. 5. Data Layer and Interoperability Standards

The data layer of the proposed architecture is specifically engineered to manage heterogeneous health data while maintaining high levels of integrity, availability, and interoperability. To handle structured transactional information, such as detailed patient records, user accounts, and facility management data, the system utilizes a Relational Database (PostgreSQL). This choice ensures ACID compliance and strong data consistency, which are vital for maintaining accurate medical histories and administrative accuracy [52].

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To accommodate the diverse nature of medical documentation, a NoSQL Database (MongoDB) is integrated to store unstructured and semi-structured data, including clinical notes and aggregated health statistics. This provides the schema flexibility required to capture varied clinical inputs that do not fit into rigid tables [53]. Furthermore, to address the specific challenge of low-connectivity environments in the DRC, an In-Memory Database (Redis) is employed. This component supports an effective offline mode through advanced caching and high-speed data synchronization, ensuring that healthcare workers can remain productive even when the primary network is unavailable [54].For high-level insights, the architecture incorporates a Big Data Platform (Hadoop), which enables large-scale analytics, comprehensive reporting, and real-time population health monitoring. This analytical power is balanced by the integration of Blockchain Technology, which provides a decentralized and secure audit trail. The blockchain ensures data integrity verification and establishes critical trust mechanisms for sensitive health transactions, making the medical record immutable and verifiable [55]. Finally, the layer is unified by strict Interoperability Standards, supporting protocols such as HL7/FHIR and utilizing RESTful APIs. These standards facilitate seamless integration with both national and international health information systems, ensuring that the data layer is not an island but a connected node in the global health network [56].

5.6 Requirements Analysis for E-Health Systems

The success of an e-health information system largely depends on a clear understanding of its requirements. In the context of the Democratic Republic of Congo, and particularly in resource-constrained environments such as North Kivu, the requirements analysis must reflect both the operational needs of healthcare stakeholders and the technical constraints of the existing infrastructure. This section presents the functional and non-functional requirements that guide the design and implementation of the proposed e-health system architecture.

Functional Requirements.

Functional requirements define what the e-health system is expected to do in order to support healthcare delivery, management, and decision-making. The proposed system must enable patient information management, including patient registration, electronic medical records, consultation history, and continuity of care across health facilities. Healthcare professionals should be able to capture, update, retrieve, and share patient data securely and efficiently.

The system must also support clinical and administrative workflows, such as appointment scheduling, laboratory and pharmacy management, and reporting of health services. These functions should be implemented through modular applications that can operate independently while remaining interoperable through standardized interfaces.

Another key functional requirement is data collection and aggregation. The system should allow health workers to collect data using mobile and web-based tools, including offline data capture where internet connectivity is limited. Collected data must be synchronized automatically when connectivity is restored and aggregated at district, provincial, and national levels for monitoring and evaluation purposes.

Interoperability is a central functional requirement. The system must exchange data with existing health information systems using standardized protocols and RESTful APIs. Integration with national platforms such as DHIS2 is essential to ensure consistency in health reporting and policy alignment.

The architecture must also include decision-support capabilities. By integrating analytics and artificial intelligence components, the system should provide alerts, trends, and recommendations to assist healthcare providers and policymakers in clinical and strategic decision-making.

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Finally, the system must incorporate security and access control functions, including user authentication, authorization, audit logging, and consent management, to ensure that only authorized users can access sensitive health information.

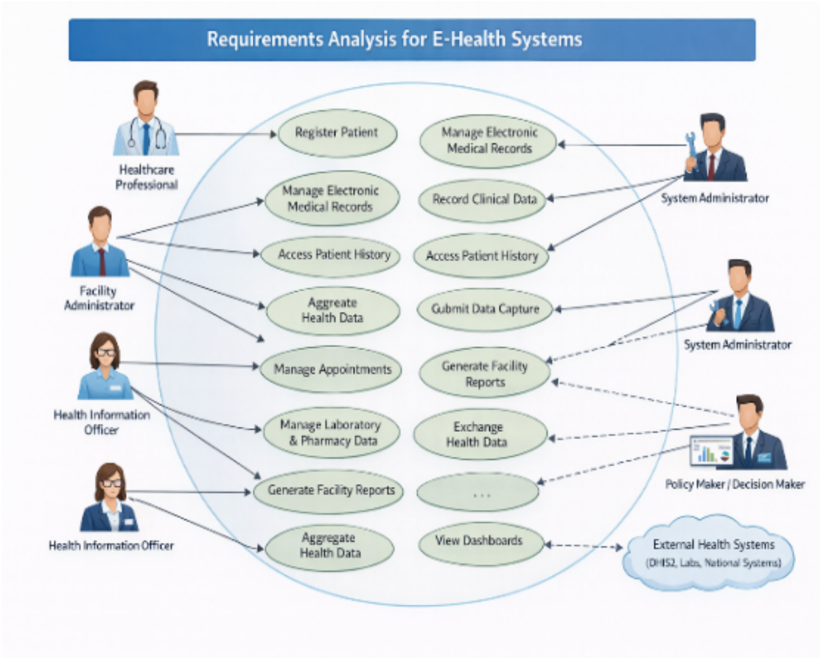

Fig. 6. Requirements Analysis for E-Health Systems

6 Implementation Considerations

6.1 Integration with Existing Health Information Systems

Successful implementation of the proposed e-health architecture requires seamless integration with existing health information systems already deployed within healthcare institutions. In the Democratic Republic of Congo, many facilities operate heterogeneous systems developed independently for specific programs such as disease surveillance, patient management, or administrative reporting. These systems often lack interoperability and standardized data structures, leading to fragmentation of health information.

The proposed architecture addresses this challenge by incorporating an interoperability layer that enables data exchange through standardized protocols and application programming interfaces. Rather than replacing existing systems, the architecture supports incremental integration, allowing institutions to preserve prior investments while improving overall system coherence.

Data migration strategies must also be carefully planned to ensure continuity of operations and preservation of historical records. Where legacy systems rely on paper-based documentation, digitization processes should be implemented gradually to avoid disruption of clinical workflows. Training programs are essential to help healthcare professionals adapt to integrated digital environments

6.2 Scalability and Sustainability

Scalability is a critical requirement for digital health systems in resource-constrained environments. The proposed architecture is designed to support phased deployment, beginning with pilot implementations in selected healthcare facilities and expanding progressively as infrastructure and capacity improve.

A modular design enables the addition of new services without requiring major system redesign. This flexibility allows the architecture to accommodate emerging technologies, increasing user demand, and evolving healthcare priorities. Cloud-based components provide additional scalability by enabling dynamic allocation of storage and computing resources.

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Sustainability depends not only on technical factors but also on financial and institutional support. Long-term system operation requires reliable funding mechanisms for infrastructure maintenance, software updates, technical support, and capacity building. Partnerships with governmental agencies, international organizations, and private stakeholders can contribute to sustainable financing models.

Capacity development is equally important. Continuous training programs should be established to enhance digital competencies among healthcare workers and technical staff, ensuring effective system utilization over time.

6.3 Governance and Policy Requirements

Robust governance structures are essential for ensuring the effective and ethical use of e-health systems. Governance encompasses regulatory frameworks, institutional policies, accountability mechanisms, and oversight bodies responsible for guiding digital health initiatives.

In the context of the Democratic Republic of Congo, the development of comprehensive national standards for health information systems is crucial. These standards should address data management practices, interoperability requirements, security protocols, and system certification procedures. Clear policies regarding data ownership, consent, and access rights are necessary to protect patient privacy and build trust among users.

Institutional governance mechanisms should define roles and responsibilities for system management, including maintenance, monitoring, and incident response. Coordination between ministries, healthcare institutions, and regulatory authorities is required to ensure alignment of digital health initiatives with national health strategies.

Ethical considerations must also be incorporated into governance frameworks. Safeguards should be implemented to prevent misuse of health data and to ensure equitable access to digital health services across different population groups.

7 Discussion

7.1 Implications for Health Informatics Research

The proposed context-aware e-health information systems architecture contributes to health informatics research by addressing a critical gap between theoretical models and practical implementation in resource-constrained environments. While prior studies have extensively examined technology adoption determinants, fewer have translated these findings into concrete architectural frameworks tailored to fragile healthcare systems.

This study demonstrates that effective digital health implementation requires the integration of socio-technical factors into system design. By aligning architectural components with empirically identified adoption determinants—such as perceived usefulness, infrastructure availability, institutional support, and trust—the proposed framework advances the concept of user-centered health information systems.

Furthermore, the architecture extends traditional enterprise architecture models by incorporating resilience and adaptability as core design principles. In contexts characterized by intermittent connectivity, limited resources, and organizational constraints, conventional high-resource architectures may be impractical. The proposed model therefore contributes to the emerging field of context-aware digital health design, emphasizing that technological solutions must reflect local realities rather than replicate models developed for high-income settings.

The research also highlights the importance of interdisciplinary approaches combining information systems, public health, and policy perspectives. Such integration is essential for developing sustainable digital health solutions capable of supporting healthcare transformation in developing countries.

7.2 Practical Implications for Healthcare Systems

From a practical perspective, the proposed architecture provides a structured roadmap for healthcare institutions seeking to implement or upgrade e-health systems. By adopting a layered design, healthcare organizations can prioritize critical components based on available resources and operational needs.

The modular nature of the framework facilitates phased deployment, enabling institutions to begin with essential services such as electronic health records and progressively integrate advanced functionalities like telemedicine and decision support systems. This approach reduces financial risk and implementation complexity while allowing continuous improvement.

The architecture also supports improved coordination of healthcare services through enhanced data sharing and interoperability. Integrated information systems can reduce duplication of efforts, minimize medical errors, and improve continuity of care across different facilities. Additionally, the incorporation of mobile health solutions extends service delivery to underserved and remote populations, thereby improving healthcare accessibility.

Security and privacy provisions embedded within the architecture are particularly important for building trust among healthcare professionals and patients. Trust is a key determinant of technology adoption, especially in environments where concerns about data misuse may hinder digital transformation initiatives.

For policymakers and health system planners, the framework offers guidance for aligning technological investments with national health priorities. It underscores the necessity of complementary actions such as workforce training, infrastructure development, and regulatory reform to ensure successful implementation.

7.3 Comparison with Existing E-Health Architectures

Existing e-health architectures developed in high-income countries typically assume reliable infrastructure, stable connectivity, and advanced institutional capacity. While these architectures emphasize interoperability, data analytics, and sophisticated clinical decision support, they may not adequately address the constraints faced by developing healthcare systems.

The proposed architecture differs in several important respects. First, it explicitly incorporates infrastructural limitations as a design parameter, advocating hybrid solutions that combine local and cloud-based resources to ensure system resilience. Second, it emphasizes scalability and modularity, enabling gradual implementation rather than large-scale deployment.

Third, the architecture integrates governance and policy considerations more explicitly than many technical frameworks. In fragile healthcare systems, institutional factors play a decisive role in determining the success or failure of digital health initiatives. By embedding governance mechanisms within the architectural design, the framework acknowledges the socio-political dimensions of technology implementation.

Compared with other context-oriented models proposed for developing countries, the present architecture offers a comprehensive approach that simultaneously addresses technical, organizational, and environmental factors. Its layered structure ensures flexibility while maintaining coherence across system components.

Overall, the comparison highlights that effective e-health implementation requires architectures specifically tailored to local contexts rather than direct transplantation of solutions from technologically advanced settings. The proposed framework therefore represents a step toward more inclusive and sustainable digital health development.

8 Conclusion

8.1 Summary of Contributions

This study proposed a context-aware information systems architecture to support sustainable e-health implementation in the healthcare sector of the Democratic Republic of Congo. Recognizing that digital health transformation in resource-constrained environments requires more than technological solutions, the research integrated infrastructural, organizational, and institutional considerations into a comprehensive architectural framework.

The proposed architecture contributes to the literature by translating empirically identified adoption determinants into a practical system design. Its layered structure—comprising infrastructure, application, data management, interoperability, and security components—ensures flexibility, scalability, and resilience under challenging conditions such as limited connectivity and unstable power supply.

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From a theoretical perspective, the study advances health informatics research by bridging the gap between technology adoption models and information systems architecture design. From a practical standpoint, it provides policymakers, healthcare institutions, and system developers with actionable guidance for planning and implementing digital health solutions adapted to fragile healthcare systems.

Overall, the framework supports a sustainable pathway for digital transformation, enabling improved healthcare accessibility, efficiency, and quality of services.

8.2 Limitations

Despite its contributions, the study has several limitations. First, the architecture was developed as a conceptual framework and has not yet been implemented or empirically validated through large-scale real-world deployment. Practical implementation may reveal operational challenges not fully captured in the design phase.

Second, the research focused primarily on healthcare professionals' perspectives and institutional factors, potentially overlooking the views of patients, community health workers, and other stakeholders. Including these perspectives could provide a more comprehensive understanding of system requirements.

Third, the study is context-specific to the Democratic Republic of Congo. While many findings may be applicable to other developing countries, differences in policy environments, technological capacity, and healthcare structures may limit direct generalization.

Finally, rapid technological evolution in digital health may require continuous adaptation of the proposed architecture to accommodate emerging innovations such as artificial intelligence, advanced analytics, and Internet-of-Things medical devices.

8.3 Future Research

Future research should focus on empirical validation of the proposed architecture through pilot implementations in healthcare facilities. Such studies would provide valuable insights into system performance, usability, cost-effectiveness, and impact on healthcare delivery outcomes.

Further investigations could also explore patient-centered perspectives on digital health adoption, particularly in rural and underserved communities. Understanding user experiences across different stakeholder groups would enhance the design of inclusive e-health solutions.

Additionally, comparative studies across multiple developing countries could identify context-specific and universal factors influencing successful implementation. This would contribute to the development of adaptable frameworks applicable to diverse healthcare environments.

Finally, future work may examine the integration of emerging technologies, including artificial intelligence, mobile health innovations, and data-driven decision support systems, to enhance the capabilities of digital health architectures while maintaining security, privacy, and ethical standards.

Statement on conflicts of interest

None

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