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# A HEALTHCARE 5.0 COMPLIANT WORKFORCE DIGITAL TWIN FRAMEWORK FOR HEALTHCARE PERSONNEL IN RESOURCE-CONSTRAINED MEDICAL FACILITIES IN SUB-SAHARAN AFRICA

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## ABSTRACT

Successive industrial revolutions have reshaped the way people are managed at work. Each one brought some new inventions that made us rethink how humans and machines fit together. The Fourth Industrial Revolution (4IR) currently underway is characterized by a combination of technologies, including Artificial Intelligence, the Internet of Things, Cloud Computing, Digital Twins, and more. And now, Industry 5.0 is shifting the focus toward something more human. It is less about pure automation and more about collaboration between humans and machines. The technologies of Industry 4.0 are transforming businesses by enabling smart, data-driven processes. However, workforce management is a key issue in healthcare despite advancements in healthcare technology. Many healthcare organizations still rely on old-fashioned systems to manage staff. Several challenges, including high turnover rates, burnout, workload imbalances, and limited real-time visibility into operations, persist and continue to hinder healthcare delivery. The existing solutions lack scalability, adaptability, and intelligence, leading to fragmented communication and poor decision-making. This study presents the development of a Workforce Digital Twin (WDT) for healthcare professionals using the Cross-Domain Digital Twin design pattern. This solution offers a transformative step forward in managing healthcare personnel by enabling data-driven, adaptive, and intelligent workforce strategies.

*Keywords: Cross-Domain Digital Twin, Healthcare 5.0, Industry 4.0, Real-time Monitoring, Workforce Digital Twin*

## 1. INTRODUCTION

In recent times, healthcare has been drifting away from the old hospital-centered mindset toward something far more personal. The goal of Healthcare 5.0 is to integrate smart technologies to provide a flexible, efficient, and personalized system. Each industrial revolution has transformed not only how we produce and consume but also how we organize work itself. The current industrial revolution has brought together Artificial Intelligence, Digital Twins, Internet of Things, and Cloud Computing. Digital twins, at their core, are detailed virtual representations of physical objects. They allow the simulation, monitoring, and control of the objects they represent. They may also predict what is happening to these objects in real life and in real time. They can involve everything from 3D models and sensor data to AI-driven analytics that learn patterns and suggest improvements [1]. As a result, powerful tools for various sectors, especially healthcare, can be developed using digital twins. Still, applying this to healthcare introduces its

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own complications [2]. The management of medical workforces has always posed challenges due to factors like high turnover and burnout. Healthcare organizations trying to balance patients' needs with human resources constraints face additional challenges with traditional workforce management systems, which are mostly static and reactive and designed for record-keeping rather than real-time decision-making. This leads to suboptimal, delayed, and inefficient patient care. Digital twins, therefore, offer a way to rethink all that. Gaps in uncoordinated and real-time workforce solutions are a source of conflict in healthcare, and they can be substantially addressed through real-time communication and integration. This is where digital twins come in, as they would enable guided decision-making using real-time data on all variables across healthcare organizations.

This study aims to investigate the potential of digital twin technology to address longstanding problems in healthcare workforce management, particularly those of real-time synchronization and unified control. The study utilizes the principles of the Cross Domain Digital Twin (CDDT) design pattern to conceptualize and realize the Workforce Digital Twin (WDT). In practice, this involves constructing a mechanism that retrieves information from sensors, smart devices, and electronic health records and utilizes it to optimize operational efficiency. The main objectives of this research are: 1) Document the methods employed by organizations in the management of their workforce; 2) Design a systematic WDT framework that is capable of modelling the dynamics of the healthcare workforce, including their adaptive fluctuations and scalability in response to varying conditions; 3) Investigate the digital twins of humans, machines, and environments, all interconnected as referenced by the CDDT in the Internet of Digital Twins (IoDT) and 4) Explore the roles that human and non-human entities may execute in the transition from the fourth to the fifth industrial revolution.

Fundamentally, this research proposes an integrated, practical, and prospective model that goes beyond a dashboard or an adaptive monitoring solution, but evolves in tandem with the demands of the healthcare industry. By combining real-time data with AI-based decision-making, this project aims to demonstrate how operations can become more efficient, responsive, and humane. Its generic form is not limited to the healthcare sector alone, and if adopted, will help other industries rethink workforce management. The study follows the Object-Oriented Analysis and Design (OOAD) approach in architecting the Workforce Digital Twin (WDT) framework. OOAD provides a systematic way to model real-world entities (such as healthcare personnel, hospital environments, and medical equipment) using objects, classes, and interactions. Through class hierarchies and object interactions, OOAD facilitates the modular implementation of CDDT layers. The work makes two main contributions. First, it presents a digital twin for a small-scale workforce unit within a healthcare system, designed to be scalable and adaptable to larger organizational settings. It demonstrates how workforce operations are coordinated in real time by connecting human, patient, equipment, and work environment data. Second, the study shows how the WDT can be extended beyond workforce coordination to support patient care. By integrating HumanDTs, the system can provide personalized care tailored to each patient. Together, these results highlight how a Workforce Digital Twin can improve work efficiency and also act as a bridge toward delivering Healthcare 5.0.

## 2. LITERATURE REVIEW

Workforce management is a strategic approach to optimizing employee productivity and efficiency within an organization. As we gear towards an era of automation, there needs to be a balanced approach to human resource development and automation. The impact of technological progress on workforce management has been profound and multifaceted. This transformation has reshaped the labor market, altering the demand for skills and the nature of work in several critical sectors. The adoption of disruptive technologies associated with the Fourth Industrial Revolution, also known as Industry 4.0, is reshaping how people work, learn, lead, manage, recruit, and interact with one

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another. A new concept is developed through the application of technologies arising from Industry 4.0 in the human resources sector, making it more agile, ensuring workers' welfare before the labor market, and unlocking human potential for new tasks to meet the increasing importance of workforce management in a globalized and competitive environment [3].

### 2.1. RESOURCE-CONSTRAINED MEDICAL FACILITIES IN SUB-SAHARAN AFRICA

The health systems of SSA are defined by severe, multi-dimensional resource deficits that limit the ability of these systems to deliver life-saving care and achieve Universal Health Coverage (UHC) [4]. For example, a quantifiable deficit reveals that the density of essential health workers (doctors, nurses, and midwives) in the WHO African Region averages 1.55 per 1000 population, which falls short of the 4.45 per 1000 required to deliver basic UHC [4]. A resource-constrained or poor locale is a region (municipality, state, or country) where the fundamental capacity to provide care for life-threatening illness is sharply limited. Resource deficits can be broadly classified as follows: 1) trained human resource shortages; 2) infrastructure and equipment deficiencies; and 3) low per capita expenditure on health.

The most profound constraint facing SSA medical facilities is the severe shortage of human capital. SSAs have fewer medical workers per capita than any other region globally [5]. The sheer scale of the shortfall is projected to reach 6.1 million healthcare workers in the African Region. If escalating disease prevalence and reduced productivity due to working conditions are factored into this projection, the actual health worker shortage could be 93 percent larger than the raw number suggests [6]. Beyond the raw number is the problem of poor deployment. Half of all health centres and health posts in rural areas have only one or a few clinical staff assigned to them. This is due to weak rural retention and the acceleration of brain drain. Several systemic factors drive healthcare workers towards emigration or to large urban centres, poor infrastructure such as unreliable electricity and inadequate drinking water, limited opportunities to earn extra income at private facilities, and the absence of clear professional development pathways. The result is increased emigration of healthcare workers to high-income countries, particularly the United States, from nearly every SSA country except South Africa [7]. Compounding quantitative shortages in human resources are qualitative deficits in human capacity. Studies reveal that large proportions of health workers demonstrate low levels of clinical knowledge, particularly in maternal and child health [5]. The consequence of this tragic indicator of resource constraint failure is the high rate of maternal and infant mortality. Sub-Saharan Africa has the world's highest maternal mortality rates at 546 deaths related to pregnancy or childbirth for every 100,000 live births, a figure that contrasts sharply with the 12 per 100,000 in high-income countries.

The inability to leverage technology and specialized care is a consequence of inadequate infrastructure and equipment, which are critically deficient in SSAs. One survey found in hospitals, the availability of at least one piece of capital medical equipment was found to be only 25.6%, with average equipment availability at 55.93% [8]. For advanced diagnostics, the scarcity is more severe. Only 11 percent of African respondent countries have at least one MRI machine per million population, and only 24 percent have at least one CT scanner [9]. Compounding the crisis of scarcity is that of functionality. Estimates from the WHO indicate that between 50% and 80% of medical equipment in developing nations is broken, nonfunctional, or scarce [8]. This is due to a systemic failure caused by a lack of planned preventive maintenance, insufficient financial resources, and a severe deficit in trained biomedical engineers.

The low operational budget available to SSA health systems is a defining constraint. Current Health Expenditure (CHE) per capita in many SSA countries ranges between $37 and $100, in sharp contrast to Western countries, which often exceed $2,000 per person [10]. This underinvestment limits access to quality care and the ability to maintain infrastructure or respond effectively to public health challenges. SSA is the region that is most reliant on development assistance for health (DAH) as a source of health spending. In 2021, 23 out of 46 countries in SSA depended on external financing for than a third of their total health budget [11]. This dependence on DAH introduces immense structural fragility, and projections estimate a peak or decrease in 13 countries through 2050, posing a significant risk of reversing critical global health gains. Finally, the reliance on private contributions to health financing is disproportionate, resulting in catastrophic costs to patients. Out-of-pocket (OOP) spending remains the main source of health financing in 30 low and lower-middle-income countries globally, including many in Sub-Saharan Africa.

### 2.2. WORKFORCE IN THE HEALTH SECTOR

Healthcare is one of the largest sectors and largest employers in many countries. The healthcare workforce encompasses all individuals involved in providing or supporting healthcare services. It includes a wide range of staff, from doctors and nurses to administrative personnel, all of whom contribute to the system's functioning. Given its size, it faces several challenges, including the shortage of skilled health workers to meet the health service needs for universal health coverage, a problem also referred to as a skilled labor crisis. A study by Rotenstein et al. [12] found that nearly half of healthcare workers experience burnout, with nurses facing the highest rates (56%), followed by other clinical staff (54%) and doctors (47%). One of the leading causes of burnout is heavy workloads, which can increase the likelihood that healthcare workers will quit. In fact, having too much work increases the chances of workers wanting to leave by more than twice. Burnout has a significant impact on the quality of care patients receive, as it is linked to poorer care and greater staff turnover. Countries are finding it hard to retain the existing health and care workers and recruit new ones to meet the increased demand for health services over the past few years [13]. There is also the mental health crisis, as employees have been exposed to higher workloads and longer working hours since the COVID-19 pandemic [11],[14]. Stress, anxiety, and depression have been common symptoms experienced by health and care workers, which contribute to increasing attrition, dissatisfaction, and reduced productivity. Healthcare worker migration remains a pressing issue, particularly in countries in sub-Saharan Africa with low and middle-income economies. The most critical constraint facing medical facilities in these places is the profound deficit in human capital. These countries possess fewer medical workers per capita than any other region globally, which has consistently been identified as a major obstacle to improving health outcomes [5]. The brain drain phenomenon is driven by factors such as low remuneration, job dissatisfaction, and limited career progression opportunities [15]. Retention strategies are crucial in mitigating workforce shortages. Alkan et al. [14] identified key factors influencing staff retention, including leadership and management support, flexible work schedules, workplace support, and improved workplace conditions. The availability of essential medical equipment has also been identified as critically deficient across countries in sub-Saharan Africa. In surveyed hospitals, the availability of at least one piece of capital medical equipment was found to be only 25.6%, with average equipment availability at 55.93%. For advanced diagnostics, the scarcity is even more severe: only 11 percent of African respondent countries had at least one MRI machine per 1 million people, and only 24 percent had at least one CT scanner [8].

### 2.3. HEALTHCARE 5.0 AND INDUSTRY 5.0

In today's world, several emerging digital technologies present opportunities to improve health service delivery. Healthcare is evolving as the times change, and it has reached a point where we can adopt technologies such as nanotechnology, 5G, drone technology, blockchain, robotics, big data, the Internet of Things, artificial intelligence, and cloud computing. All these technologies make Healthcare 5.0 possible. Healthcare 5.0 represents a shift towards patient-centric, digitally driven healthcare, integrating advanced technologies to personalize and optimize care. It emphasizes patient empowerment, proactive health management, and the seamless integration of human

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expertise with artificial intelligence, big data, IoT, and other technologies. Mbunge et al. [16] discussed how healthcare 1.0 evolved into healthcare 5.0. The first era of healthcare used paper-based systems because digital technologies were nonexistent. To improve the privacy and security of health records while enhancing maintenance and scalability, healthcare 2.0, known as e-Health, was introduced. With technological advancement in the medical field, telehealth and electronic health records were added to healthcare 2.0, which subsequently led to the introduction of healthcare 3.0. We're currently in the age of healthcare 4.0 where emerging technologies such as AI, Internet of Things, digital twins, blockchain technology, and machine learning have been adopted to tackle the issues in the previous era, where the electronic health records were prone to active security attacks by malicious entities to gain access to sensitive information to be sold or used for personal purposes. Healthcare is not the only sector that has benefited from technological advancements over the years. The term Industry 4.0, coined as the fourth industrial revolution, refers to a higher level of automation to improve operational productivity and efficiency by connecting the virtual and physical worlds within an industry. Industry 5.0 is focused on human-machine connectivity and coexistence. It emphasizes a more human-centric, sustainable, and resilient approach, fostering collaboration between humans and smart machines.

### 2.4. WORKFORCE MANAGEMENT IN HEALTHCARE 5.0

Industry 5.0 reaffirms the role of workers in the workplace, where humans and machines work together to improve process efficiency by leveraging the ingenuity and brainpower of human labor. Workforce management in healthcare 5.0 represents a significant evolution from traditional approaches driven by the core principles of human-centricity, sustainability, and resilience. It's about optimizing collaboration between healthcare professionals and advanced technologies to deliver personalized, predictive, and efficient care while prioritizing the well-being and development of the workforce. Digitalization of human resources practices is accelerating, which is changing how it manages daily operations. The change promotes reduced human intervention while boosting resilience and productivity. Some of these shifting HR practices and strategies include training and development, evaluative functions, managing remote teams, automation, and resource management [17]. Digital twins are seen as game changers in healthcare 5.0, acting as a perfect representation of its core principles: hyper-personalization, predictability, sustainability, and human-centricity. They play a significant role in workforce development as they can be used to train and upskill employees across various industries. Hazrat et al. [18] explore the transformative potential of Digital Twin (DT) technology in engineering education. The paper focuses on integrating DT-based teaching and learning practices into engineering education, aligning workforce capabilities with advancements in Industry 4.0 and Industry 5.0 technologies. [19] Schneider et al. [19] also developed a digital twin for a wafer transportation system. They used it to train workers in a semiconductor manufacturing plant, highlighting its role in improving staff training.

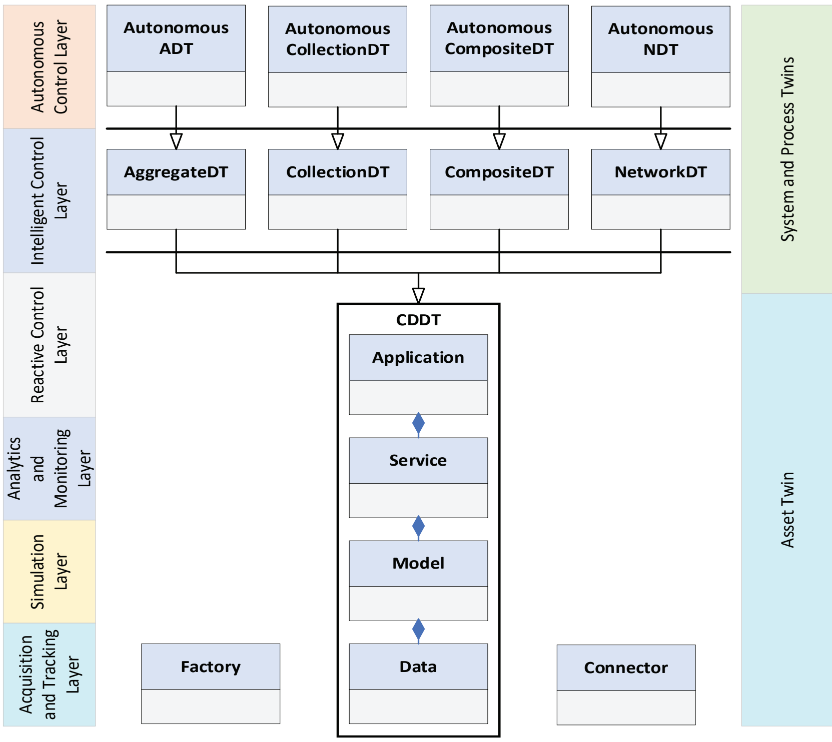


Figure 1: Cross-Domain Digital Twin (CDDT) Design Pattern

They essentially create dynamic, living virtual replicas of physical entities, constantly updated with realtime data, and these "twins" can be applied at various levels within the healthcare ecosystem.

## 2.5. DIGITAL TWINS

Digital Twins are not just simple replicas; they incorporate the properties of their physical counterparts at multiple scales. It spans various disciplines, serving as the backbone of Industry 4.0, including computer science, information technology, communications, engineering, automation integration, and physics, among others. Singh et al. [20] proposed a study of digital twins from their origins to their future, their advantages, types of DTs, applications, and the challenges digital twins face. Their paper discusses the origins of digital twins in the aerospace industry and how they are expected to revolutionize other sectors. By the 2010s, advancements in Artificial Intelligence (AI), Internet of Things (IoT), cloud computing, and big data analytics propelled DT technology into mainstream adoption. Now digital twins have become a crucial tool for enhancing operational efficiency, reducing downtime, and enabling predictive maintenance in multiple industries [21]. The use of Digital Twin (DT) technology in healthcare is revolutionizing our approach to diagnosing, treating, and managing various medical conditions. This technological advancement has enabled the development of living, data-driven models of patients, organs, medical devices, and even entire hospital systems.

The concept of a Human Digital Twin takes this even further. A Human Digital Twin, in essence, is a virtual replica of a human being that captures and records a person's information in real time, including vital statistics and other behavioral patterns. This sort of feedback transforms medical records from static, historical documents and habitual records into dynamic, evolving living records. Such records enable clinicians to provide fully personalized medical attention, including predictive diagnostics, remote surveillance, and optimized operational streamlining across the entire medical care structure [22]. The DigiTwin Consortium is a collaborative international project involving 32 countries that is developing patient-specific digital twins to enable physicians to

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model various treatment options virtually before they dispense actual medications [23]. These models run thousands of experiments safely in the background, identifying what works best while minimizing the risk of side effects. The implications of diseases like cancer, diabetes, or heart conditions are massive since small adjustments in therapy could make the difference between managing symptoms and achieving real recovery. Non-human twins also exist, such as digital twins of equipment that can virtually replicate an MRI machine or a ventilator within a hospital system, allowing the prediction of faults or the optimization of usage before breakdowns occur. It is not just a 3D rendering but a dynamic simulation that receives a constant stream of data from sensors on the actual device. The Dassault Systèmes' Living Heart Project has developed a digital twin of the human heart, allowing cardiologists to perform virtual surgeries, test medical devices, and refine their procedures in a zero-risk environment [22]. This technology is instrumental in complex heart surgeries where minor deviations can have significant consequences. Digital twins are also changing medical training. Instead of learning purely through textbooks and cadaver dissections, medical students and young surgeons can now practice with interactive virtual models, significantly improving their skills before they operate on real patients. There are several types of digital twins, and they don't just apply to the healthcare sector. For example, a process digital twin is a virtual model of an entire workflow or operational system. Instead of representing a single person or device, it represents a sequence of actions and provides insight into how different components interact to achieve an outcome. Sun et al. [2] discuss the application of digital twins in oncology, where researchers use virtual models of tumors to analyze growth patterns, evaluate drug effectiveness, and simulate radiotherapy responses. These virtual models allow the specialists to make more informed decisions about chemotherapy dosages, radiation therapy precision, and surgical strategies.

## 2.6. THE CROSS-DOMAIN DIGITAL TWIN DESIGN PATTERN

The Cross-Domain Digital Twin design pattern in Fig. 1 is a 5-layer architecture for DTs across all problem domains that support the ACE design dimensions [24]. The network of digital twins connected through the cloud is known as the Cloud of Digital Twins (CoDT). There are constraints placed on digital twins in the CoDT. Firstly, all DTs on the CoDT are proxies to the physical object they virtualize. They connect to the physical twin through the Internet, and all other connections are to other DTs on the cloud. Secondly, all DTs implement ACE: A indicates Autonomous & AI-Driven; C, Collaborative & Conversational; and E, Evolvable and Extensible. The different layers in the CDDT have different roles and responsibilities. The data layer represents cloud storage, and one of its components is a Connector that specializes in exchanging data between digital twins and their physical counterparts. Models of the physical object are implemented in the model layer. The service layer is the architectural tier responsible for abstracting the underlying complexity of physical assets, data ingestion mechanisms, and intricate computations in the cyber domain. Functionally, this layer serves as the unified carrier of data and applications, offering rich information services and comprehensive development interfaces to client systems. The application layer implements the CDDT, with specializations such as the CompositeDT, NetworkDT, and CollectionDT. The intelligence layer may evolve CDDTs with NetworkDT and CollectionDT. The CollectionDT represents homogeneous DTs, while the NetworkDT is a network of DTs that may be homogeneous or heterogeneous. Both DTs at the Intelligence layer generate large amounts of data necessary for training machine learning algorithms and predictive analytics methods. The autonomous layer evolves CDDT by inheriting from CollectionDT, CompositeDT, or NetworkDT, and creating one of three Autonomous DT classes in the process. An approach to creating AutonomousXDTs involves using imitation and reinforcement learning. The learning approaches should produce CDDTs capable of conversational collaboration with other autonomous DTs. The autonomous layer terminates CDDT evolution and implements the C design dimension, for Collaboration and Conversational in the ACE.

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## 3. A WORKFORCE DIGITAL FRAMEWORK FOR HEALTHCARE 5.0

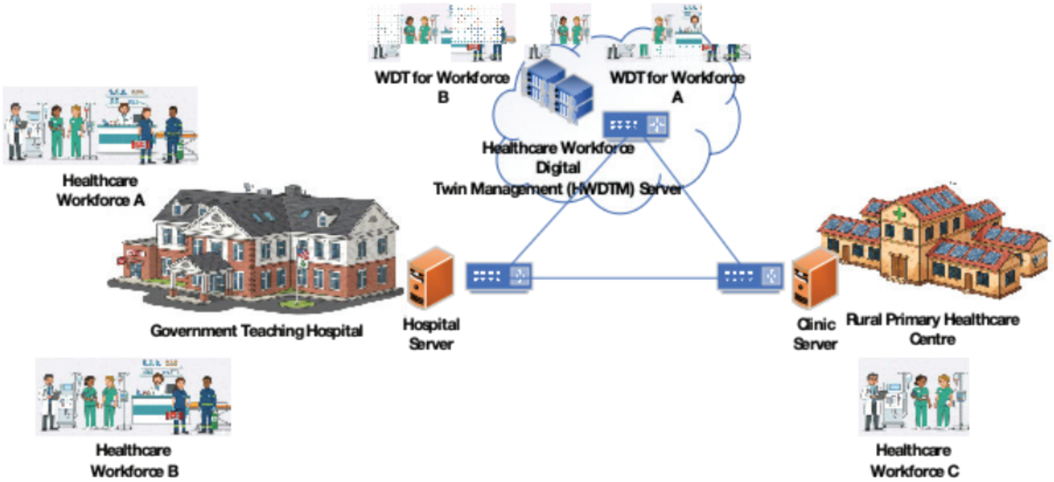


Figure 2: The Schematic Diagram of a Workforce Digital Twin Management Platform

The chronic shortage of medical infrastructure and skilled human resources in sub-Saharan Africa presents a complex logistical challenge that traditional management systems have struggled to address [25]. To navigate these constraints, this study proposes a paradigm shift utilizing cross-domain digital twin (DT) technology [26]. While Digital Twins have historically been applied to industrial manufacturing [21], this work extends the concept to the social services sector by integrating three distinct operational domains: personnel management, equipment leasing and maintenance, and healthcare delivery. This integration is designed to optimize the allocation of scarce resources across a heterogeneous geographical landscape, ranging from densely populated urban centers to dispersed rural villages.

Central to this methodology is the Healthcare Workforce Digital Twin Management (HWDTM) system (see Fig. 3), a cloud-based infrastructure conceptualized as a Workforce Digital Twin Platform-as-a-Service (PaaS). As detailed by Xiong & Gao [26], HWDTM provides the requisite scalability to support facilities of varying magnitudes. It facilitates the automatic instantiation of Workforce Digital Twins (WDTs) for institutions ranging from large-scale Government Teaching Hospitals to localized primary healthcare centres with minimal staffing.

Unlike static asset twins, the WDT is a process digital twin [27]. It dynamically coordinates the interplay between medical personnel, shared medical equipment, and physical infrastructure (e.g., consulting rooms and operating theatres). By simulating these interactions, the WDT aims to deliver high-quality care within a low-resource environment. The architecture functions on a dual-layer optimization model: 1) Local Level: The WDT optimizes immediate logistical flows within a specific facility. 2) Regional Level: The HWDTM platform aggregates data to manage resource distribution across the broader state or region, preventing resource hoarding and underutilization in urban centres at the expense of rural clinics.

A critical motivation for this architecture is the mitigation of two pervasive issues in the region: high Out-of-Pocket (OOP) expenditure for patients, which often leads to catastrophic health spending [4], and the high prevalence of clinician burnout due to excessive workloads [28]. The proposed system addresses this by introducing "Personnel DTs" (e.g., DoctorDT, PharmacistDT, NurseDT, MidwifeDT). These virtual agentic DTs are designed to autonomously handle routine clinical tasks, such as the diagnosis of common infectious diseases, the management of chronic conditions, and the monitoring of standard treatment protocols. By offloading these repetitive tasks to the Digital Twin, the system aims to reduce the cognitive load on human personnel and lower the cost of access for patients. In this study, we present a proof-of-concept of

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the healthcare workforce digital twin, developed via simulation and validated through limited cloud-based trials. It should be noted that while the architectural framework for these agents is established here, the development of the fully autonomous, agentic DT algorithms remains a subject for future research and is outside the scope of the current work [26].

The Workforce Digital Twin (WDT) in healthcare 5.0 is represented as a Process Digital Twin, whereby the WDT is not just a static digital replica of the entities that make up the workforce but rather a dynamic model that simulates, monitors, optimizes, and controls the processes involved in workforce management. The WDT represents the end-to-end processes that drive workforce management in healthcare institutions. It leverages the Cross-Domain Digital Twin (CDDT) design pattern and emphasizes workflow simulation, monitoring, and optimization [24]. The data layer serves as the foundation for all data collection and connectivity. This layer integrates data from various sources, which is funneled through a connector that feeds structured data into models in the service layer. The DataStore component stores all data about humans, equipment, and the work environment. All models of the physical object are implemented at the model layer. The application layer manages the core application logic for coordinating the system's digital twins. It implements the WDT as an AggregateDT in the CDDT design pattern. The intelligence layer evolves the CDDT with CollectionDT, NetworkDT, and AggregateDT. In our case, the WDT is represented as an AggregateDT. The Intelligence layer collects data necessary for training machine learning algorithms and predictive analytics methods, such as burnout risk prevention and optimal shift allocation.

## 3.1. SYSTEM REQUIREMENTS

The system requirements for the Workforce Digital Twin are grouped into two broad categories: functional and nonfunctional requirements. Functional requirements describe what the system actually does. Non-functional requirements focus more on how the system behaves as a whole. In the context of Sub-Saharan Africa, the WDT must support coordination that goes beyond a single hospital. Many health centers rely on small rotating teams or shared equipment, making cross-facility visibility essential for stabilizing service delivery. For this reason, some of the system's functional requirements explicitly account for multi-facility scheduling and the challenges of resource-constrained environments.

### 3.1.1. Functional requirements

The functional requirements describe the concrete capabilities the system must provide in order to operate the digital twins effectively. These requirements define the core actions and behaviors that enable the WDT to coordinate personnel, patient, and equipment twins within a healthcare environment.

#### FR1: User Management and Access Control

The system supports user registration, authentication, and role-based access control for different user categories (e.g., healthcare personnel and administrators).

#### FR2: Workforce Control Interface

The system should have a clear, intuitive dashboard that serves as the command center for workforce operations.

#### FR3: Data Ingestion and Integration

The system must be integrated with IoT devices, wearable sensors, and hospital information systems to continuously capture and process live data streams. This involves not only collecting data but also pushing updates through the closed-loop

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system.

**FR4: Predictive Analytics**

The system must provide the necessary data in the right format for predictive analytics. These models will analyze historical and real-time data to forecast and provide recommendations.

**FR5: Multi-Facility Workforce and Equipment Coordination**

The system should support scheduling and resource allocation across multiple healthcare facilities. This is particularly relevant in Sub-Saharan Africa, where health centers often face uneven workforce distribution, shortages of skilled personnel, and limited access to critical medical equipment. The WDT must allow administrators to view personnel and equipment availability across facilities and reassign resources where needed to close density gaps and mitigate the effects of brain drain

#### 3.1.2. Nonfunctional requirements

Nonfunctional requirements specify the qualities and constraints that shape how the system performs the specified functions. They do not give specific functions but describe how the WDT can operate safely, efficiently, and sustainably in real-world deployment.

**NFR1: Scalability**

The system must be able to support future growth and potential increase in user volume.

**NFR2 Regulatory Compliance**

Ensure compliance with healthcare industry regulations and relevant data privacy regulations.

**NFR3 Performance**

The system should respond to user interactions quickly, ensuring a seamless user experience.

**NFR4 Reliability**

Ensure constant system uptime to prevent disruptions in workforce management.

### 3.2. DIGITAL TWINS IN THE WORKFORCE ECOSYSTEM

The Workforce ecosystem consists of actors, namely: healthcare personnel (doctors, nurses, pharmacists, etc.), patients, and equipment. Each actor is represented virtually in the workforce digital twin (see Fig. 3). That is, WorkforceDT is an aggregate of EquipmentDT, PatientDT, and PersonnelDT. Throughout the lifetime of the WorkforceDT, patients, personnel, and equipment can be assigned and removed. The following paragraphs present a brief description of digital twins.

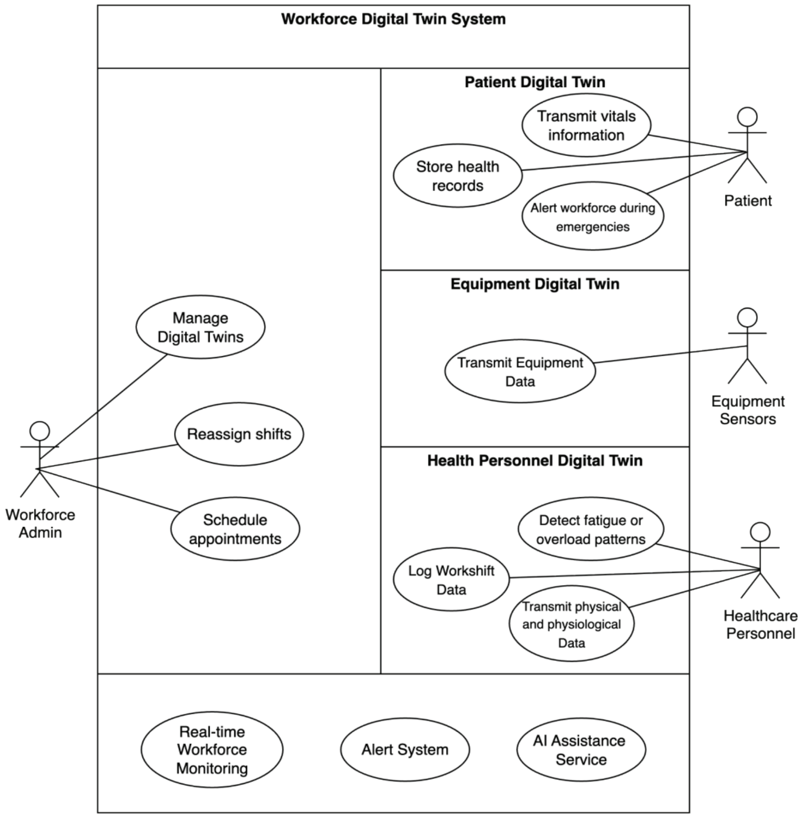


Figure 3: Workforce Digital Twin Use Case Diagram

Equipment Digital Twin: An EquipmentDT is a virtual representation of a physical healthcare device or machine, connected to patients in real time via sensors. An example is an MRI machine, a physical asset equipped with sensors that measure temperature, vibration, power consumption, magnetic field strength, and patient usage data. The equipment's digital twin runs in the cloud and is continuously updated with live data. Predictive models can detect early signs of unusual operation and report them back to the physical equipment, alerting the system and automatically adjusting operating parameters. This shows the closed-loop system as defined in digital twin terminology.

Patient Digital Twin: A PatientDT extends the HumanDT. The HumanDT is a virtual representation of a person's physiological state that captures the static and dynamic data of the individual. The extension occurs when the individual is put in the healthcare system as a patient. It becomes specialized, condition-specific, and clinically actionable. The PatientDT integrates clinical data alongside HumanDT data and supports real-time patient monitoring. There are different classes of patients to consider. Types of patients could be outpatients, inpatients, and emergency patients. A patient can be connected to sensors, and their PatientDT can build specific trends, stress triggers, and track patterns, which their assigned healthcare personnel can monitor and make updates that act back on the patient.

Personnel Digital Twin: A PersonnelDT extends a HumanDT. It is placed in a workforce or organizational context, in this case, a hospital or clinic. It is a role-specific twin that incorporates not only human attributes but also job-related context and performance data. For example, a HumanDT is just a person with certain skills and health, but a PersonnelDT could be a nurse assigned to a ward with a shift schedule, workload, and performance metrics. Other examples of PersonnelDT include doctors and other hospital staff. Data flows from the human staff to PersonnelDT, which then sends insights to the WorkforceDT. The WDT can send commands back and notify staff in real time.

**Workforce Digital Twin:** The WorkforceDT represents the entire workflow of the system, involving multiple other actors. It models how all elements interact with each other to achieve outcomes. It is dynamic, works in realtime, and evolves with the system. Data comes in aggregated streams from all other DTs, and the WorkforceDT serves as a process-level DT that runs analytics and provides a holistic, real-time simulation of the work system. Commands, insights, and optimizations flow back into operations, e.g., shift adjustments, patient flow optimization, etc.

## 3.3. USE-CASE NARRATIVES

### Real-Time Workforce Monitoring

The workforce admin uses the system to track, monitor, and manage healthcare personnel in real-time. This ensures that there is continuous visibility into workforce availability, workload distribution, and potential issues such as burnout or staff shortages.

### Adding a New Digital Twin

The Workforce Digital Twin administrator creates and configures a new Digital Twin instance within the Workforce Digital Twin (WDT) system. This could be for a new PersonnelDT, PatientDT, or EquipmentDT. The process involves defining entity attributes, linking data sources, and ensuring proper integration with the system.

### Healthcare Equipment Monitoring

How the system monitors the equipment conditions. For this use case, smart sensors continuously collect data and send updates to the WDT system. The WDT system then processes and analyzes sensor data to detect anomalies. If an anomaly is detected, it alerts the system and takes automated actions, if applicable. The dashboard is then updated in real-time to display the current conditions.

### Assigning Shift Changes to Healthcare Personnel

This use case explains how the system handles workforce scheduling and shift management for healthcare personnel. The system analyzes patterns in staff availability, workload, and past scheduling trends to ensure an even distribution of duties. When changes are needed, the WDT can automatically reassign staff while still respecting organizational policies. Once adjustments are made, the system immediately notifies the affected personnel and updates the central workforce dashboard in real-time.

### Logging Personnel Shift Data

In this use case, healthcare workers interact directly with the WDT system to record their shifts. Each time a worker starts or completes a shift, they log their work hours, break times, and any relevant updates into the system. The system then stores this information in the hospital database and allows the WorkforceDT to make informed decisions on actions to take.

## 3.4. MESSAGE SEQUENCE CHART

The message sequence chart shown in Fig. 4 illustrates the interaction between the workforce admin, the application interface, the WDT system, and the connected digital twins during real-time workforce monitoring. When the admin enters data into the application interface, the system triggers an authentication process. Once authenticated, the system retrieves workforce data from various digital twins, including personnel, equipment, and patient twins, and processes this information to analyze the current workforce status.

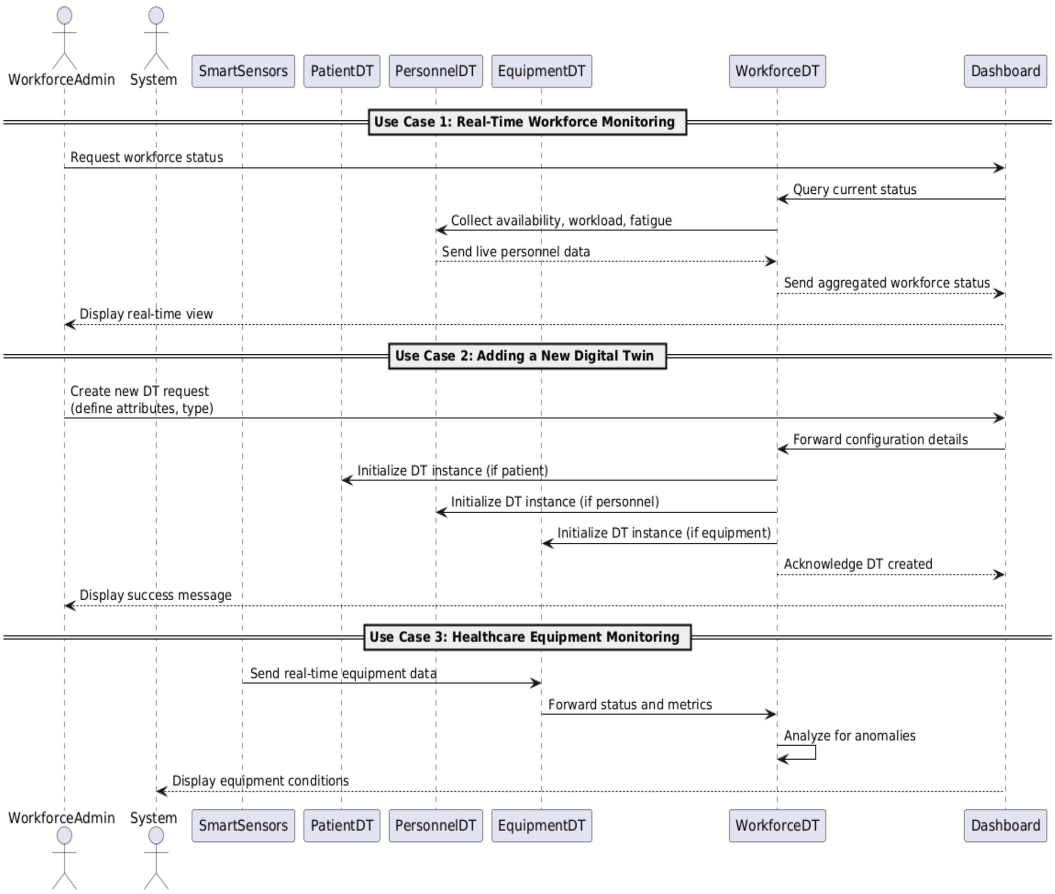


Figure 4: Message Sequence Chart

## 3.5. STATE CHART

The state chart in Fig. 5 depicts the lifecycle of adding a new digital twin to the Workforce Digital Twin system. It begins with the system in an idle state, awaiting an administrator's action. When the administrator initiates the process, the system transitions to the creation state, prompting the user to select the type of digital twin to create. After choosing the DT type, the administrator enters the required attributes and links the twin to its relevant data sources, such as hospital databases or IoT sensors. The system then performs data validation to ensure completeness and accuracy. If the validation succeeds, the digital twin transitions to an active state and becomes part of the WDT ecosystem.

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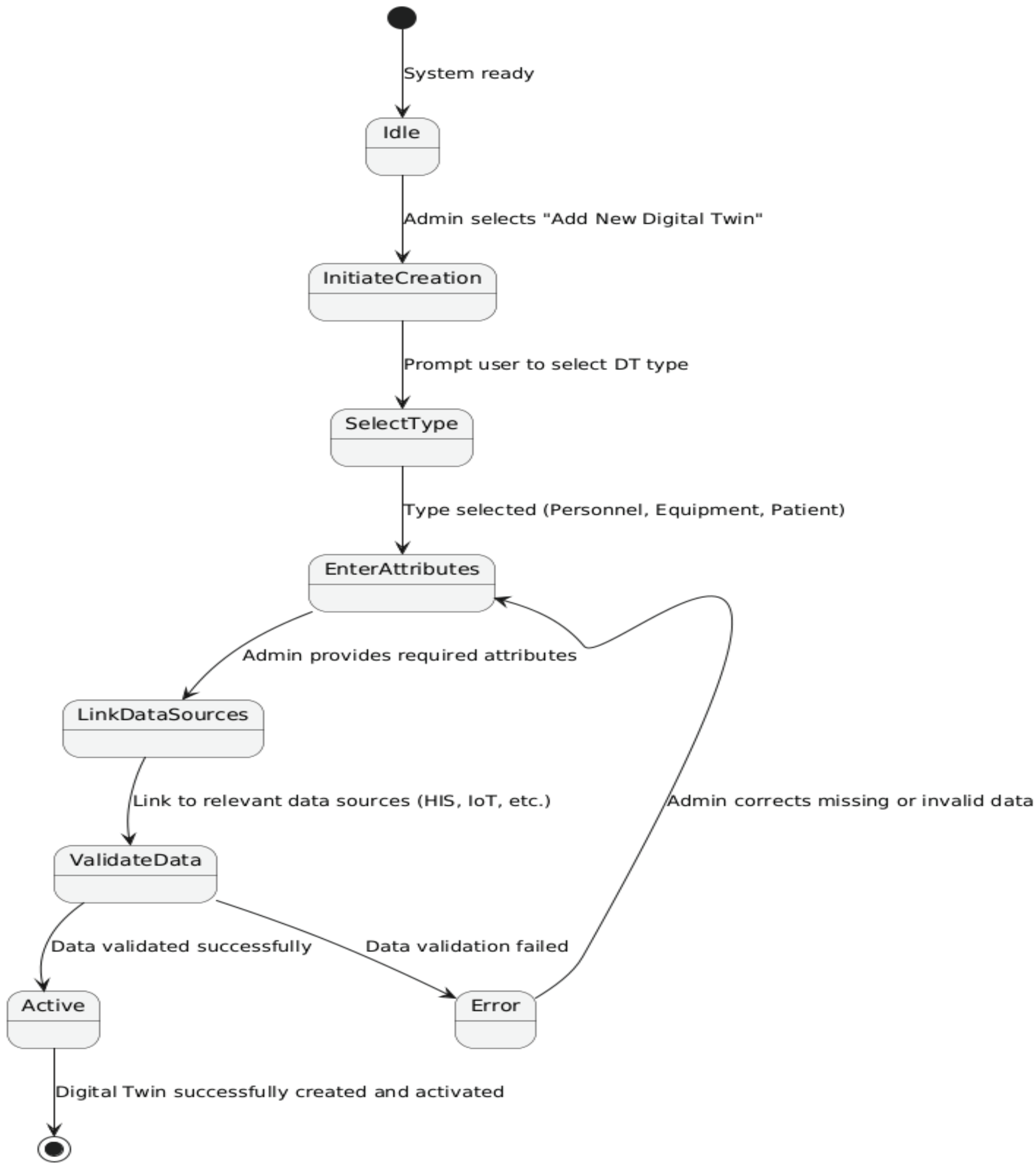


Figure. 5: State chart of the Workforce Digital Twin

## 3.6. CLASS DIAGRAM

The DTs in the WDT system are implemented by the Cross Domain Digital Twin (CDDT) design pattern. The Workforce Digital Twin will be an AggregateDT that encompasses several other DTs, such as the PersonnelDT, PatientDT, and EquipmentDT, as shown in Fig. 6. The WDT models the entire healthcare workflow and aggregates these DTs into a unified operational twin. The figure also shows how the PersonnelDT and PatientDT evolved from the HumanDT. The HumanDT is a representation of an individual as a human being, regardless of their role. Other DTs relating to humans can be derived from the HumanDT, depending on their specifications or the data they would require. EquipmentDT has an aggregation relationship with PatientDT, as one or more pieces of equipment can be assigned to a specific patient in the workforce ecosystem. That is, the PatientDT also serves as an aggregate for EquipmentDT by implementing the IAggregateDT interface.

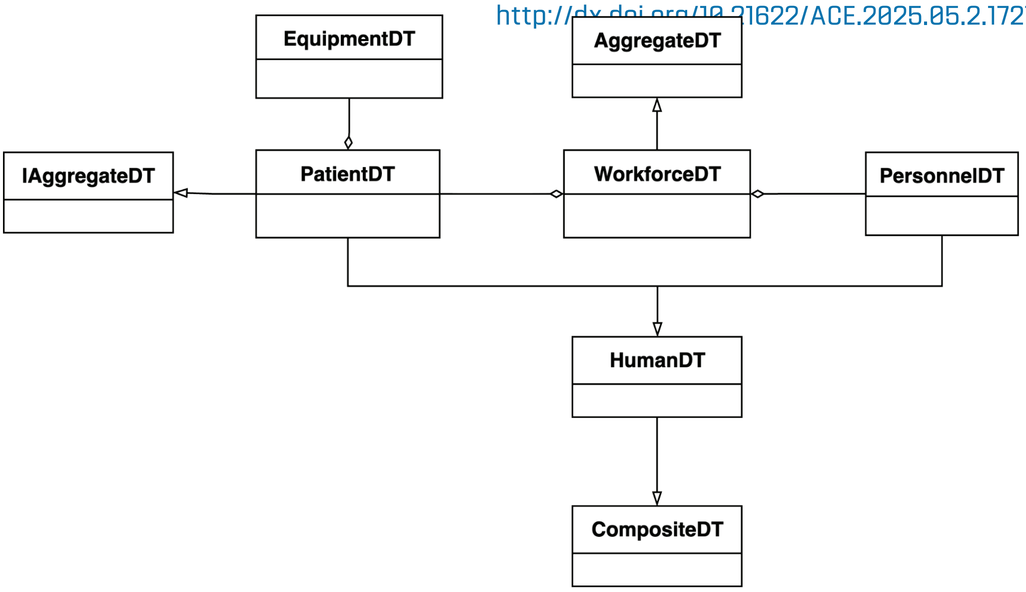


Figure 6: Design pattern for WorkforceDT

## 4. IMPLEMENTATION, RESULTS, AND DISCUSSIONS

This section presents the implementation of the WDT system for healthcare 5.0. The system was developed using the Cross-Domain Digital Twin (CDDT) design pattern, enabling seamless integration of multiple digital twins. Each DT was implemented as an independent, yet operable, component with well-defined attributes, dynamic behaviors, and interfaces.

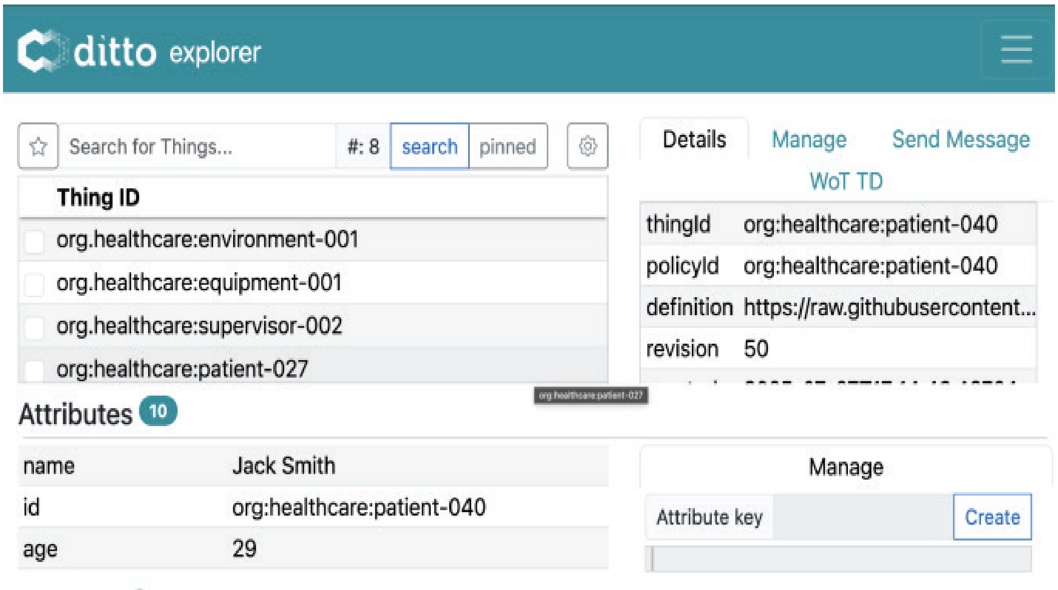


Figure 7: Eclipse Ditto Platform

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  },
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    }
  }
```

Figure 8: Workforce DT definition

## 4.1. IMPLEMENTATION

The realization of the framework includes the creation of the Digital Twin Layer. Eclipse Ditto (Fig. 7) served as the core digital twin orchestration platform in the system, responsible for managing the lifecycle, state, and real-time interactions of each twin (Patient, Health Personnel, and Equipment). For each pair of digital twins there is a custom connector. This connector is the communication interface between two DTs and ensures that when one DT updates, the related DT receives the data in the specified format. Each entity was represented as a "Thing" in Eclipse Ditto. These "Things" are JSON-based representations that contain: thingId-A unique identifier, e.g., org:healthcare:patient-001, definition- A URI pointing to the Thing model hosted on the Internet that describes the structure the twin should follow, attributes- static or descriptive information about the twin (e.g., name, gender, age), features- Dynamic or behavioral data about the twin (e.g., heart rate, status, temperature). Eclipse Ditto internally uses MongoDB to persist twin data, ensuring that twin state survives server restarts, historical values can be queried, and data changes are durable and reliable. The basic functions of the Digital Twin layer include creating digital representations of humans and non-human DTs, updating twins with new data, and ensuring consistency and accuracy.

## 4.2. RESULTS

The Workforce Digital Twin, as shown in Fig. 10, serves as the central orchestrator, coordinating and aggregating data from all other digital twins. It ensures consistent updates from other DTs, enhances interoperability, and creates system-wide awareness. The system's frontend has been built with the React framework. React served as the core framework for building the responsive, web-based frontend of the Workforce Digital Twin system. It enabled real-time monitoring, data visualization, twin management, and

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user interaction with the digital twin data hosted on Eclipse Ditto. Figure 9 shows the login page. Before the Workforce Digital Twin system can be accessed, users must log in to the system. The project involves potentially sensitive medical data, which requires this security measure for proper access control. The system's interface comprises the main dashboard, where the user can view various parts of the workforce and interact with the system. It also features the Patient Overview page in Fig. 11, which shows various information about the twin and allows actions to be performed on it. The system also allows the creation of new digital twins using a form for data entry. Fig. 12 shows a view of an Equipment DT. It features information about the equipment, the patient is currently assigned to, live equipment data and the activity log. Fig. 13 shows a view of the PersonnelDT, attributes of the personnel, and tabs to access other features of the DT.

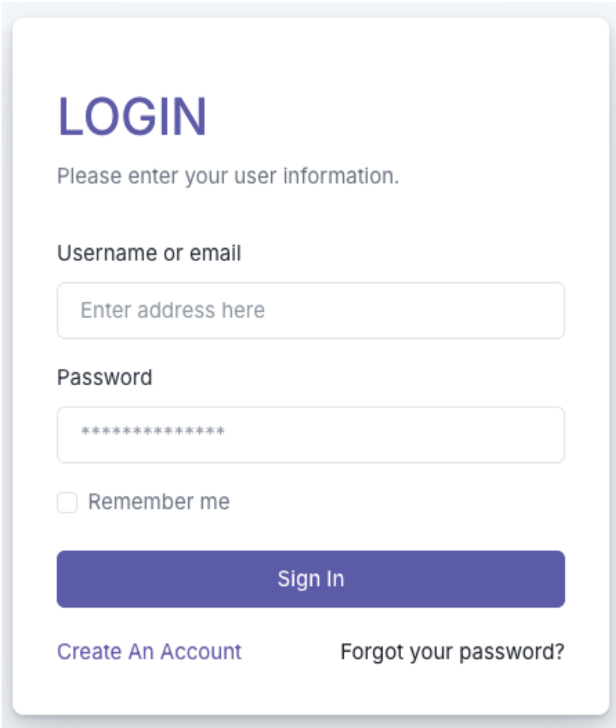


Figure 9: Login form

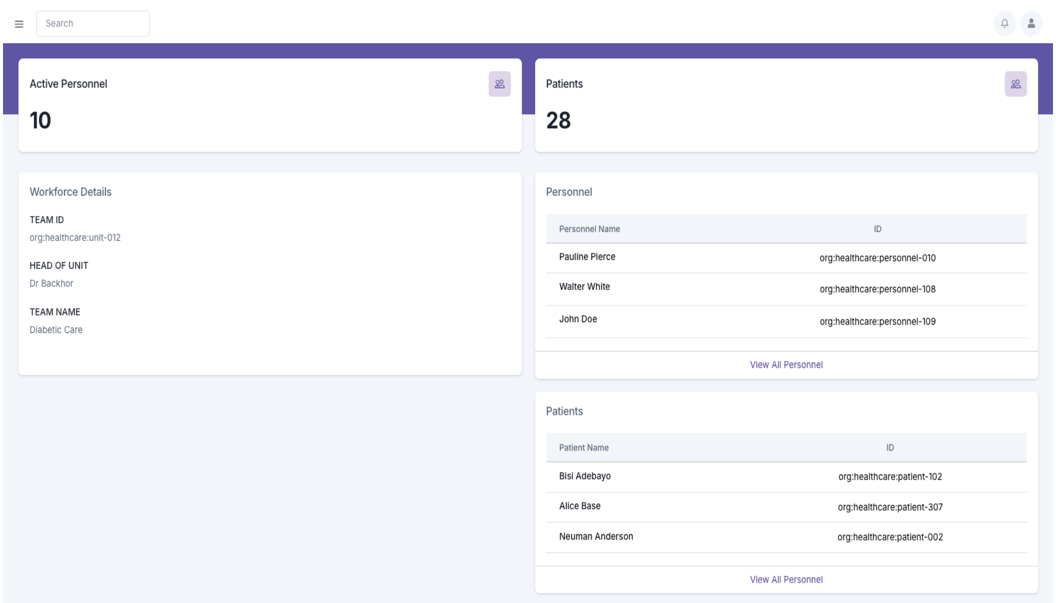


Fig. 10: WDT Dashboard

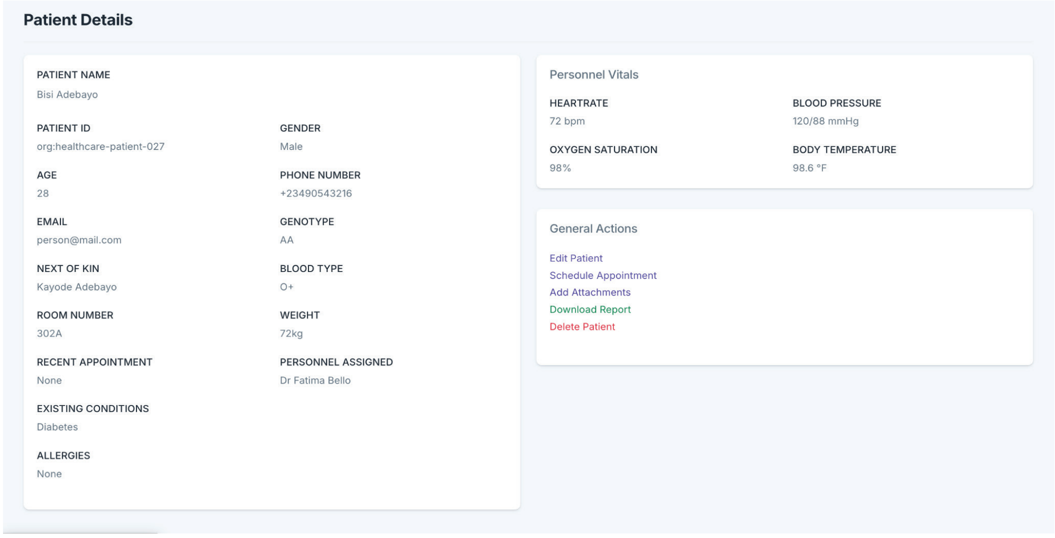


Figure 11: Patient DT View


Figure 12: Equipment Digital Twin View

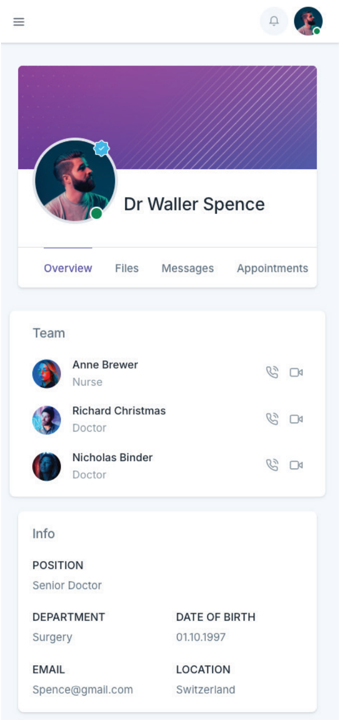


Figure 13: Personnel DT view

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### 4.3. DISCUSSION

The implementation and results demonstrate that the system meets the functional and nonfunctional requirements defined earlier in the study.

**Functional Requirements**

FR1: The system successfully implements user management and access control through a secure authentication interface, as shown in Fig. 9. This prevents unauthorized access and aligns with the system's need for controlled visibility over sensitive workforce and patient information.

FR2: The WDT Dashboard in Fig. 10 provides an intuitive interface for real-time monitoring and access to personnel, equipment, and patient digital twins, fulfilling the requirement for centralized workforce coordination.

FR3: Although the current study relies on simulated vitals and operational data, the ingestion mechanism mirrors the expected deployment setup. Each twin continuously receives updates from its associated data feed. The connectors ensure that when one twin changes state, the related twins receive the appropriate updates in a closed-loop manner. This demonstrates the system's ability to support real-time synchronization across multiple heterogeneous twins.

FR4: The Intelligence Layer structures twin data in a format suitable for analytical models. While the system currently focuses on data collection rather than executing predictive algorithms, the architecture prepares each twin to output structured behavioral and historical data needed for models such as burnout estimation, workload balancing, or attrition detection. This satisfies the requirement in terms of data readiness and integration points for future analytics.

FR5: The system architecture naturally supports multi-facility coordination because each PersonnelDT and EquipmentDT exists independently in the CDDT pattern and can be grouped under different facility contexts. Administrators can view all twins from multiple centers within the same dashboard, and the connector system allows workforce or equipment reassignment without redefining the underlying twins. While the current deployment focuses on a single site, the design accommodates the realities of resource-constrained regions where staff and equipment must often be redistributed to manage shortages.

**Nonfunctional Requirements**

NFR1: The system design ensures scalability by leveraging the CDDT design pattern, enabling the addition of new digital twins or the expansion of existing ones without disrupting operations.

NFR2: Although the work uses simulated data, the authentication layer, role-based access, and reliance on secure data channels demonstrate alignment with the privacy requirements expected in healthcare environments.

NFR3: Performance is supported through lightweight frontend technologies and efficient backend synchronization. This supports timely decision-making and ensures that real-time monitoring remains viable as twin interactions increase.

NFR4: Reliability is achieved through the persistence features of Eclipse Ditto, which store twin states in MongoDB. This ensures that each twin retains its history and attributes across refreshes, restarts, or temporary disruptions.

### 4.4. LIMITATIONS

The primary limitation of this study lies in the nature of data for system validation. While the functional logic of the Workforce Digital Twin (WDT) was successfully verified using the Eclipse Ditto Platform, the system currently relies on simulated data streams for personnel vitals, equipment status, and environmental conditions. This approach was sufficient to validate the architectural integrity of the Cross-Domain Digital Twin (CDDT) design pattern and ensure that simulated outputs matched the data stored within the twins. However, it does not account for real-world complexities such as sensor noise, hardware calibration errors, or unstable real-world sensor data. The assumption that physical sensors can be easily integrated remains a theoretical capability that requires field validation to ensure data accuracy in a production environment.

Furthermore, while the framework is contextualized for resource-constrained facilities in Sub-Saharan Africa, the current implementation assumes a stable cloud infrastructure for the Cloud of Digital Twins (CoDT). The study does not yet empirically test the system's resilience against specific infrastructure deficits common in the target region, such as intermittent internet connectivity or low-bandwidth environments, which may hinder the real-time synchronization required for the WDT.

Another limitation is the absence of a formal method for assessing burnout, workload imbalance, or attrition risk within the prototype. While the intelligence layer is positioned to report such analytics, the specific predictive models required to translate this data into actionable insights are not yet implemented. Advanced analytics, such as attrition risk prediction and sentiment analysis of workforce patterns, are necessary additions to realize the intelligence layer's potential fully.

## 5. CONCLUSION

This research represents a significant step towards managing the workings in a healthcare setting. The study set out to explore how digital twins can be used to improve real-time workforce monitoring, and through careful planning, research, design, and implementation, those goals were achieved. The implementation presented in this study serves as a proof of concept demonstrating that a Workforce Digital Twin can operate as a coordinated, real-time system within a healthcare context. By creating functional PersonnelDTs, PatientDTs, and EquipmentDTs on Eclipse Ditto and synchronizing them through connectors, the prototype successfully replicated the core behaviors expected of a full deployment. Overall, this project demonstrates the value and feasibility of using digital twins to bridge the gap between physical healthcare operations and digital oversight. Deploying the Workforce Digital Twin (WDT) in healthcare offers opportunities for better workforce management, improved patient outcomes, and greater operational efficiency, but comes with challenges and ethical concerns that must be addressed before the technology is deployed responsibly. These concerns range from data security and privacy concerns to worker well-being, privacy, and moral responsibility.

The transition from monitoring mechanical assets to monitoring human physiological and behavioral states introduces significant ethical complexities regarding surveillance. Real-time monitoring of personnel raises legitimate concerns about autonomy, consent, and the potential for misuse. In the context of Healthcare 5.0, which emphasizes human-centricity, the applications of such monitoring data must be strictly governed. There is an inherent tension between using surveillance data for operational efficiency and the potential for intrusive micromanagement. Future iterations of this framework must therefore be accompanied by rigid ethical guidelines that prioritize the physical twin's well-being over raw productivity metrics.

While this project successfully demonstrates the potential of digital twins for healthcare 5.0 workforce management, several areas warrant improvement and expansion for future development.

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