Journal Health of Indonesian
Volume 3, Number 02, 2025 (No 104-124)
E.SSN 2987-0313 (Online)

Patient Flow and Service Efficiency in Public Hospitals: Data-Driven Approaches, Strategies, Challenges, and Future Directions

[1]Okechukwu Chiedu Ezeanyim, [1]Emeka Celestine Nwabunwanne, [1]Nkemakonam Chidiebube Igbokwe, [1*]Charles Onyeka Nwamekwe
Industrial/Production Engineering Department, Nnamdi Azikiwe University, P.M.B. 5025 Awka, Anambra State – Nigeria

Article Info
Corresponding Author:
Charles Onyeka Nwamekwe
E-mail:
co.nwamekwe@unizik.edu.ng

ABSTRACT
Public hospitals in resource-constrained environments face persistent challenges in patient flow and service efficiency, often resulting in overcrowded emergency departments, delayed admissions, and prolonged waiting times. This review synthesizes literature on data-driven and operational strategies that address these inefficiencies, focusing on predictive analytics, discrete-event simulation, artificial intelligence, and digital dashboards. Findings reveal that integrating simulation-based capacity planning, workforce scheduling, and proactive bed management with digital decision-support tools can significantly enhance throughput and reduce systemic bottlenecks. However, the successful adoption of these strategies requires overcoming barriers such as limited data interoperability, inadequate infrastructure, staff resistance to change, and ethical concerns related to patient data use. Emerging trends, including digital twins, mobile health solutions, and AI-driven predictive models, highlight opportunities for scalable and context-appropriate interventions. The review emphasizes the critical role of governance, interdisciplinary collaboration, and policy support in sustaining efficiency gains. Ultimately, structured, data-enabled frameworks are necessary to build resilient hospital systems that advance equitable healthcare access and contribute to achieving Sustainable Development Goals (SDGs) in low- and middle-income countries.

Keywords:
Patient flow, Service efficiency, Public hospitals, Predictive analytics, Data-driven healthcare

INTRODUCTION

Background to Patient Flow Challenges in Public Hospitals

Public hospitals worldwide face persistent patient flow challenges when demand for services outpaces available resources, resulting in long waiting times, overcrowded emergency departments, delays in diagnostic testing, and bottlenecks in admission and discharge processes (Hou et al., 2022; Turgay et al., 2023; Batubara et al., 2020). These manifestations of inefficiency impede timely access to care and can lead to extended lengths of stay and postponed treatments, which place strain on clinical workflows and hospital capacity planning efforts (Hou et al., 2022; Turgay et al., 2023) Consequently, patient

experiences suffer, clinicians experience increased workloads and stress, and trust in public health systems may be eroded when access barriers become routine (Okpala et al., 2025; Ezeanyim et al., 2025). The persistent nature of congestion in public hospitals is further supported by studies that emphasize the misalignment between demand growth and resource availability, particularly during high-demand periods or surges in patient volume (Turgay et al., 2023; Batubara et al., 2020). Collectively, these challenges illustrate how inefficiencies in patient flow translate into suboptimal outcomes for both patients and providers, undermining the resilience and legitimacy of public health facilities (Hou et al., 2022; Okpala et al., 2025).

The literature thus points to a need for data-driven, systems-level approaches to diagnose and mitigate flow bottlenecks. Evidence from simulation-based studies demonstrates that congestion and queuing can be effectively addressed through decongestion interventions and redesigned care pathways, utilizing Lean methodologies and other process-improvement paradigms (Hou et al., 2022; Batubara et al., 2020). Related work indicates that data-driven initiatives focused on patient safety and quality enabled by hospital information systems and analytics—can lead to safer, more reliable care trajectories and improve perceived service quality, which, in turn, enhances patient loyalty and trust (Okpala et al., 2025; Ezeanyim et al., 2025). Moreover, governance and technological infrastructure (electronic administration systems) are prerequisites for such transformations, as illustrated by studies linking data-enabled management with efficiency gains and improved patient satisfaction in public hospitals. Together, these findings highlight that data-driven capacity planning, coupled with targeted process redesign, holds promise for alleviating chronic flow problems in public hospitals while potentially enhancing patient and staff experiences (Turgay et al., 2023; Hou et al., 2022; Okpala et al., 2024).

Significance of Service Efficiency in Resource-Constrained Settings

In resource-constrained settings, budgets, infrastructure, and staffing are limited, making efficient patient flow not merely desirable but essential for the survival of health systems. Strengthening hospital management capacity in LMICs and building managerial competencies are critical to translate scarce resources into reliable access to care, reduce waste, and avert system collapse under demand pressures (Hou et al., 2022). Empirical work from LMIC and mixed-resource contexts also emphasizes that efficient service delivery helps optimize resource allocation and can underpin equitable access when capital and personnel cannot be expanded rapidly (Hou et al., 2022; Ezeanyim et al., 2025). At the same time, capacity-building and governance improvements are central to sustaining efficiency gains, as managerial and organizational readiness shape the success of decongestion and optimization initiatives (Ezeanyim et al., 2025).

Data-driven approaches are central to achieving efficiency gains in settings with limited inputs. Studies demonstrate that measuring and benchmarking hospital performance with data-enabled methods supports capacity planning, queuing reduction, and the redesign of care pathways to better align demand with constrained resources (Turgay et al., 2023; Batubara et al., 2020; Ezeanyim et al., 2025). Governance and information systems infrastructure are prerequisites for such transformations, enabling continuous monitoring, decision support, and accountability that underpin safer, more reliable, and more equitable care trajectories in public hospitals facing resource pinch-points (Okpala et al., 2024; Ezeanyim et al., 2025). Concrete manifestations include data-driven capacity planning, Lean-

and simulation-informed decongestion strategies, and enhanced hospital administration through electronic systems, all of which contribute to lower operational costs and improved staff productivity while expanding timely access for patients (Ezeanyim et al., 2025; Okpala et al., 2025; Okpala et al., 2025; Turgay et al., 2023).

Aim and Scope of the Review

This review aims to explore data-driven and operational strategies for enhancing patient flow and service efficiency in public hospitals, with particular attention to resource-constrained contexts. The paper synthesizes existing literature, highlights challenges and barriers, and discusses emerging trends that may shape the future of healthcare operations management.

CONCEPTUAL FOUNDATIONS

Defining Patient Flow and Service Efficiency

Patient flow refers to the movement of patients through the stages of care from admission to discharge, across departments and care pathways, including diagnostics, treatment, and transfers, with bottlenecks shaping the patient journey (Hou et al., 2022; Batubara et al., 2020). Service efficiency emphasizes the effective use of time, personnel, and infrastructure to deliver optimal care, encompassing capacity planning, queue reduction, and redesign of care pathways enabled by data-driven management and Lean-inspired approaches (Okpala et al., 2025). Together, these constructs form a core dimension of health service delivery, linking operational performance to patient outcomes, staff workload, and system resilience in public hospitals (Batubara et al., 2020).

Discrete-event simulation (DES) and related data-driven approaches underpin modelling of patient flow and testing interventions to improve efficiency, enabling capacity planning, queuing reduction, and pathway redesign under resource constraints (Turgay et al., 2023; Batubara et al., 2020). Empirical applications span emergency departments, radiology, and outpatient services, illustrating DES's capacity to evaluate decongestion strategies, staffing changes, and throughput improvements prior to implementation (Okpala et al., 2025; Vázquez-Serrano et al., 2021). Software tools such as simmer for R facilitate DES implementation, lowering barriers for health-system analysts seeking evidence-based improvement of patient flow and service efficiency (Ezeanyim et al., 2025). Across the literature, DES is repeatedly used to inform planning and optimize resource use in complex care pathways (Batubara et al., 2020; Okpala et al., 2025).

The Burden of Resource Constraints in Public Healthcare Systems

Public hospitals frequently operate under chronic resource shortages, including limited bed spaces, understaffed wards, and inadequate technological infrastructure. These constraints exacerbate inefficiencies that drive overcrowding, delays in treatment, and diminished quality of care (Nwamekwe et al., 2020; Nwamekwe & Nwabunwanne, 2025). The resulting bottlenecks in inpatient and emergency pathways not only extend patient waiting times but also compromise safety and staff well-being, underscoring the vulnerability of public systems to demand surges and limited capital (Nwamekwe & Nwabunwanne, 2025). In pandemic and high-demand contexts, these pressures become even more pronounced as bed occupancy and staffing gaps constrain the system's ability to deliver timely care, highlighting the critical need for proactive capacity management and performance monitoring

(García-Vicuña et al., 2023; Nwamekwe & Nwabunwanne, 2025). Moreover, the literature links resource bottlenecks to broader declines in care quality and patient experience when throughput cannot be sustained by available inputs (Nwamekwe et al., 2020).

Policy and practice increasingly point to data-driven approaches to mitigate the burden of constrained resources. Capacity planning, queuing reduction, and care-pathway redesign informed by discrete-event simulation and other data-enabled methods have shown promise for optimizing scarce beds, staff, and equipment, thereby improving access and reducing waste under resource limits (Cudney et al., 2019; Vázquez-Serrano et al., 2021; Farooq et al., 2024). Empirical work demonstrates that Lean-inspired and simulation-guided interventions, coupled with hospital information systems, can translate limited inputs into safer, more reliable care trajectories and enhanced productivity, particularly in public settings where scaling resources is constrained (Nwamekwe et al., 2020; Nwamekwe et al., 2024; Farooq et al., 2024). Additionally, predictive data approaches such as bed-demand forecasting and flow prediction in emergency departments (EDs) offer tools for proactive management to avert avoidable delays and lengthening of stays during periods of high demand (García-Vicuña et al., 2023; Nwamekwe & Nwabunwanne, 2025). Together, these findings support a data-driven foundation for sustaining service efficiency in resource-constrained public hospitals (Cudney et al., 2019; Vázquez-Serrano et al., 2021; Nwamekwe et al., 2024; Farooq et al., 2024).

Frameworks in Health Operations Management

Health operations management employs structured frameworks such as Lean, Six Sigma, and queuing theory to enhance service delivery in public hospitals. These models aid in identifying bottlenecks, streamlining processes, and minimizing waste across care pathways, from admission to discharge and through diagnostics, treatment, and transfers (Antony et al., 2019). Their adaptation to healthcare has demonstrated value, although contextual modifications are often required in low-resource environments to address local constraints, governance, and workforce capacity. Moreover, queuing theory-informed and data-driven approaches, including discrete-event simulation, support capacity planning and bottleneck analysis, enabling the testing of decongestion and throughput strategies before implementation (Cudney et al., 2019).

In practice, Lean, Six Sigma, and their integrated Lean Six Sigma variants have shown effectiveness in improving patient flow and reducing waste, with sustainability depending on leadership, culture, and governance that promote continuous improvement. The literature emphasizes the importance of governance structures, workforce development, and alignment with health information systems for successful adoption in low-resource settings, facilitating data-driven decision-making and monitoring. Emerging directions include maturity models and Delphi-based guidance to sustain Lean adoption in healthcare, alongside the incorporation of Industry 4.0 concepts to scale improvements in complex health systems. Collectively, these frameworks—adapted to local contexts and supported by data and governance provide a solid foundation for advancing efficiency in public hospital operations (Antony et al., 2019).

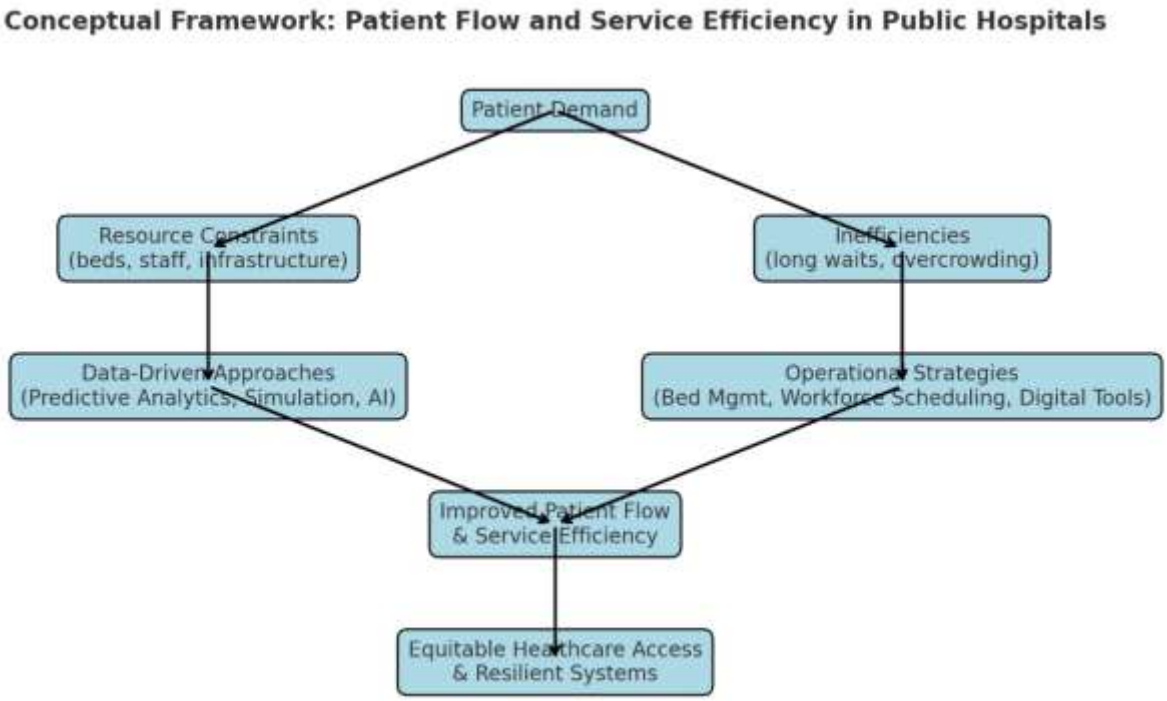

Figure 1: Conceptual Framework: Patient Flow and Service Efficiency in Public Hospitals

Figure 1 is the conceptual diagram: a framework showing how patient demand, resource constraints, and inefficiencies connect to data-driven and operational strategies that improve patient flow and service efficiency, ultimately supporting equitable healthcare access.

Data-Driven Approaches to Enhancing Patient Flow

Predictive Analytics for Demand Forecasting and Capacity Planning

Predictive models in health operations leverage historical and near real time data to forecast patient arrivals, identify upcoming peak demand periods, and estimate resource requirements across care pathways. Such forecasting underpins proactive decisions about staffing, bed occupancy, and equipment deployment, enabling hospitals to anticipate surges and align capacity with expected demand (Turgay et al., 2023; Nwamekwe et al., 2024; Qian et al., 2020). In practice, multivariate time series approaches have been used to predict hospital census and inpatient demand during pandemic waves, informing capacity planning and contingency responses while machine learning-based capacity planning systems have been deployed at national scales to guide resource allocation during COVID 19 crises (Qian et al., 2020). Similar predictive work supports surge planning for laboratory and diagnostic services, where anticipatory capacity models help ensure test availability amid patient influxes (Lyon et al., 2020). Together, these studies illustrate how data-driven forecasting translates historical patterns into actionable staffing and resource decisions (Turgay et al., 2023; Nwamekwe et al., 2024; Qian et al., 2020; Lyon et al., 2020).

Realizing the benefits of predictive analytics for demand forecasting and capacity planning requires robust data infrastructures, governance, and integration with health information systems, so forecasts translate into timely actions (Nwamekwe and Okpala, 2025). Empirical evidence indicates that accurate predictions can reduce crowding and wait times by informing proactive staffing and bed management decisions, thereby improving

throughput and patient flow under pressure during crises like COVID-19 (Lyon et al., 2020; Nwamekwe et al., 2024; Qian et al., 2020; Nwamekwe and Okpala, 2025). To ensure trust and implementability, many approaches couple forecasting with simulation or optimization techniques testing capacity scenarios before live deployment and enabling evidence-based capacity expansions or reallocations (Turgay et al., 2023). Finally, sustained success depends on governance, data quality, and interoperability across systems to monitor performance, adjust models, and scale predictive capabilities across hospital networks (Nwamekwe and Okpala, 2025; Turgay et al., 2023; Qian et al., 2020).

Simulation Models for Patient Pathway Optimization

Discrete-event simulation (DES) provides a structured, risk-free platform to represent complete patient pathways from admission to discharge and to test the effects of process changes before they are implemented in real operations (Cudney et al., 2019; Williams et al., 2020). By capturing the sequence of care activities, interdepartmental handoffs, and resource dependencies, DES helps identify bottlenecks such as bed occupancy, transfer delays, and throughput constraints. It also facilitates evaluation of alternative staffing, space, and equipment configurations to optimize resource use under realistic constraints (Cudney et al., 2019; Williams et al., 2020). The versatility of DES is evident across settings ranging from bed management and emergency department (ED) throughput to intra-hospital transfers demonstrating its capacity to model end-to-end pathways and enable scenario analyses prior to live deployment (Cudney et al., 2019; Schneider et al., 2018).

The practical value of DES in guiding pathway optimization extends to crisis contexts and complex hospital networks. Pandemic- and epidemic-related planning has leveraged DES to balance scarce resources and forecast bed demands, ICU occupancy, and surgical backlogs, informing surge responses while preserving essential care (García-Vicuña et al., 2023). Beyond single facilities, DES has been used to optimize outpatient and emergency pathways in regional and national settings, including case studies from Tunisian hospitals and Nigerian clinics, leading to reductions in waiting times and improved throughput. More recently, integrating DES with process mining and digital twin concepts has proven effective for end-to-end, data-driven optimization of hospital pathways, enabling iterative testing and continuous improvement in resource allocation and patient flow across networks. Collectively, these studies underscore DES as a foundational tool for pathway-level optimization in public hospitals, particularly where resources are constrained and timely care is critical (Williams et al., 2020; Schneider et al., 2018).

Machine Learning and Artificial Intelligence in Patient Flow Management

AI-driven models can identify patterns in patient admissions, predict discharge times, and recommend interventions by learning from large datasets, thereby enhancing real-time decision-making in dynamic hospital environments (Hou et al., 2022; Turgay et al., 2023; Okpala et al., 2025). In practice, such models have been applied to forecast emergency department arrivals, predict bed occupancy, and support discharge readiness and transfer decisions, enabling proactive staffing and resource allocation under fluctuating demand (Batubara et al., 2020; Turgay et al., 2023; Okpala et al., 2025).

To maximize impact, AI methods are commonly integrated with health information systems and complemented by simulation and optimization techniques to test strategies before live deployment (Batubara et al., 2020; Ezeanyim et al., 2025; Okpala et al., 2025).

However, achieving reliable, equitable, and privacy-preserving AI in health requires high-quality data governance, validation, and transparency about model performance and biases (Okpala et al., 2025; Batubara et al., 2020; Turgay et al., 2023). Looking forward, the field is moving toward hybrid AI–DES–digital-twin ecosystems that support end-to-end optimization of patient flows across hospital networks, leveraging real-time data streams and advanced analytics (Ezeanyim et al., 2025; Batubara et al., 2020).

Real-Time Data and Digital Health Dashboards

Digital dashboards provide healthcare managers with live updates on patient numbers, bed occupancy, and service queues, enabling rapid situational awareness and communication of key performance indicators (KPIs) across units. This capability is exemplified by Igbokwe et al., who describe an electronic dashboard at Johns Hopkins Hospital that visualizes ten key performance indicators and communicates them systematically to stakeholders (Igbokwe et al., 2025). Complementary work demonstrates capacity-management dashboards that reveal real-time occupancy and queuing metrics to inform staffing and bed allocation decisions (U-Dominic et al., 2025). Evidence from hospital command centres highlights how integrated dashboards support centralized coordination across departments during both routine operations and crises (Nwamekwe et al., 2025). Furthermore, dashboard analytics in various hospital settings show how real-time visualization can translate data into actionable insights, improving throughput and mitigating emergency department overcrowding.

Real-time dashboards depend on a robust health information infrastructure and governance to ensure timely, accurate data updates and appropriate access controls, enabling them to drive timely actions. U-Dominic et al. illustrate that enterprise-capacity dashboards require integrated data sources to support proactive capacity management in paediatric settings (U-Dominic et al., 2025). Similarly, Nwamekwe et al. discuss the development and operationalization of hospital command centres that translate real-time data into coordinated decision support (Nwamekwe et al., 2025). The broader literature on dashboard analytics reinforces their role in providing end-to-end visibility across care pathways and networks, facilitating rapid responses to emerging bottlenecks and capacity shortfalls. Foundational work demonstrates that KPI visualization enhances coordination among clinicians and managers (Igbokwe et al., 2025).

Strategies for Resource Optimization in Public Hospitals

Workforce Scheduling and Task-Shifting

Efficient workforce scheduling is essential to ensure adequate staff coverage during peak demand periods, thereby reducing bottlenecks and protecting patient safety and care quality. Data-driven demand forecasting and dynamic rostering enable proactive deployment of nurses and support staff, aligning staffing with acuity and anticipated surges in units such as the emergency department and inpatient wards (Singh et al., 2025). Empirical evidence links nurse staffing levels to important patient outcomes, including inpatient mortality and nurse–patient interactions, underscoring the clinical and experiential value of scheduling policies that maintain appropriate staffing ratios. However, the effectiveness of baseline staffing hinges on how demand is modelled; relying solely on average demand can misallocate resources, highlighting the need for surge-aware planning and capacity forecasting.

Task-shifting and expanded skill-mix can mitigate staffing shortages by enabling lower-level health workers to perform routine duties, allowing physicians and specialists to focus on high-complexity care. Practical demonstrations include multi-skill nurse staffing tools that optimally distribute nursing effort across units to improve throughput while maintaining safety. Systematic work on staffing mix and policy emphasizes that successful task-shifting requires training, clearly defined scopes of practice, and governance to ensure patient safety and quality, complemented by supportive policy frameworks. Simulation-based studies further show that flexible staffing and cross-training can reduce waiting times and improve throughput when paired with clear protocols and supervision. Additionally, evidence from emergency department staffing suggests that targeted increases in medical specialist staffing can enhance patient flow and satisfaction when aligned with demand.

Bed Management and Capacity Utilization

Proactive bed management relies on predicting discharge times, coordinating admissions across departments, and minimizing unnecessary occupancy to streamline inpatient throughput. Discharge-time forecasting using interpretable analytics significantly supports timely bed turnover and smoother admission flow, thereby reducing the risk of bed bottlenecks (Bertsimas et al., 2022). Studies on emergency department (ED) and inpatient bed demand forecasting enhance admission scheduling and cross-unit coordination, aligning bed availability with anticipated patient arrivals. Additionally, substantial improvements in bed utilization and reductions in idle capacity through data-driven planning highlight the value of proactive occupancy control in lowering delays and enabling quicker inpatient care during demand spikes (Ahmed, 2025; Singh et al., 2025). Qualitative research supporting hospital-wide flow emphasizes that improved occupancy management can lead to meaningful enhancements in overall throughput and patient experience.

Achieving these improvements requires robust data infrastructures and governance to translate forecasts into actionable bed-allocation decisions. Evidence from predictive operations management suggests that measurable enhancements in bed utilization and staff productivity occur when forecasting is paired with optimization and applied in real-time (Ahmed, 2025). National and regional-scale planning systems demonstrate how data-driven bed-demand forecasts can coordinate resource distribution across hospitals during crises, increasing system resilience (Qian et al., 2020). To mitigate implementation risks, researchers recommend coupling predictive models with simulation or optimization to stress-test bed allocation scenarios before actual implementation, thus reducing waiting times and avoidable occupancy during surges (Qian et al., 2020). Taken together, these findings underscore that integrating accurate bed-demand forecasts with capacity planning and governance can facilitate proactive bed management and improve capacity utilization in public hospitals (Bertsimas et al., 2022).

Queue Management and Appointment Systems

Digital appointment systems and structured queuing reduce patient waiting times and improve service order in public hospitals. Online scheduling platforms and e-health dashboards provide patients with accessible appointment options while enabling real-time visibility into queues and throughput, supporting more predictable service delivery (Kitsios et al., 2023; Nwamekwe et al., 2025). Appointment-slot optimization using two-stage stochastic programming demonstrates how allocating time slots under uncertainty can

shorten waits and better align demand with available capacity. In addition, intelligent outpatient schedulers, including multi-agent scheduling approaches, enable dynamic adjustments to patient arrivals and resource availability, further enhancing throughput and service reliability in outpatient settings (Nwamekwe et al., 2025).

Simple interventions, such as staggered appointments, have shown measurable impact in reducing congestion and smoothing patient flow across clinics and procedures (Okeagu et al., 2024; Chiang et al., 2019). Multi-appointment scheduling studies highlight how distributing visits across specified slots can alleviate peak-load pressure, while optimization efforts for elective surgeries and operating room scheduling illustrate the throughput gains achievable when scheduling constraints and patient preferences are considered (Okeagu et al., 2024; Chiang et al., 2019). Complementary work using stochastic and reinforcement-learning–driven scheduling further corroborates improvements in wait times and resource utilization when appointment timing is designed to balance demand with capacity. Collectively, these findings underscore the value of integrating digital appointment systems with rigorously designed queuing and scheduling strategies to advance patient flow in public hospitals (Kitsios et al., 2023; Nwamekwe et al., 2025; Okeagu et al., 2024).

Integration of Low-Cost Digital Tools in Resource-Limited Contexts

In resource-limited contexts, mobile-based reporting tools, SMS reminders, and lightweight scheduling platforms offer cost-effective ways to enhance hospital efficiency when sophisticated IT systems are unaffordable. Evidence from large public-hospital networks indicates that mobile smartphone-based services enable patient self-management and appointment access, even in settings with limited infrastructure (Huang et al., 2024). Lightweight web-based appointment systems augmented with SMS alerts have demonstrated tangible reductions in no-shows and improved scheduling reliability, providing a feasible alternative to full IT overhauls in constrained environments. Complementary work on digital registration and appointment reminders illustrates how small-scale digital platforms can alleviate queue pressures and shorten patient waiting times without requiring heavy capital investments. Broader studies of digital service platforms supporting e-appointments further underscore the practicality and acceptability of low-cost digital solutions in public hospitals (Kitsios et al., 2023).

The adoption of these low-cost tools requires attention to governance, data quality, and user training to ensure reliable and privacy-preserving operation within limited technical ecosystems (Onyeka et al., 2024). Real-world deployments show that online and SMS-enabled scheduling can improve patient flow and satisfaction when integrated with basic health information systems and staff workflows (Onyeka et al., 2024). Additional evidence from smartphone-enabled services highlights high patient access to appointment services, suggesting strong potential for scalable improvements in throughput with minimal capital outlay (Huang et al., 2024). Collectively, the literature supports a pragmatic strategy: deploy mobile, SMS, and lightweight scheduling tools as a first wave of digital modernization in resource-constrained public hospitals, leveraging their low cost and wide reach to reduce wait times and balance demand with capacity (Huang et al., 2024; Kitsios et al., 2023).

Challenges and Obstacles

Data Availability, Quality, and Interoperability Issues

Incomplete records, fragmented databases, and poor interoperability severely hinder the effective deployment of data-driven approaches in public hospitals. Empirical work and reviews highlight how data gaps arise from inconsistent documentation, legacy IT, and siloed information across departments and facilities, which in turn undermine capacity planning, predictive analytics, and longitudinal analyses essential for managing patient flow (Chuma, 2025; Emeka et al., 2025). The fragmentation is further compounded by inconsistent data standards and limited cross-institution data exchange, creating barriers to aggregating real-time operational insights necessary for end-to-end pathway optimization (Chuma, 2025; Mello et al., 2022). These interoperability challenges reverberate across low- and middle-income countries (LMICs) and high-demand settings, where disparate systems impede timely access to critical patient information and hinder coordinated responses to surges (Nwamekwe et al., 2025; Holmgren et al., 2022).

Addressing these obstacles requires robust governance, data standards, and interoperable exchange mechanisms. Semantic interoperability and standardized data formats, such as HL7 FHIR mappings, are repeatedly emphasized as foundational to enabling cross-system data integration and reuse for hospital operations (Mello et al., 2022; Bossenko et al., 2024). Emerging evidence also points to transformative solutions like blockchain-enabled data sharing to enhance security, traceability, and interoperability across heterogeneous systems, although these solutions are contingent on governance frameworks. Moreover, national and regional experiences suggest that interoperable data sharing can improve care coordination, patient access, and system resilience during crises, underscoring the policy and practical importance of investing in interoperable health information infrastructures (Holmgren et al., 2022). Taken together, these sources illuminate how data availability and interoperability are linchpins of data-driven patient-flow optimization in public hospitals and why ongoing standardization and governance investments are essential (Chuma, 2025; Chidiebube et al., 2025; Bossenko et al., 2024; Holmgren et al., 2022).

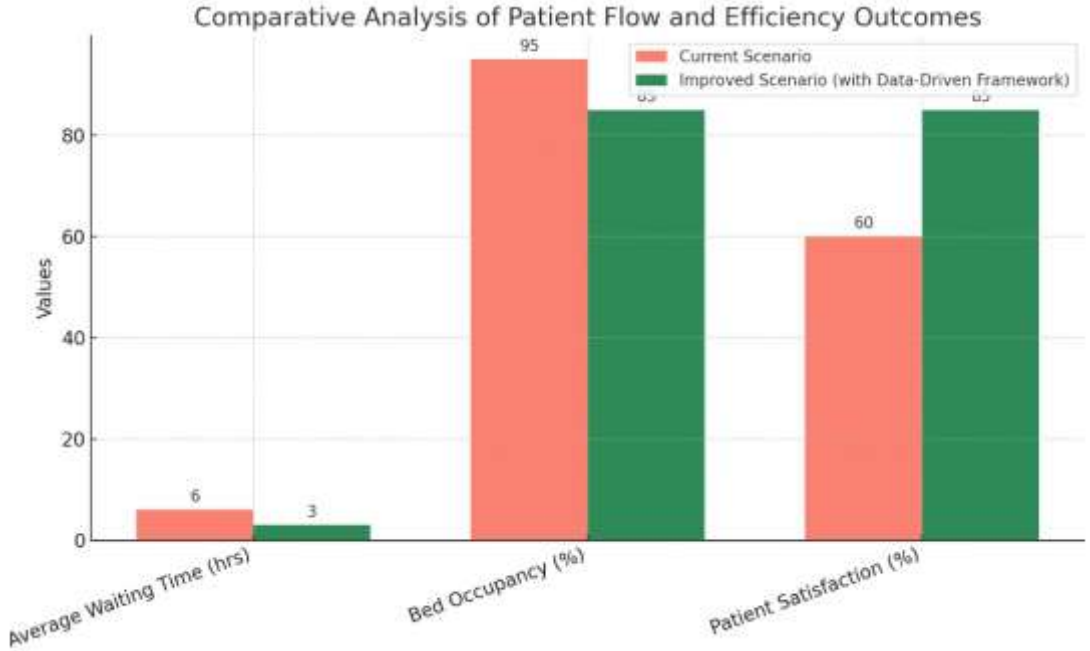

Figure 2: Comparative Analysis of Patient Flow and Efficiency Outcomes

As shown in figure 2 is a comparative bar chart showing current vs improved patient flow outcomes. It demonstrates how applying predictive analytics and operational strategies can reduce waiting times, optimize bed occupancy, and increase patient satisfaction.

Resistance to Change and Low Digital Literacy among Staff

Healthcare workers may resist new systems due to insufficient training, fear of redundancy, or limited confidence in digital tools. Empirical evidence indicates that electronic medical record (EMR) adoption and digital transformations are impeded by gaps in training and readiness, as shown in Indonesian public hospitals where infrastructure and staff skills influenced adoption trajectories (Nwamekwe & Igbokwe, 2024). Moreover, concerns about knowledge and attitudes toward new health information practices can hinder progress during crises. Research on change management in public health settings further emphasizes the importance of staff engagement, leadership support, and the establishment of new routines as pivotal to integrating new practices effectively. Training and development theories highlight the link between employee commitment and successful technology uptake (Igbokwe et al., 2025). Additionally, the reality that IT adoption is often constrained by workforce capacity and readiness suggests that without targeted training and effective governance, digital tools may struggle to gain traction (Renata & Bernarto, 2025). Collectively, these factors illustrate how training deficits, security concerns, and confidence gaps contribute to resistance to change in resource-constrained public-hospital contexts.

To counteract resistance, targeted strategies aimed at building digital literacy, confidence, and organizational readiness are essential. A robust body of work has demonstrated that well-designed training and development interventions can enhance staff performance and engagement, thereby reducing barriers to adoption in public health settings. The need for inclusive change-management processes that engage frontline staff in the transformation journey is highlighted in studies like the one conducted in Israel, reinforcing its significance in facilitating successful transitions. Additionally, ongoing professional development exemplified in Ghana underscores the importance of sustained improvements for nursing competence. Furthermore, evidence regarding training's impact on emergency-response capacity emphasizes the value of equipping staff with skills relevant to crisis situations to mitigate anxiety and resistance. Lastly, governance and cultural factors affecting IT adoption, along with the necessity of aligning digital initiatives with staff workflows and safety cultures, emerge as critical facilitators for overcoming resistance and achieving durable digital modernization in public hospitals (Renata & Bernarto, 2025; Igbokwe et al., 2025; Nwamekwe & Igbokwe, 2024).

Financial and Infrastructure Constraints

The adoption of advanced data systems in public hospitals is financially demanding, entailing substantial upfront investments in electronic medical records, data warehouses, analytics platforms, and the governance frameworks necessary to support them (Nwamekwe & Igbokwe, 2024). Interoperability-related costs further elevate the financial burden, as harmonizing data standards, performing cross-system mappings, and integrating multiple departmental systems across facilities require additional capital and skilled personnel (Chuma, 2025; Mello et al., 2022; Bossenko et al., 2024). Moreover, ROI for these investments hinges on governance structures and policy incentives that enable scalable deployment,

which can be particularly challenging in resource-constrained settings where budgetary pressures and competing priorities are acute (Holmgren et al., 2022; Nwamekwe et al., 2025).

Infrastructural constraints compound these financial barriers. Inadequate power supply and unreliable internet connectivity directly limit the reliability and timeliness of data-driven solutions, especially in LMICs where infrastructure fragility undermines real-time data collection and exchange (Nwamekwe & Igbokwe, 2024; Nwamekwe et al., 2025). The burden is amplified by fragmented devices and uneven data capture, which impede seamless interoperability and end-user access to timely information (Emeka et al., 2025; Mello et al., 2022; Bossenko et al., 2024). Consequently, even when digital tools exist, persistent connectivity and energy gaps hinder data-driven decision-making, underscoring the need for phased, governance-backed adoption and targeted investments to strengthen connectivity, power stability, and standards-driven interoperability (Nwamekwe et al., 2025; Holmgren et al., 2022; Bossenko et al., 2024).

Ethical and Privacy Concerns in Patient Data Use

The use of sensitive patient data raises fundamental issues of confidentiality, informed consent, and compliance with legal frameworks, a challenge that is amplified in low-resource environments where data protection laws may be weak or unevenly enforced (Esmaeilzadeh, 2019). Blockchain-enabled health information exchange offers a potential pathway to enhance transparency and give patients greater control over who accesses their data, but its effectiveness hinges on governance, appropriate consent mechanisms, and user acceptance to ensure trust and participation (Esmaeilzadeh, 2019). Moreover, even when data-sharing initiatives are technically feasible, gaps in privacy policies and perceived transparency can undermine trust in health-information exchanges, leading to reduced data sharing and engagement by patients and providers (Esmaeilzadeh, 2019). The broader literature also cautions that privacy and security considerations must accompany any move toward cloud-based or mobile health solutions to prevent breaches and preserve patient confidence.

To address these ethical and privacy challenges, strategies centre on governance by design, privacy-preserving technologies, and secure data-sharing frameworks that balance data utility with patient rights. Emerging approaches include distributed-ledger and blockchain-based health information exchanges (HIEs) to enable auditable, patient-centric data sharing while maintaining interoperability standards (Esmaeilzadeh, 2019; Tan et al., 2023). Federated learning and privacy-preserving analytics offer avenues to extract actionable insights without centralizing sensitive records, thereby reducing exposure while supporting clinical decision-making. A robust privacy-by-design ethos encompassing transparent privacy disclosures, informed consent processes, and ongoing governance remains essential for sustaining trust and participation in data-driven public-hospital environments, particularly where regulatory protections are evolving or incomplete (Esmaeilzadeh, 2019). In sum, advancing data-driven patient-flow initiatives requires integrating privacy, security, and ethical considerations into the core architecture of health information systems (Tan et al., 2023).

Emerging Trends and Future Directions

AI-Driven Predictive Models for Real-Time Patient Flow

Next-generation predictive models will use AI to provide real-time forecasts of patient flow and demand across hospital services, enabling dynamic allocation of staff, beds, and

equipment to avert bottlenecks. A growing body of work demonstrates that interpretable analytics applied to electronic health record data can forecast short-term discharges, identify patients at risk of prolonged stays, predict discharge destinations, and anticipate flows into critical care, thereby informing bed management and staffing decisions in real time (Bertsimas et al., 2022). Evidence from emergency departments shows predictive models that forecast bed demand from ED attendances can meaningfully inform capacity planning and alleviate congestion during peak periods, while rapid deployments of hospital-focused predictive analytics during the COVID-19 pandemic illustrate how workload forecasts can drive surge responses and resource reallocation across networks. Across hospital systems, interdisciplinary predictive-analytics efforts have produced census forecasts and structured visualizations that support proactive management and timely decisions under crisis conditions and targeted predictions of admission locations in EDs enable preemptive bed preparation and resource allocation. Complementary work on waiting-time forecasting with interpretable machine learning further demonstrates the potential to address patient dissatisfaction while maintaining transparency.

To operationalize these forecasts, researchers are integrating AI with prescriptive analytics, optimization, and simulation to generate decision-support tools that can guide real-time adjustments in care pathways and capacity. The literature notes that interdisciplinary task forces during COVID-19 delivered forecast-driven guidance and dashboards, illustrating how predictive insights can inform operational decisions under uncertainty and hybrid predictive–optimization frameworks have been shown to reduce wait times and improve satisfaction by aligning forecasted demand with available capacity in outpatient and inpatient settings. Emerging approaches include automated arrival predictors and ED-admission-location forecasts that support preemptive bed allocation and routing decisions, enhancing throughput in high-demand contexts. However, realizing these benefits hinges on interpretability, robust data governance, and clinician engagement to ensure trust and responsible deployment of AI-driven real-time patient-flow forecasting.

Digital Twins and Advanced Simulation in Healthcare

Digital twin technology can create virtual replicas of hospital systems or patient trajectories, enabling managers and clinicians to test interventions virtually before applying them in the real world. This concept is supported by studies that define patient digital twins and outline their clinical and operational utility, especially in cardiology and chronic disease management. Empirical and theoretical work also demonstrates the feasibility of patient-focused twins assembled from multimodal data to predict outcomes such as discharge timing, ICU needs, and treatment responses, thereby informing bed management, staffing, and care pathways in real time. Extending beyond the patient level, healthcare system level digital twins are described as tools to optimize workflows and resource allocation, underscoring their potential to transform both clinical decision-making and operational resilience. The emergence of AI-augmented digital twins paired with medical imaging, wearables, and IoT data further expands the scope for precision medicine and pathway optimization across health networks.

Despite these prospects, substantial challenges remain for widespread adoption. Critical barriers include data quality, interoperability, governance, and privacy concerns, which must be addressed to realize reliable and scalable digital twins in practice (Esmaeilzadeh, 2019; Esmaeilzadeh, 2019). Recent reviews emphasize the need for standardized data

representations and robust privacy-by-design approaches to enable secure, auditable twin systems that patients and clinicians can trust (Mello et al., 2022; Bossenko et al., 2024; Esmaeilzadeh, 2019). Governance frameworks covering consent, data provenance, and accountability are highlighted as prerequisites for successful implementation, particularly for patient-centric twins and cross-institution data sharing (Esmaeilzadeh, 2019; Tan et al., 2023; Nwamekwe et al., 2025). Ongoing work also points to the necessity of validation, transparency, and user-centred design to ensure clinical usefulness and acceptance among healthcare professionals while recognizing the substantial computational and organizational resources required to operationalize digital twins in routine care (Nwamekwe et al., 2025). Collectively, the literature suggests a trajectory wherein digital twins, anchored by strong data governance and interoperable infrastructures, will enable increasingly sophisticated simulations, real-time decision support, and adaptive healthcare delivery in public hospitals (Nwamekwe et al., 2025).

Mobile Health (mHealth) Solutions for Patient Engagement

Mobile platforms are increasingly central to engaging patients in their own care, reducing no-shows, and providing self-management support. Systematic reviews across health behaviour change apps show positive engagement and potential impacts on activity, diet, and related behaviours, underscoring the broad applicability of mHealth for patient involvement. Scoping reviews identify key engagement-enhancing features personalized content, feedback, reminders, logging, self-monitoring, and goal setting that hospitals can leverage to improve uptake and adherence in outpatient and chronic-care settings (Oakley-Girvan et al., 2021). Empirical work highlights the importance of perceived usability and acceptability; user-centred app designs that prioritize ease of use and relevance to patients' needs correlate with higher engagement and satisfaction in mental health contexts. Collectively, these findings support deploying mobile apps as facilitators of self-management and care continuity, particularly when integrated with clinical workflows and patient education efforts.

Nevertheless, realizing the engagement benefits of mHealth requires addressing design and implementation challenges. Evidence indicates substantial variability in engagement depending on app credibility, content quality, and alignment with patient expectations, as observed in content analyses of mobile apps for specific conditions where engagement was constrained by quality and trust issues. Early and ongoing adoption pressures such as clinician buy-in, workflow integration, and governance remain critical barriers; qualitative studies emphasize the need for user-centred development, stakeholder involvement, and clear value propositions to achieve durable engagement in real-world settings. Additional work on patient preferences and usability suggests tailoring features to patient cohorts and validating engagement through rigorous evaluation, including co-design with patients and providers to sustain use over time. As mobile health matures, combining patient-centred design with robust governance and interoperability will be essential to translate engagement into measurable improvements in access, adherence, and outcomes across public hospital systems (Oakley-Girvan et al., 2021; Bo et al., 2023).

Policy Recommendations for Sustainable Implementation

Governments must establish policy frameworks that explicitly enable digital health adoption, provide sustainable funding mechanisms, and set robust data protection standards

to support scalable patient-flow enhancements in public hospitals. Systematic reviews of mHealth interventions highlight the need for policy readiness and funding to sustain digital health pilots and scale successful models, particularly in low- and middle-income settings (Marcolino et al., 2018). Broader analyses emphasize governance and accountability as critical to the trusted deployment of mobile health solutions. In addition, improving health literacy and ensuring inclusive access are essential policy considerations that underpin equitable uptake of mHealth innovations, especially where disparities in digital capabilities exist. Policy guidance is also necessary to align adoption with user needs and clinical workflows (Marcolino et al., 2018).

To translate policy into durable impact, funding models and governance structures must support ongoing evaluation, data protection, and interoperability across systems. Flexible funding mechanisms such as grants, subsidies, and reimbursement schemes can sustain digital health initiatives beyond initial pilot phases and incentivize integration with existing hospital information systems (Marcolino et al., 2018). Standards-based interoperability and privacy-by-design approaches are crucial for enabling secure data exchange, fostering patient trust, and facilitating scalable analytics across facilities. Governance frameworks should incorporate clear accountability, consent processes, and regular auditing to address evolving regulatory landscapes. Finally, engaging clinicians, patients, and administrators in co-design and ongoing improvement efforts will enhance uptake and ensure that policy instruments translate into meaningful improvements in access, efficiency, and patient outcomes (Marcolino et al., 2018).

CONCLUSION

Summary of Key Insights

This study highlights the pressing challenges and potential strategies for improving patient flow and service efficiency in public hospitals, with a particular focus on resource-constrained settings such as Nigeria. The review synthesized evidence on data-driven approaches, simulation models, predictive analytics, and digital dashboards, all of which provide promising tools for alleviating congestion and improving throughput in hospitals where demand consistently exceeds available resources. Key insights reveal that inefficiencies in patient flow manifested as long waiting times, overcrowded emergency departments, delays in admissions, and inadequate discharge processes directly undermine both patient outcomes and staff well-being. Beyond clinical implications, these bottlenecks erode trust in the public health system and reinforce inequities in healthcare access.

The analysis further underscores that resource limitations such as insufficient bed spaces, understaffed facilities, and poor infrastructure exacerbate patient-flow inefficiencies. However, the literature demonstrates that targeted operational improvements, including Lean-inspired process redesign, simulation-based capacity planning, and real-time data monitoring, can mitigate these inefficiencies even in constrained environments. A central takeaway is that governance and leadership capacity play pivotal roles: without robust information systems, clear accountability, and institutional readiness for change, technical innovations cannot deliver their full benefits.

Collectively, these insights emphasize the necessity of aligning technical, managerial, and policy-level interventions. Hospitals must adopt integrated frameworks that combine predictive and simulation-based tools with workforce scheduling, proactive bed management, and digital queuing systems. While data quality and interoperability remain

significant obstacles, emerging technologies such as blockchain-enabled health information exchange and privacy-preserving analytics hold promise. Ultimately, sustainable improvements in patient flow depend not only on technological innovations but also on context-appropriate implementation strategies, robust governance, and active engagement of healthcare workers.

Implications for Practice and Policy in Resource-Constrained Hospitals

The findings of this review carry substantial implications for both practice and policy. For hospital administrators, the integration of data-driven decision-making into daily operations is no longer optional but essential. Proactive workforce scheduling, task-shifting strategies, and cross-training can ease staffing pressures and ensure adequate coverage during peak demand. Similarly, predictive bed-demand forecasting and digital dashboards provide hospital managers with actionable intelligence, allowing for faster admission, discharge, and referral decisions. These strategies have the potential to reduce overcrowding, shorten waiting times, and improve patient satisfaction, all without requiring significant capital expansion.

From a policy perspective, resource-constrained governments must prioritize investments in health information systems, interoperability frameworks, and governance structures that can sustain data-driven practices. National and sub-national policies should encourage the adoption of simulation and predictive analytics across hospital networks, supported by standardized data exchange formats such as HL7 FHIR. Equally important is the development of funding mechanisms, such as grants and subsidies, to enable hospitals to acquire and maintain digital infrastructures. Policymakers should also design supportive regulations around data security and patient privacy, as ethical concerns remain central to the acceptance of digital solutions.

Moreover, this study reveals that efficiency gains alone are insufficient without addressing broader systemic inequities. Policies must consider financial barriers to care, geographical inequities in hospital distribution, and the need for inclusive digital literacy programs to prepare healthcare workers for technological transitions. Incorporating circular economy principles—such as equipment reuse and recycling—into hospital operations can further support sustainability in environments where capital is scarce. By aligning hospital practices with supportive policy frameworks, resource-constrained countries can create resilient health systems that not only optimize service efficiency but also improve equitable access to quality healthcare.

Call for Interdisciplinary Research and Context-Specific Solutions

Improving patient flow in resource-constrained hospitals is inherently an interdisciplinary challenge, demanding collaboration between engineers, clinicians, health informaticians, policymakers, and social scientists. The complexity of hospital operations—spanning patient admission, diagnostic services, treatment, discharge, and interdepartmental coordination—means that solutions cannot be siloed within any single discipline. Operations researchers bring expertise in simulation and optimization; health informaticians provide insights into data governance and digital infrastructures; clinicians ensure that interventions align with patient safety and clinical workflows; and policymakers create the enabling environment for sustainable adoption. Without such interdisciplinary cooperation, attempts at reform risk fragmentation and limited scalability.

This review also emphasizes the necessity of tailoring solutions to the local context. While high-income countries can adopt advanced digital twins and AI-driven forecasting, low- and middle-income countries (LMICs) may initially benefit more from low-cost mobile applications, SMS-enabled appointment systems, and lightweight digital dashboards. Research must therefore prioritize context-sensitive innovations, building from basic digital infrastructures toward more advanced predictive systems as governance and capacity mature. Case studies from Nigeria and other LMICs illustrate that importing solutions from high-resource settings without contextual adaptation often leads to failure.

Future research should also embrace participatory approaches, engaging hospital staff and patients in the co-design of interventions. This enhances not only adoption but also sustainability by ensuring that solutions reflect real-world constraints and cultural practices. Research gaps remain in areas such as federated learning for patient data privacy, cost–benefit analyses of digital interventions, and evaluation of circular-economy principles in hospital operations. By advancing interdisciplinary and context-specific research agendas, stakeholders can co-create robust, scalable, and ethically responsible solutions that improve patient flow while advancing the broader goals of Sustainable Development Goals (SDGs) 3 and 9.

REFERENCE

Ahmed, M. (2025). Ai-driven predictive operations management: a business science framework for dynamic hospital resource optimization and clinical workflow efficiency. International Journal of Professional Business Review, 10(8), e05628. https://doi.org/10.26668/businessreview/2025.v10i8.5628

Antony, J., M, V., Sreedharan, V., Chakraborty, A., & Gunasekaran, A. (2019). A systematic review of lean in healthcare: a global prospective. International Journal of Quality & Reliability Management, 36(8), 1370-1391. https://doi.org/10.1108/ijqrm-12-2018-0346

Batubara, H., Lesmana, R., Dharmastiti, R., & Herliansyah, M. (2020). A proposed model for outpatient care service improvement using the healthcare lean approach and simulation.. https://doi.org/10.2991/assehr.k.200515.041

Bertsimas, D., Pauphilet, J., Stevens, J., & Tandon, M. (2022). Predicting inpatient flow at a major hospital using interpretable analytics. Manufacturing & Service Operations Management, 24(6), 2809-2824. https://doi.org/10.1287/msom.2021.0971

Bossenko, I., Randmaa, R., Piho, G., & Ross, P. (2024). Interoperability of health data using fhir mapping language: transforming hl7 cda to fhir with reusable visual components. Frontiers in Digital Health, 6. https://doi.org/10.3389/fdgth.2024.1480600

Chiang, A., Jeang, A., Chiang, P., Chiang, P., & Chung, C. (2019). Multi-objective optimization for simultaneous operating room and nursing unit scheduling. International Journal of Engineering Business Management, 11. https://doi.org/10.1177/1847979019891022

Chidiebube, I. N., Nwamekwe, C. O., Chukwuemeka, G. H., & Wilfred, M. (2025). OPTIMIZATION OF OVERALL EQUIPMENT EFFECTIVENESS FACTORS IN A FOOD MANUFACTURING SMALL AND MEDIUM ENTERPRISE. Journal of Research in Engineering and Applied Sciences, 10(1), 836-845.

Chuma, K. (2025). 'a tough nut to crack': inconsistent standards as roadblocks to data interoperability of health information systems in public hospitals in the gauteng

province of south Africa. Oxford Open Digital Health, 3. https://doi.org/10.1093/oodh/oqaf013

Cudney, E., Baru, R., Guardiola, I., Materla, T., Cahill, W., Phillips, R., ... & Masek, C. (2019). A decision support simulation model for bed management in healthcare. International Journal of Health Care Quality Assurance, 32(2), 499-515. https://doi.org/10.1108/ijhcqa-10-2017-0186

Emeka, U. C., Okpala, C., & Nwamekwe, C. O. (2025). CIRCULAR ECONOMY PRINCIPLES'IMPLEMENTATION IN ELECTRONICS MANUFACTURING: WASTE REDUCTION STRATEGIES IN CHEMICAL MANAGEMENT. International journal of industrial and production engineering, 3(2), 29-42.

Ezeanyim, O. C., Ewuzie, N. V., Aguh, P. S., Nwabueze, C. V., and Nwamekwe, C. O. (2025). Effective Maintenance of Industrial 5-Stage Compressor: A Machine Learning Approach. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 96-118. https://dergipark.org.tr/en/pub/gujsa/issue/90827/1646993

Farooq, F., Choudhary, R., Batool, H., Chaudhry, N., & Ehsan, M. (2024). Reducing waiting time and improving patient flow inpublicsectorhospitals using business process engineering and simulation. Pakistan Journal of Science, 76(01), 178-188. https://doi.org/10.57041/vol76iss01pp178-188

García-Vicuña, D., López-Cheda, A., Jácome, M., & Mallor, F. (2023). Estimation of patient flow in hospitals using up-to-date data. application to bed demand prediction during pandemic waves. Plos One, 18(2), e0282331. https://doi.org/10.1371/journal.pone.0282331

Holmgren, A., Everson, J., & Adler-Milstein, J. (2022). Association of hospital interoperable data sharing with alternative payment model participation. Jama Health Forum, 3(2), e215199. https://doi.org/10.1001/jamahealthforum.2021.5199

Hou, W., Qin, S., & Thompson, C. (2022). Effective response to hospital congestion scenarios: simulation-based evaluation of decongestion interventions. International Journal of Environmental Research and Public Health, 19(23), 16348. https://doi.org/10.3390/ijerph192316348

Huang, X., Wang, Y., Yang, X., Jiang, R., Liu, Y., & Wang, H. (2024). Patient-centric mobile medical services accessed through smartphones in the top 100 Chinese public hospitals: cross-sectional survey study. Jmir Formative Research, 8, e45763. https://doi.org/10.2196/45763

Igbokwe, N. C., Christiana, C., Nweke, C. O. N., & Onyeka, C. (2025). Data-Driven Solutions for Shuttle Bus Travel Time Prediction: Machine Learning Model Evaluation at Nnamdi Azikiwe University. African Journal of Computing, Data Science and Informatics (AJCDSI), 1(1), 31-55.

Igbokwe, N. C., Okeagu, F. N., Onyeka, N. C., Onwuliri, J. B., & Godfrey, O. C. (2024). MACHINE LEARNING-DRIVEN MAINTENANCE COST OPTIMIZATION: INSIGHTS FROM A LOCAL INDUSTRIAL COMPRESSOR CASE STUDY. Jurnal Inovasi Teknologi dan Edukasi Teknik, 4(11), 2.

Kitsios, F., Stefanakakis, S., Kamariotou, M., & Dermentzoglou, L. (2023). Digital service platform and innovation in healthcare: measuring users' satisfaction and implications. Electronics, 12(3), 662. https://doi.org/10.3390/electronics12030662

Lyon, M., Bajkov, A., Haugrud, D., Kyle, B., Wu, F., & Lyon, A. (2020). Covid-19 pandemic planning: simulation models to predict biochemistry test capacity for patient surges. The

Journal of Applied Laboratory Medicine, 6(2), 451-462. https://doi.org/10.1093/jalm/jfaa231

Marcolino, M., Oliveira, J., D'Agostino, M., Ribeiro, A., Alkmim, M., & Novillo-Ortiz, D. (2018). The impact of mhealth interventions: systematic review of systematic reviews. Jmir Mhealth and Uhealth, 6(1), e23. https://doi.org/10.2196/mhealth.8873

Mello, B., Rigo, S., Costa, C., Righi, R., Donida, B., Bez, M., ... & Schunke, L. (2022). Semantic interoperability in health records standards: a systematic literature review. Health and Technology, 12(2), 255-272. https://doi.org/10.1007/s12553-022-00639-w

Nwamekwe C. O., and Nwabunwanne E. C. (2025). Circular Economy and Zero-Energy Factories: A Synergistic Approach to Sustainable Manufacturing. Journal of Research in Engineering and Applied Sciences (JREAS), 10(1), 829-835. https://qtanalytics.in/journals/index.php/JREAS/article/view/4567

Nwamekwe C. O., Ewuzie Nnamdi Vitalis, Igbokwe Nkemakonam Chidiebube, & Nwabueze Chibuzo Victoria. (2025). Evaluating Advances in Machine Learning Algorithms for Predicting and Preventing Maternal and Foetal Mortality in Nigerian Healthcare: A Systematic Approach. International Journal of Industrial and Production Engineering, 3(1), 1-15. https://journals.unizik.edu.ng/ijipe/article/view/5161Renata, A. and Bernarto, I. (2025). Service quality, job satisfaction, and information technology. Jurnal Ad Ministrare, 18-28. https://doi.org/10.71309/administrare.v12i1.7378

Nwamekwe C. O., Ezeanyim O. C., and Igbokwe N. C. (2025). Resilient Supply Chain Engineering in the Era of Disruption: An Appraisal. International Journal of Innovative Engineering, Technology and Science (IJIETS), 9(1), 11-23. https://hal.science/hal-05061524/

Nwamekwe, C. O., & Chikwendu, O. C. (2025). Circular economy strategies in industrial engineering: From theory to practice. International Journal of Multidisciplinary Research and Growth Evaluation, 6(1): 1773-1782. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212103754_MGE-2025-1-288.1.pdf

Nwamekwe, C. O., & Chikwendu, O. C. (2025). Machine learning-augmented digital twin systems for predictive maintenance in highspeed rail networks. International Journal of Multidisciplinary Research and Growth Evaluation, 6(1), 1783-1795. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212104201_MGE-2025-1-306.1.pdf

Nwamekwe, C. O., & Nwabunwanne, E. C. (2025). Immersive Digital Twin Integration in the Metaverse for Supply Chain Resilience and Disruption Management. Journal of Engineering Research and Applied Science, 14(1), 95-105.

Nwamekwe, C. O., and Igbokwe, N. C. (2024). Supply Chain Risk Management: Leveraging AI for Risk Identification, Mitigation, and Resilience Planning. International Journal of Industrial Engineering, Technology & Operations Management, 2(2), 41–51. https://doi.org/10.62157/ijietom.v2i2.38Esmaeilzadeh, P. (2019). The impacts of the perceived transparency of privacy policies and trust in providers for building trust in health information exchange: empirical study. Jmir Medical Informatics, 7(4), e14050. https://doi.org/10.2196/14050

Nwamekwe, C. O., and Igbokwe, N. C. (2024). Supply Chain Risk Management: Leveraging AI for Risk Identification, Mitigation, and Resilience Planning. International Journal of

Industrial Engineering, Technology & Operations Management, 2(2), 41–51. https://doi.org/10.62157/ijietom.v2i2.38

Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., & Sunday, A. P. (2025). Resilience and Risk Management in Social Robot Systems: An Industrial Engineering Perspective. Culture education and technology research (Cetera), 2(2), 1-12.

Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., & Aguh, P. S. (2025). Human-Robot Collaboration in Industrial Engineering: Enhancing Productivity and Safety. Journal of Industrial Engineering & Management Research, 6(5), 1-20.

Nwamekwe, C. O., Chinwuko, C. E. & Mgbemena, C. E. (2020). Development and Implementation of a Computerised Production Planning and Control System. UNIZIK Journal of Engineering and Applied Sciences, 17(1), 168-187. https://journals.unizik.edu.ng/ujeas/article/view/1771

Nwamekwe, C. O., Ewuzie, N. V., Okpala, C. C., Ezeanyim, C., Nwabueze, C. V., Nwabunwanne, E. C. (2025). Optimizing Machine Learning Models for Soil Fertility Analysis: Insights from Feature Engineering and Data Localization. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 36-60. https://dergipark.org.tr/en/pub/gujsa/issue/90827/1605587

Nwamekwe, C. O., Ewuzie, N.V., Igbokwe, N. C., Nwabunwanne, E. C., & Ono, C. G. (2025). Digital Twin-Driven Lean Manufacturing: Optimizing Value Stream Flow. Letters in Information Technology Education (LITE), 8 (1), pp.1-13. https://hal.science/hal-05127340/

Nwamekwe, C. O., Okpala, C. C., & Nwabunwanne, E. C. (2025). Design Principles and Challenges in Achieving Zero-Energy Manufacturing Facilities. Journal of Engineering Research and Applied Science, 14(1), 1-21.

Nwamekwe, C. O., Okpala, C. C., and Okpala, S. C., (2024). Machine Learning-Based Prediction Algorithms for the Mitigation of Maternal and Fetal Mortality in the Nigerian Tertiary Hospitals. International Journal of Engineering Inventions, 13(7), PP: 132-138. https://www.ijeijournal.com/papers/Vol13-Issue7/1307132138.pdfTurgay, S., Faruk, Ö., & Elik, Ö. (2023). Data-driven approaches to hospital capacity planning and management. Information and Knowledge Management, 4(2). https://doi.org/10.23977/infkm.2023.040202

Nwamekwe, C., Ewuzie, N., Igbokwe, N., Okpala, C., & U-Dominic, C. (2024). Sustainable Manufacturing Practices in Nigeria: Optimization and Implementation Appraisal. Journal of Research in Engineering and Applied Sciences, 9(3). https://qtanalytics.in/journals/index.php/JREAS/article/view/3967

Oakley-Girvan, I., Yunis, R., Longmire, M., & Ouillon, J. (2021). What works best to engage participants in mobile app interventions and e-health: a scoping review. Telemedicine Journal and E-Health. https://doi.org/10.1089/tmj.2021.0176

Okeagu, F., Nwamekwe, C., & Nnamani, B. (2024). Challenges and Solutions of Industrial Development in Anambra State, Nigeria. Iconic Research and Engineering Journals, 7(11), 467-472. https://www.irejournals.com/formatedpaper/1705825.pdf

Okpala C. C., Chukwudi Emeka Udu, & Charles Onyeka Nwamekwe. (2025). Sustainable HVAC Project Management: Strategies for Green Building Certification. International Journal of Industrial and Production Engineering, 3(2), 14-28. https://journals.unizik.edu.ng/ijipe/article/view/5595.

Okpala, C. C., Ezeanyim, O. C., & Nwamekwe, C. O. (2024). The Implementation of Kaizen Principles in Manufacturing Processes: A Pathway to Continuous Improvement. International Journal of Engineering Inventions, 13(7), 116-124. https://www.ijeijournal.com/papers/Vol13-Issue7/1307116124.pdf

Okpala, C. C., Udu, C. E., & Nwamekwe, C. O. (2025). Artificial Intelligence-Driven Total Productive Maintenance: The Future of Maintenance in Smart Factories. International Journal of Engineering Research and Development (IJERD), (21)1, 68-74. https://www.ijerd.com/paper/vol21-issue1/21016874.pdf

Onyeka, N. C., Vitalis, E. N., Chidiebube, I. N., U-Dominic, C. M., & Chibuzo, N. (2024). Adoption of Smart Factories in Nigeria: Problems, Obstacles, Remedies and Opportunities. International journal of industrial and production engineering, 2(2), 68-81. https://journals.unizik.edu.ng/ijipe/article/view/4167

Qian, Z., Alaa, A., & Schaar, M. (2020). Cpas: the uk's national machine learning-based hospital capacity planning system for covid-19. Machine Learning, 110(1), 15-35. https://doi.org/10.1007/s10994-020-05921-4

Schneider, A., Besselink, P., Zonderland, M., Boucherie, R., Hout, W., Kievit, J., ... & Rabelink, T. (2018). Allocating emergency beds improves the emergency admission flow. Informs Journal on Applied Analytics, 48(4), 384-394. https://doi.org/10.1287/inte.2018.0951

Singh, A., Farmer, P., Tully, J., Waterman, R., & Gabriel, R. (2025). Forecasting surgical bed utilization: architectural design of a machine learning pipeline incorporating predicted length of stay and surgical volume. Journal of Medical Systems, 49(1). https://doi.org/10.1007/s10916-025-02201-3

Tan, B., Chen, Y., Zhou, Y., Li, S., & Dong, Z. (2023). A cross-institution information-sharing scheme based on a consortium blockchain. Electronics, 12(21), 4512. https://doi.org/10.3390/electronics12214512

U-Dominic, C. M., Orji, I. J., Nkemakonam, C. I., Onyeka, N. C., & Nwufo, M. A. (2025). A Decision Methodology for Six-Sigma Implementation in the Nigerian Small and Medium Scale Enterprise (SME). Unizik Journal of Technology, Production and Mechanical Systems, 5(1), 186-202.

Vázquez-Serrano, J., Peimbert-García, R., & Cárdenas–Barrón, L. (2021). Discrete-event simulation modeling in healthcare: a comprehensive review. International Journal of Environmental Research and Public Health, 18(22), 12262. https://doi.org/10.3390/ijerph182212262

Williams, E., Szakmány, T., Spernaes, I., Muthuswamy, B., & Holborn, P. (2020). Discrete-event simulation modelling of critical care flow: new hospital, old challenges. Critical Care Explorations, 2(9), e0174. https://doi.org/10.1097/cce.0000000000000174