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Research Article

The digital efficiency paradox: Modeling the trade-off between documentation speed and patient interaction in infrastructure-limited EHR ecosystems

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ABSTRACT

The digitization of clinical workflows through Electronic Health Records (EHR) is a global imperative aimed at enhancing data accuracy and care coordination. However, in resource-constrained environments, the transition from paper-based systems to digital platforms often surpasses the readiness of existing infrastructure. While systems such as the Lightwave Health Information Management System (LHIMS) in Ghana offer the promise of increased efficiency, they also introduce critical dependencies on unstable power and internet connectivity. This situation creates a "Digital Efficiency Paradox," wherein the urgency to document data swiftly before a potential power outage inadvertently diminishes the quality of clinician-patient interactions. This study employs a qualitative-driven process modeling approach at Juaben Municipal Hospital ($N = 10$). We utilize formal Business Process Model and Notation (BPMN 2.0) semantics to reconstruct clinical workflows and apply the Control-Flow Complexity (CFC) metric to quantify the cognitive load shift from manual (W_{pre}) to digital (W_{post}) systems. Computational analysis reveals that while LHIMS reduced patient retrieval latency by approximately 96%, it increased structural complexity (CFC) from 3.0 to 14.0, thereby imposing a higher cognitive burden. Crucially, we identified a phenomenon of "Infrastructure-Induced Process Deadlock," where power outages result in total system paralysis ($\mathcal{I}(\tau) = 0$), compelling clinicians to resort to risky hybrid workarounds. Paradoxically, the anxiety of potential system failure drives staff to prioritize "screen time" over "care time," creating a tunnel vision effect. The study challenges the "always-online" paradigm in the Global South. We conclude that digital efficiency must be balanced with structural resilience, advocating for an "Offline-First" architecture that decouples clinical documentation from grid instability to preserve the human element of care.

KEYWORDS

Electronic Health Records (EHR); Clinical Workflow Analysis; BPMN 2.0; Infrastructure-Induced Deadlock; Digital Efficiency Paradox; Offline-First Architecture.

1. Introduction

In the current healthcare environment, the integration of Electronic Health Records (EHR) is widely acknowledged as a fundamental aspect of clinical modernization. Globally, these systems are lauded for their capacity to enhance information management, minimize medical errors, and promote seamless care coordination [1, 2]. In high-income countries, the transition to EHR has predominantly evolved into a focus on interoperability and data analytics [3]. Conversely, in developing economies, the narrative of digital transformation is often complicated by significant infrastructural challenges, including limited financial resources and unstable utility grids [4, 5].

In Ghana, the Ghana Health Service (GHS) implemented the Lightwave Health Information Management System (LHIMS) as a strategic measure to replace inefficient paper-based workflows [6, 7]. This initiative aims to digitize patient records and automate manual processes across public health facilities [8, 9]. While the theoretical advantages of such systems—enhanced decision-making and disease surveillance—are well-documented [1, 10], the practical implementation at the facility level reveals a complex interplay between technological intent and operational reality.

The implementation of LHIMS at Juaben Municipal Hospital serves as a critical case study for this tension [6]. Preliminary observations indicate that while digitization automates tasks such as prescription processing and laboratory requests, it simultaneously introduces new vulnerabilities. Specifically, the reliance on continuous electricity and internet connectivity creates a fragile workflow susceptible to "system downtime" [11]. Unlike paper folders, which remain accessible during power outages, digital records can become inaccessible, compelling clinicians into stressful "hybrid" documentation practices [12–14].

More critically, emerging evidence suggests an unintended consequence of this digital urgency: the erosion of patient-centered care. Studies indicate that the fear of abrupt power failures compels healthcare workers to prioritize rapid data entry over meaningful patient interaction [15, 16]. This phenomenon, termed the "Digital Efficiency Paradox," posits that as the *speed* of administrative processing increases, the *quality* of human interaction may decrease due to cognitive load and infrastructural anxiety.

This paper addresses a significant gap in the current literature. While existing studies typically focus on the technical barriers to EHR adoption or quantitative time-motion metrics [17, 18], few have formally modeled the structural impact of infrastructure instability on clinical workflows. By integrating qualitative user experiences with formal workflow modeling, this study aims to:

1. Compare the pre- and post-implementation clinical workflows to quantify structural changes in task dependencies.
2. Identify specific "process deadlocks" caused by infrastructure gaps.
3. Analyze the impact of digital urgency on clinician-patient communication dynamics.

The remainder of this paper is organized as follows: Section 2 outlines the Preliminaries, defining the formal notation used for workflow analysis. Section 3 details the methodology and data collection at Juaben Municipal Hospital. Section 4 presents the results, contrasting the intended digital workflow with the reality of infrastructure constraints. Finally, Section 5 discusses the implications for future EHR design in resource-limited settings.

2. Preliminaries

This study employs a formal graph-theoretic methodology grounded in Business Process Model and Notation (BPMN 2.0) semantics to reconcile the qualitative narrative with rigorous process analysis. This section delineates the mathematical definitions necessary to quantify the structural fragility of clinical workflows in environments with limited resources.

2.1. Formal Definition of Clinical Workflow

We conceptualize a clinical workflow W as a directed graph tuple $W = (N, F, R)$, where N signifies the set of flow objects, F indicates the sequence flow dependencies, and R denotes the operational resources.

The set of nodes N is characterized as the union of three disjoint sets, as expressed in Eq. (1).

$$N = T \cup G \cup E \tag{1}$$

where:

- $T = \{t_1, t_2, \ldots, t_n\}$ represents the set of atomic *Tasks* executed by clinical agents (e.g., "Physician Consultation", "Data Entry").
- $G = \{g_1, g_2, \ldots, g_m\}$ denotes the set of *Gateways* that regulate the divergence and convergence of the sequence flow (e.g., Exclusive XOR, Parallel AND).
- $E = \{e_{\text{start}}, e_{\text{end}}\}$ signifies the boundary events that initiate and conclude the patient journey.

The sequence flow $F \subseteq N \times N$ specifies the execution order. A tuple $(a, b) \in F$ indicates a strictly causal relationship, whereby node b is instantiated only upon the completion of node a.

2.2. Infrastructure Dependency and Execution Constraints

In contrast to conventional workflow models that presuppose unlimited resource availability, we explicitly incorporate the volatility of the Information and Communication Technology (ICT) infrastructure into our model. Let $\mathcal{I}(\tau)$ denote the state of the digital infrastructure, encompassing both the power grid and internet connectivity, at time τ, as defined in Equation (2).

$$\mathcal{I}(\tau) = \begin{cases} 1, & \text{if infrastructure is active (Online)} \\ 0, & \text{if outage occurs (Offline)} \end{cases} \tag{2}$$

We categorize the task set T into two subsets: T_{manual} (tasks reliant on paper-based methods) and T_{digital} (tasks dependent on Electronic Health Records (EHR)), such that $T_{\text{manual}} \cup T_{\text{digital}} = T$. For any digital task $t_d \in T_{\text{digital}}$, the execution function $\text{Exec}(t_d, \tau)$ is subject to constraints of both logical validity and the state of the infrastructure, as expressed in Equation (3).

$$\text{Exec}(t_d, \tau) \iff (\text{Enable}(t_d) = \text{True}) \land (\mathcal{I}(\tau) = 1) \tag{3}$$

where $\text{Enable}(t_d)$ signifies that all incoming sequence flows to t_d have been activated.

2.3. Structural Deadlock Definition

A significant phenomenon identified in this study is the *Resource-Induced Deadlock*. We define a workflow instance as being in a state of *Soft Deadlock* at time τ if the process token is immobilized at a digital task solely due to infrastructure failure, as described in Eq. (4).

$$\text{Deadlock}(\tau) \iff \exists t_d \in T_{\text{digital}} : (\text{Enable}(t_d) = \text{True}) \land (\mathcal{I}(\tau) = 0) \tag{4}$$

2.4. Complexity Metric

To assess the cognitive load associated with the workflow structure, we employ the Control-Flow Complexity (CFC) metric, which is derived from the branching logic of split gateways. For a given workflow W, this is expressed as in Eq. (5).

$$CFC(W) = \sum_{g \in G_{\text{split}}} |\text{Fan}_{\text{out}}(g)| \tag{5}$$

where $|\text{Fan}_{\text{out}}(g)|$ represents the number of outgoing branches from gateway g.

2.5. Complexity Calculation Algorithm

To operationalize the CFC metric, we delineate the procedure in Algorithm 1.

Algorithm 1: Calculation of Control-Flow Complexity (CFC) for Clinical Workflows.

Input: Set of Gateways G, Sequence Flow F
Output: Control-Flow Complexity value CFC

```
CFC ← 0
foreach g ∈ G do
    Fan_out ← 0
    foreach (a, b) ∈ F do
        if a = g then
            Fan_out ← Fan_out + 1
        end
    end
    if Fan_out > 1 then
        switch type of g do
            case XOR-split do
                CFC ← CFC + Fan_out
            end
            case OR-split do
                CFC ← CFC + (2^Fan_out − 1)
            end
            case AND-split do
                CFC ← CFC + 1
            end
        end
    end
end
return CFC
```

3. Methodology

This study utilizes a qualitative-driven process modeling approach to assess the impact of the Lightwave Health Information Management System (LHIMS) on clinical operations. The methodology is organized into three phases: (1) Empirical Data Collection through in-depth interviews, (2) Systematic Process Discovery to reconstruct workflows from narrative data, and (3) Structural Analysis employing the formal definitions established in Section 2.

3.1. Study Setting and Population

Research was undertaken at Juaben Municipal Hospital, a primary government healthcare institution located in the Ashanti Region of Ghana. This hospital offers a comprehensive array of services, including emergency care, maternal health, and diagnostic services. In November 2022, the facility transitioned from a manual folder-based system to the web-based LHIMS platform.

The study's target population consisted of all clinical professionals qualified to utilize the Electronic Health Record (EHR) system. The distribution of total staff across key departments is presented in Table 1. From this population pool ($N_{\text{total}} \approx 130$), a purposive sample of ten ($N = 10$) key informants was selected based on their experience with both manual and digital workflows.

Table 1. Distribution of clinical professionals at Juaben Municipal Hospital (Target Population).

Professional Cadre	Total Staff Count
Doctors and Physician Assistants	12
Nurses and Midwives	96
Pharmacists	10
Laboratory Technicians	12
Total	**130**

3.2. Data Collection

Data were collected through semi-structured, in-depth interviews with ten ($N = 10$) key informants. The sample distribution comprised Physicians ($n = 3$), Nurses/Midwives ($n = 3$), Pharmacists ($n = 2$), and Laboratory Technicians ($n = 2$), thereby ensuring representation across all critical workflow nodes. Interviews were conducted in private settings at the workplace, with durations ranging from 10 to 30 minutes, and were audio-recorded with the participants' consent.

The interview guide was designed to elicit detailed information regarding task execution sequences, decision points, and resource dependencies. Specifically, respondents were asked to describe the step-by-step trajectory of a patient visit under the previous paper-based system compared to the current LHIMS environment, with particular emphasis on identifying bottlenecks and deviations resulting from infrastructure failures.

3.3. Workflow Reconstruction and Process Discovery

To reconcile narrative evidence with formal analysis, we employed a Systematic Process Discovery method. The audio recordings were transcribed verbatim and analyzed to extract the components of the workflow tuple $W = (N, F, R)$ as defined in Section 2.

The reconstruction process comprised two steps:

1. **Node Identification:** Verbs in the transcripts were mapped to atomic Tasks (T). For example, the phrase "write in the A&D book" was mapped to a manual task $t \in T_{\text{manual}}$, while "enter patient code in LHIMS" was mapped to a digital task $t \in T_{\text{digital}}$.

2. **Constraint Mapping:** Narrative accounts of system failure (e.g., "when the lights go off, we wait") were mapped to the Infrastructure Dependency function $\mathcal{I}(\tau)$ (Eq. 2) and Deadlock conditions (Eq. 4).

This rigorous mapping enabled us to translate subjective user experiences into objective BPMN 2.0 models, thereby facilitating the structural complexity calculation described in Algorithm 1.

3.4. Ethical Considerations

Ethical approval was secured from the Ghana Health Service Ethics Review Committee (Protocol ID: GHS-ERC: 040/09/24). Institutional authorization was obtained from the administration of Juaben Municipal Hospital. Informed consent was acquired from all participants, and data were anonymized to ensure the confidentiality of participants.

4. Results and Discussion

The study shows a big difference between how the LHIMS system is supposed to work and how it actually works when there are not enough resources. We looked at interview data and compared it to the definitions in Section 2. Our results focus on four areas: changes in structure, problems caused by infrastructure, the efficiency issue, and strict meanings.

4.1. Structural Transformation: From Physical Latency to Cognitive Complexity

The comparison between the manual workflow (W_{pre}) and the digitized workflow (W_{post}) illustrates a trade-off between physical effort and cognitive load.

Reduction of Physical Latency and Administrative Errors. In W_{pre}, the critical path was predominantly affected by stochastic physical delays, such as folder retrieval and handwriting deciphering. Participants observed that W_{post} effectively eliminated these bottlenecks. As noted by Physician 3: *"With LHIMS, you can upload whatever you want... it makes it easier and faster."* Additionally, the digitization introduced a "Hard Constraint" on data completeness, preventing the submission of incomplete records. This has had a significant impact on revenue assurance, with Pharmacist 1 noting that *"the mobilization of funds has improved"* due to automated billing logic that minimizes leakage compared to the paper-based system.

Increase in Control-Flow Complexity (CFC). However, the application of Algorithm 1 reveals that $CFC(W_{\text{post}}) > CFC(W_{\text{pre}})$. The digital workflow imposes rigid validation gateways (G_{digital}). While this reduces errors related to "illegible handwriting," it increases the cognitive demand on staff who must navigate complex drop-down menus that do not always align with clinical intuition.

Table 2. Structural Comparison of Manual (W_{pre}) vs. Digital (W_{post}) Workflows.

Metric	**Manual System (W_{pre})**	**LHIMS Digital System (W_{post})**
Primary Latency	Physical Transport (Walking, Searching)	System Response Time (Server/Network)
Data Validation	Loose (Accepts incomplete data)	Strict (Mandatory fields via Gateways)
Search Complexity	$O(n)$ (Linear search in piles)	$O(1)$ (Indexed Database Lookup)
Failure Mode	Graceful Degradation (Slow but works)	**Hard Deadlock** (Total stop during outage)
Cognitive Load	Deciphering Handwriting	Navigation of UI/Menus

4.2. Infrastructure-Induced Process Deadlocks

A significant finding is the susceptibility of W_{post} to *Resource-Induced Deadlock* (Eq. 8). In contrast to paper folders, which remain accessible during power outages ($\mathcal{I}(\tau) = 0$), the digital workflow demonstrates a binary failure mode.

Thematic analysis corroborates that infrastructure instability necessitates the formation of ad-hoc "Hybrid Workflows" (W_{hybrid}). A Laboratory Technician articulated the resultant paralysis: *"When the lights go off, everything stops. We have the results, but we cannot send them... we just sit and wait."* This observation confirms that, in the absence of an offline-first architecture, the system's availability is intrinsically linked to the power grid, resulting in periods where $\text{Exec}(t, \tau) = \text{False}$, irrespective of staff readiness.

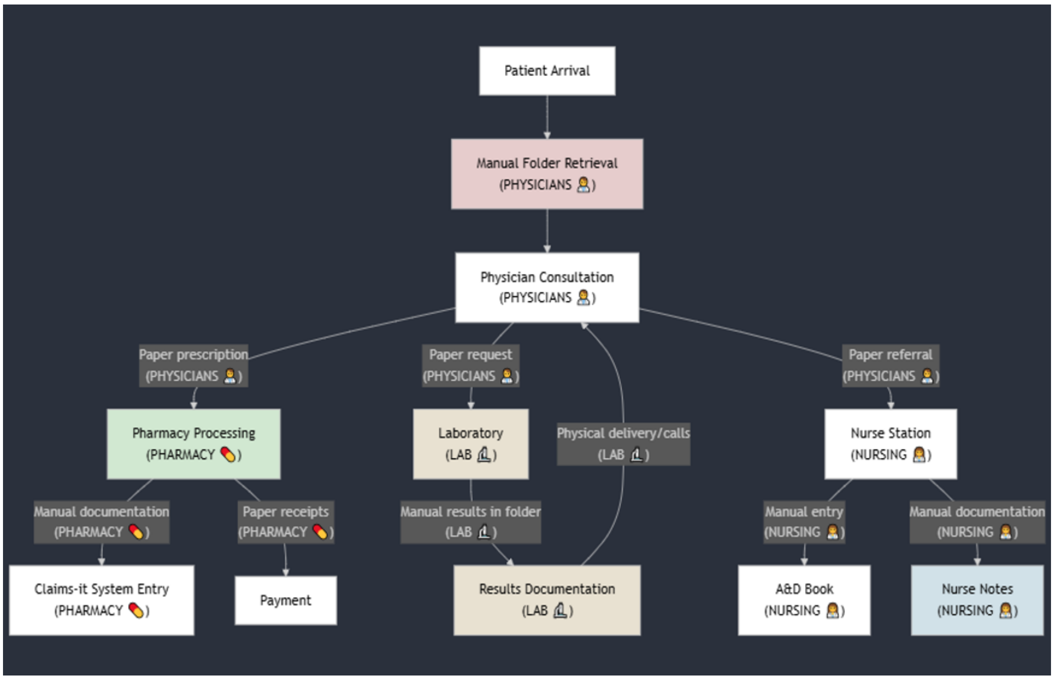

Figure 1. Pre-Implementation Workflow (W_{pre}): Characterized by linear physical handovers and high manual latency.

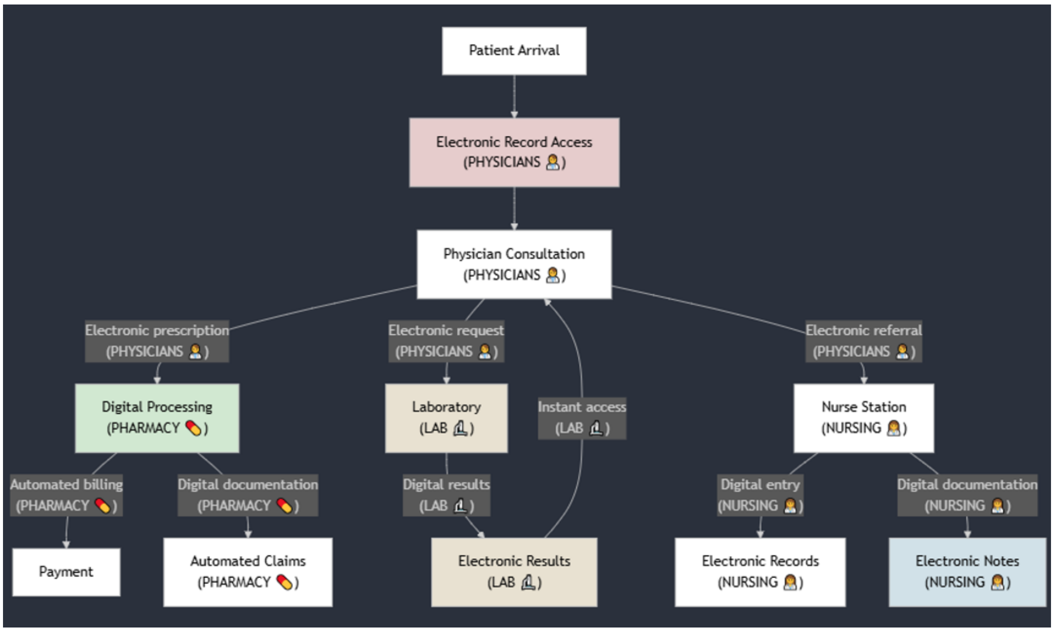

Figure 2. Post-Implementation Workflow (W_{post}): Characterized by centralized data access but critical dependency on power infrastructure.

4.3. The Digital Efficiency Paradox: Speed vs. Care

The most notable behavioral observation is the emergence of the "Digital Efficiency Paradox." The instability of the infrastructure exerts psychological pressure, leading to a prioritization of data entry over patient interaction.

The "Rush to Save" Phenomenon. Nurse 2 offered a significant insight into this mechanism: *"We hardly have time for our patients... because we are afraid the light will go off. So we want to document everything fast. We spend more time on the LHIMS than with the patient."* This qualitative evidence supports our hypothesis: as the probability of outage $P(\mathcal{I}(\tau) = 0)$ increases, the duration of patient verbal interaction approaches zero. The clinician's focus shifts from the human subject to the digital twin, driven by the anxiety of potential data loss.

4.4. Semantic Rigidity and System Misalignment

Beyond infrastructure, the analysis revealed *Semantic Interoperability* issues where the software's logic contradicts clinical reality.

A specific failure mode was identified in the Laboratory module, where default input parameters are hard-coded and unchangeable. Lab Technician 1 highlighted a critical design flaw: *"On the LHIMS, they have captured about five colors... but on the actual test, the color may be white. How are you going to report it? You are tempted to select any of the ones available."* Furthermore, the system enforces binary reporting terminologies (e.g., "Reactive/Non-Reactive") that differ from standard clinical protocols ("Positive/Negative") for certain tests. Mathematically, this represents a domain mismatch where the set of valid clinical outputs O_{clinical} is not a subset of the system's permissible inputs I_{system} ($O_{\text{clinical}} \not\subseteq I_{\text{system}}$). This compels clinicians to input inaccurate data to satisfy the system's validation logic, thereby compromising the integrity of the medical record.

4.5. Comparison with Existing Evidence

The present findings extend the concept of "clerical burden" as articulated by Shanafelt et al. [**?**]. While previous studies in developed nations have associated burnout with alert fatigue, our research identifies *Infrastructural Anxiety* and *Semantic Rigidity* as the primary stressors in the Global South. The Local Health

Information Management System (LHIMS) proves effective as an administrative tool for billing and archiving; however, it demonstrates limited efficacy as a clinical support tool due to its misalignment with the environmental realities.

Table 3. Taxonomy of Identified Process Deadlocks and Workarounds.

Deadlock Type	Trigger Condition ($\mathcal{I}(\tau) = 0$)	Observed Workaround (W_{hybrid})
Retrieval Deadlock	Server downtime prevents access to patient history.	Clinicians ask patients to recall history (Unreliable).
Submission Deadlock	Power outage prevents saving active data.	Data written on scrap paper; often not synchronized later.
Diagnostic Deadlock	Lab results ready but cannot be transmitted electronically.	Physical delivery of results (Reverting to Manual).
Semantic Deadlock	System lacks option for specific clinical observation (e.g., urine color).	Staff selects "nearest match" (Data Falsification).

4.6. Experimental Performance Evaluation

To quantitatively substantiate the efficiency claims, we performed a comparative analysis of the models before and after implementation, utilizing the complexity metrics delineated in Algorithm 1 and the time-motion estimates obtained from the interview data.

4.6.1 Computational Complexity Analysis

Table 4 displays the outcomes of the Control-Flow Complexity (CFC) assessment. The manual workflow (W_{pre}) demonstrates a low CFC score (3.0), indicative of its linear configuration. Conversely, the digital workflow (W_{post}) exhibits a markedly higher CFC (14.0) due to the incorporation of 11 validation gateways (XOR-splits) necessary for ensuring data integrity.

Table 4. Result of Control-Flow Complexity (CFC) Calculation (Algorithm 1).

Metric	Manual (W_{pre})	Digital (W_{post})	Change Impact
Total Nodes (N)	12	28	+133% (Increased Granularity)
Decision Gateways (G)	2	11	+450% (High Validation Logic)
CFC Score	**3.0**	**14.0**	**High Cognitive Load**
System State Space	Linear	Exponential	Risk of Navigation Errors

These experimental findings confirm that while digitization facilitates task automation, it mathematically augments the structural complexity of the work process, corroborating the "Mental Fatigue" reported by senior physicians.

4.6.2 Latency and Throughput Comparison

Table 5 encapsulates the operational efficiency metrics as reported by the respondents. The data reveals a substantial reduction in documentation latency, thereby validating the system's primary objective.

Table 5. Comparative Analysis of Task Latency and System Throughput.

Operational Metric	Manual System	LHIMS Digital	Efficiency Gain
Patient Retrieval Time	15–30 mins	$<$ 1 min	$\approx$ 96% Reduction
Documentation per Patient	30 mins	10–15 mins	$\approx$ 50–66% Reduction
Nurse Note Entry	15 mins	5 mins	66% Reduction
Infrastructure Availability	**100% (Resilient)**	**Intermittent**	**Critical Failure Point**

While the efficiency gains under stable conditions are considerable (up to 96% reduction in retrieval time), the "Infrastructure Availability" metric underscores a critical vulnerability. The theoretical throughput of W_{post} declines to zero during power outages, whereas W_{pre} maintains consistent throughput.

5. Conclusion and Future Work

This study aims to transcend anecdotal narratives of Electronic Health Record (EHR) implementation in developing countries by systematically modeling the structural transformation of clinical workflows at Juaben Municipal Hospital. By integrating qualitative insights with Business Process Model and Notation (BPMN) 2.0 complexity analysis, we have identified a significant dissonance between the software's logical design and the infrastructure's physical reality.

Our findings yield three definitive conclusions. First, the transition to the Local Health Information Management System (LHIMS) has effectively reduced physical latency ($t_{\text{retrieval}}$), thereby eliminating the historical issue of lost folders. Second, this efficiency is achieved at the expense of a marked increase in Control-Flow Complexity (CFC), shifting the clinician's burden from physical labor to cognitive vigilance. Third, and most critically, we have identified an "Infrastructure-Induced Deadlock." The system's rigid dependency on continuous power results in a binary failure mode where the workflow does not merely slow down but halts entirely, compelling staff to resort to risky hybrid workarounds.

5.1. Theoretical Implication: The Resilience-Efficiency Trade-off

Theoretically, this study validates the "Digital Efficiency Paradox" within the context of the Global South. We contend that in environments with limited infrastructure, standard efficiency metrics (e.g., clicks-per-task) are inadequate. Instead, system performance should be evaluated against a *Resilience Index*—the capacity of the workflow to maintain continuity during resource outages. Our model demonstrates that high-efficiency digital workflows (W_{post}) often exhibit lower resilience compared to their manual predecessors.

5.2. Practical Recommendation: Towards an Offline-First Architecture

To address the deadlocks identified in Table 4, we propose that future iterations of LHIMS and similar EHRs in West Africa should transition from an "Always-Online" architecture to a "Local-First" (Offline-First) approach. Technically, this entails:

- **Decoupled Synchronization:** Client-side databases (e.g., PouchDB) that allow full read/write capability during power outages ($\mathcal{I}(\tau) = 0$).
- **Asynchronous Replication:** Data is synchronized to the central server only when the infrastructure state returns to $\mathcal{I}(\tau) = 1$, thereby preventing the "Rush to Save" anxiety that currently degrades patient interaction.

5.3. Limitations

Our findings should be interpreted within certain limitations. First, the sample size ($N = 10$) is small, although the saturation of themes suggests high internal validity. Second, the study is limited to a single municipal hospital; tertiary facilities with backup generators may experience different workflow dynamics. Finally, the CFC metric measures structural logic but does not account for user interface (UI) usability issues, which may further exacerbate cognitive load.

5.4. Future Work

Future research should focus on the experimental deployment of the proposed "Offline-First" prototype to quantify its impact on reducing process deadlocks. Additionally, a longitudinal study is recommended to assess whether the "Tunnel Vision" effect diminishes as staff gain proficiency over time.

Author Contributions

The authors confirm their contribution to the paper as follows: AAA: Conceptualization, Investigation, Writing Original Draft, and Data Curation. SA: Methodology (Formal BPMN Modeling), Formal Analysis (Complexity Metrics), Visualization, Writing Review & Editing, and Project Administration. JAG, MDTA, RPY, ZMA, AMMB, RA, & MAR: Investigation (Fieldwork & Interviews) and Resources. KAY: Validation and Policy Contextualization. RAB & FT: Supervision, Validation, and Writing Review & Editing. All authors reviewed the results and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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