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Original Research Article

Optimizing End-to-End HIV Clinic Operations Using Advanced Process Mapping: A Framework for Enhancing Pre-Exposure Prophylaxis (PrEP) Uptake and Care Outcomes

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Abstract: This study presents a novel framework for optimizing HIV clinic operations with a focus on enhancing the delivery of pre-exposure prophylaxis (PrEP) services. The research uses advanced process mapping, synthetic data modeling, and visual analytics to investigate and identify operational inefficiencies across the PrEP care continuum from patient intake and risk assessment through prescription, adherence monitoring, and post-treatment follow-up. Instead of relying on conventional surveys, the study generates synthetic datasets to simulate staff satisfaction, clinic throughput, and error rates under different workflow configurations. These simulations are visualized through intuitive yet uncommon formats, including bar charts, radar charts, and swimlane Gantt charts. Findings reveal that workflow redesigns can significantly improve staff-reported task clarity, reduce clinical errors, and enhance operational efficiency without increasing resource burdens. The approach offers a scalable, low-risk, pre-implementation diagnostic tool for health systems aiming to integrate PrEP into diverse care settings. By combining implementation science with systems engineering, this study contributes a practical and replicable model for improving the structural quality of HIV prevention services.

Keywords: PrEP implementation, process mapping, HIV clinic optimization, synthetic data modeling, healthcare workflow analysis.

INTRODUCTION

HIV prevention through biomedical interventions, particularly PrEP, is gaining global momentum as a key tool to combat the ongoing HIV epidemic. PrEP, when taken as tenofovir disoproxil/emtricitabine, is well known to prevent HIV acquisition. But success is increasingly determined by adherence and retention rather than pharmacologic potency alone (MacDonald *et al*., 2023). However, real world application of PrEP in clinical and community settings shows deeply ingrained systemic barriers that prevent its wider adoption and use (Magnus *et al*., 2023). Despite its proven efficacy, PrEP access is inconsistent and plagued by structural barriers. Magnus *et al*. (2023) break these down into three main categories: provider and clinic characteristics, cost and socio-structural disparities. For example, a major barrier to PrEP diffusion has been lack of provider training and

comfort with prescribing PrEP, especially in non-specialty clinics. This is compounded by institutional inefficiencies such as staffing shortages, unclear prescribing protocols and no wraparound services like adherence counseling or PrEP navigation, all of which are critical to preventive care (Magnus *et al*., 2023). As process mapping in healthcare aims to visualize and fix these operational inefficiencies, it's a great way to address the misalignment of clinical workflow with PrEP implementation requirements.

Moreover, integrating PrEP into existing healthcare services, such as family planning (FP) clinics, offers a promising route to enhance its uptake, especially among women and adolescent girls in high-prevalence settings. However, integration efforts are hampered by poor risk perception among clients and insufficient provider training, resulting in low uptake and poor retention despite high awareness levels (Gotsche *et al*., 2022). The Evidence for Contraceptive Options and HIV Outcomes (ECHO) trial further underscored the necessity of embedding HIV prevention into FP services, given the high incidence of HIV in such settings (Gotsche *et al*., 2022). However, most FP clinics are structurally unprepared to offer PrEP due to gaps in workforce readiness, the absence of standardized counselling tools, and systemic exclusion of women in implementation studies. The Scottish national PrEP programme is a key example of how implementation science can inform improvements in adherence and retention through rigorous process evaluation. MacDonald *et al*. (2023) utilized the Behaviour Change Wheel and Theoretical Domains Framework to identify intervention points along the PrEP care cascade in their study. Key findings indicated that users often discontinued PrEP due to logistical issues, such as inflexible appointment systems and confusing guidance on on-demand dosing, as well as psychosocial factors like stigma and misinformation (MacDonald *et al*., 2023). These findings emphasize that even in well-resourced contexts, the procedural complexity of PrEP services can undermine their accessibility and sustainability.

Process mapping is an essential tool for operationalizing the procedural complexity of PrEP services. By breaking down care pathways into discrete, measurable steps from eligibility screening and baseline diagnostics to follow-up reviews, process maps help clinics identify inefficiencies, reduce duplication of effort and optimise resource allocation. Especially given the need for earlier intervention in the drug development and service integration phases (Magnus *et al*., 2023). Rather than treating implementation challenges reactively, a forward looking strategy embedded in the design and rollout phases could ensure smoother PrEP roll out across all service points including primary care and FP clinics. This paper proposes a new methodological framework combining process mapping with synthetic data modelling to simulate and optimise PrEP workflows in HIV clinics. Instead of relying on traditional surveys, the study will create a hypothetical yet evidence-based dataset of task durations, error rates and staff satisfaction. These metrics will be visualised through rare and informative charts including Bar charts and chord diagrams to show bottlenecks and flow inefficiencies. This aligns with global calls for implementation science in HIV prevention (Gotsche *et al*., 2022; Magnus *et al*., 2023; MacDonald *et al*., 2023) and will equip health systems with scalable tools to improve clinical practice through data driven design.

LITERATURE REVIEW

PrEP for HIV prevention has shown to be effective in reducing HIV transmission when implemented in clinical settings. The approval and rollout of PrEP regimens like tenofovir disoproxil fumarate/emtricitabine (TDF/FTC) and more recently long-acting cabotegravir have expanded biomedical prevention options (Magnus *et al*., 2023; Gotsche *et al*., 2022). But despite clinical efficacy and increasing global endorsement, PrEP in real life is not evenly adopted, limited by a constellation of structural, procedural and behavioral barriers that hinder its widespread and equitable delivery (MacDonald *et al*., 2023; Estcourt *et al*., 2023). The healthcare system's structural readiness is one of the biggest obstacles to PrEP diffusion. According to Magnus *et al*. (2023) three main categories of barriers persist: provider and clinic level (e.g. limited training, not comfortable discussing sexual health), cost and insurance logistics and socio-cultural disparities (stigma and systemic bias). These barriers are not only for current oral and injectable PrEP but will persist or even worsen as new PrEP modalities like implants and vaginal rings emerge. Previous studies also found that primary care settings are less likely to offer PrEP compared to specialty clinics due to time constraints, workforce limitations and lack of integration protocols (Turner *et al*., 2018 as cited in Magnus *et al*., 2023).

The lack of inclusive implementation research that reflects diverse risk groups and delivery models is equally concerning. Gotsche *et al*. (2022) conducted a scoping review across 38 studies and highlighted that most integration research focused on high-income countries, particularly the United States. Even in low- and middle-income settings, where HIV prevalence is often higher, service integration is hampered by low client risk perception, pill burden, provider biases, and lack of cost-effectiveness data. In Zimbabwe, only 4.1% of

women accessing family planning (FP) services took up PrEP despite high awareness levels (Gombe *et al*., 2018, cited in Gotsche *et al*., 2022). Despite exposure and knowledge, this low uptake underscores the importance of system-level facilitators, an area that remains under-addressed in the literature. The integration of PrEP into non-specialist and community care environments, such as family planning clinics, has been advocated by global health authorities, including the WHO and UNAIDS. However, empirical evidence supporting these integrations remains limited and often anecdotal. The Evidence for Contraceptive Options and HIV Outcomes (ECHO) trial revealed a high incidence of HIV among FP clinic attendees, suggesting a missed opportunity for concurrent HIV prevention services (ECHO Consortium, 2019, as cited in Gotsche *et al*., 2022). Similarly, secondary studies cited in Estcourt *et al*. (2023) note the critical timing for intervention during the initiation phase of PrEP, where clarity in eligibility, provider confidence, and system prompts play pivotal roles.

Scotland's national PrEP programme provides valuable insights into the successes and shortcomings of centralized implementation strategies. Process evaluations from this program have highlighted a mismatch between operational workflows and the behaviorally complex nature of PrEP care. MacDonald *et al*. (2023) found that both providers and patients experience challenges at multiple touchpoints: from inconsistent dosing guidance and limited appointment flexibility to emerging stigmas related to non-use of PrEP. These barriers are exacerbated in resource-stretched clinics where multidisciplinary needs, such as STI testing, renal monitoring, and psychosocial counseling, are managed by understaffed teams.

Although the Behaviour Change Wheel and Theoretical Domains Framework were applied to generate recommendations in the Scottish studies (MacDonald *et al*., 2023; Estcourt *et al*., 2023), they primarily addressed behavioral constructs rather than operational inefficiencies. Process inefficiencies, including delays in task execution, lack of real-time data flow, and poor inter-role coordination, were acknowledged but not quantified. Furthermore, the absence of standard process diagrams or simulations in these evaluations limits the replicability and scalability of their findings.

A notable gap in the literature is the lack of applied visual process analysis, such as Business Process Model and Notation (BPMN), Value Stream Mapping, or swim lane diagrams, which are tools frequently used in operations research and systems engineering but rarely applied in clinical HIV prevention research. While MacDonald *et al*. (2023) and Estcourt *et al*. (2023) produced text-based process summaries and logic models, there is little evidence of these being developed into dynamic process maps that can be evaluated, simulated, or optimized. Additionally, most evaluations, including those conducted in Scotland, rely on qualitative data or retrospective surveys. Few studies generate or simulate synthetic datasets that can predict outcomes such as staff satisfaction, error rates, or throughput efficiency. This is critical in many low-resource clinics' absence of real-time monitoring capabilities. Turner *et al*. (2018, as cited in Magnus *et al*., 2023) and O'Connell *et al*. (2020, as cited in Gotsche *et al*., 2022) also note that implementation assessments are often conducted too late after drug approval or program deployment, rather than being embedded in the design and rollout phases.

While there is growing recognition of the need for implementation science in HIV prevention, the literature reveals a methodological void regarding proactive operational diagnostics. Specifically, there is a lack of:

1. Process-oriented studies that map and analyze end-to-end clinic workflows.
2. Synthetic data models that simulate operational outcomes.
3. Integration of PrEP services into routine healthcare settings using visual and analytic tools.

This study addresses these gaps by proposing an operational research model that uses advanced process mapping techniques and rare visual diagrams, such as Bar charts flows and chord charts, to model HIV clinic workflows. The study seeks to move beyond narrative evaluations toward a replicable, data-driven optimization framework by generating synthetic data to simulate key performance indicators.

Research Objectives

- To design high-resolution process maps for PrEP-related workflows.
- To define performance metrics that align with hypothetical clinic improvements.
- To propose data constructs that validate satisfaction, efficiency, and safety gains.

Research Questions

1. How can advanced process mapping expose bottlenecks in PrEP care delivery?
2. Which synthetic metrics can simulate improvements in clinic operations?
3. What visual tools best represent end-to-end HIV clinic processes for PrEP uptake?

METHODOLOGY

This study employs a mixed-methods, simulation-based approach centered on designing and analyzing advanced process maps for HIV clinic operations, specifically focused on PrEP service delivery. The methodology integrates process engineering principles, synthetic data generation, and behavioral implementation science to evaluate and visualize the full continuum of care, from initial patient intake through adherence monitoring and post-treatment review. This approach was adopted to bridge an evident gap in the literature. Most PrEP implementation studies rely on qualitative assessments or retrospective evaluations rather than forward-facing, operationally embedded planning tools (MacDonald *et al*., 2023; Magnus *et al*., 2023). The research design follows a multi-phase structure, beginning with conceptualizing and developing high-resolution process maps. These were created using Business Process Model and Notation (BPMN) and Value Stream Mapping (VSM) techniques, chosen for their ability to highlight task flows, delays, decision nodes, and inter-role dependencies within clinical settings. The process design draws heavily on the workflow structures described in the Scottish national PrEP rollout (Estcourt *et al*., 2023), which outlined four key stages: patient identification, risk screening, initiation and prescribing, and retention in care through scheduled reviews. Additional mapping insights were derived from structural barriers outlined by Magnus *et al*. (2023), particularly regarding task fragmentation and administrative burden in specialty versus primary care clinics.

The second phase of the methodology involves the construction of a synthetic dataset that mirrors operational metrics relevant to PrEP service efficiency and quality. This includes time-on-task per clinic role, patient throughput per day, documentation error rates, and Likert-scale-based proxies for staff satisfaction. Data generation was inspired by simulation frameworks applied in implementation science literature, such as the factorial design logic recommended by Damschroder *et al*. (2009) and adapted in recent PrEP process evaluations (Estcourt *et al*., 2023; MacDonald *et al*., 2023). Monte Carlo simulations were programmed in Python to model thousands of patient journeys through the proposed workflows, using randomized but realistic input parameters derived from prior studies and clinic audits (Turner et al., 2018, as cited in Magnus *et al*., 2023).

Synthetic metrics were also developed based on operational metrics from the PrEP Implementation in Young Women and Adolescents (PrIYA) program in Kenya and the Prevention Options for Women Evaluation Research (POWER) study, both of which looked at uptake and persistence in FP settings (Gotsche *et al*., 2022). We included measures such as workload, consultation length and frequency of patient-provider interactions in the dataset to simulate staff reported satisfaction and burnout. The RE-AIM (Reach, Efficacy, Adoption, Implementation, and Maintenance) framework guided variable selection to ensure relevance to real world implementation (Brant *et al*., 2020 as cited in Gotsche *et al*., 2022).

Data outputs were structured to reflect three distinct operational states of the HIV clinic:

1. Baseline (pre-intervention) reflecting existing inefficiencies.
2. Transitional (during implementation), incorporating redesigned pathways.
3. Optimized (post-mapping intervention) assuming full protocol adherence and resource adequacy.

Descriptive statistics were computed for key metrics to analyze these states, including wait times, consultation duration, and prescription error rates. Additionally, correlational analyses assessed associations between staff satisfaction and process variables such as task switching frequency and communication density. Visualizations were generated using Bar charts to depict patient flow, chord diagrams to illustrate inter-role handoffs, radar charts for comparative efficiency scores, and Gantt-style swimlane charts to represent task distribution over time. These charts were selected for their rarity in HIV operations research and their ability to convey multi-layered dynamics visually and intuitively. The process mapping phase was supplemented with theoretical grounding from the Theoretical Domains Framework (TDF) and Behaviour Change Wheel (BCW) to contextualize behavioral factors influencing adherence and retention (Michie et al., 2011; Cane *et al*., 2012; MacDonald *et al*., 2023). For example, clinic staff's motivation and perceived behavioral control were modeled as variables influencing workflow compliance, echoing concerns raised by providers in Scotland who cited inflexible appointment systems and insufficient training as barriers (MacDonald *et al*., 2023).

This study does not draw on live patient data or active clinical trials but instead uses simulation as a pre-implementation tool. This position of the research is unique in the literature by offering a blueprint for clinics or health systems to model interventions before committing to resource-intensive changes. Such foresight aligns with recommendations from Magnus *et al*. (2023), who argue for earlier integration of implementation

planning within the drug development and approval timeline rather than post hoc analysis after rollout challenges have already manifested. Ethical considerations were minimal as no human subjects were involved; however, sensitivity to real-world applicability and transferability was ensured through iterative feedback from subject-matter experts and alignment with existing PrEP program goals as outlined by WHO and UNAIDS (Gotsche *et al*., 2022). This methodology combines process mapping, synthetic data modeling, and visual analytics grounded in implementation science. It seeks to understand operational challenges and proactively simulate and recommend optimized solutions for end-to-end PrEP delivery in HIV clinics.

Data Structure (Synthetic Survey Framework)

To assess and quantify the effects of operational process redesign in an HIV clinic offering PrEP services, this study employs a carefully constructed synthetic survey framework. This framework is designed to model the experiences, perceptions, and outcomes of clinic staff and system performance, using generated data rather than live subject responses. Doing so allows for predictive assessment of proposed interventions without the ethical and logistical constraints of real-time experimentation—an increasingly encouraged approach in implementation science (Gotsche *et al*., 2022; Damschroder *et al*., 2009). The synthetic data structure mirrors the domains typically covered in post-implementation evaluations but adapts them for simulation. Metrics are grouped into three overarching dimensions aligned with the core claims in the study's abstract: (1) staff satisfaction, (2) operational efficiency, and (3) error minimization. This framework is informed by insights from previous large-scale PrEP implementation studies, including Scotland's national programme (MacDonald *et al*., 2023; Estcourt *et al*., 2023), as well as structural evaluations conducted in the United States and sub-Saharan Africa (Magnus *et al*., 2023; Gotsche *et al*., 2022).

1. Staff Satisfaction Metrics

The first set of synthetic variables captures subjective staff perceptions of workflow before and after process redesign. These are modeled using a 5-point Likert scale (1 = Strongly Dissatisfied to 5 = Strongly Satisfied), reflecting metrics validated in organizational behavior and healthcare quality literature (Turner *et al*., 2018, as cited in Magnus *et al*., 2023). Simulated staff responses include:

- Perceived clarity of clinical workflows
- Workload manageability across shift durations
- Interdisciplinary communication quality
- Job satisfaction related to PrEP service tasks
- Stress levels associated with documentation, screening, and patient counseling

These dimensions were influenced by earlier studies reporting that PrEP responsibilities, when ambiguously distributed or concentrated among undertrained staff, reduce morale and increase burnout (Magnus *et al*., 2023; Gotsche *et al*., 2022). In the Scottish evaluation, inflexible review appointments and lack of systemic follow-up protocols detracted from provider engagement (MacDonald *et al*., 2023).

2. Operational Efficiency Metrics

To simulate the clinic's functional capacity, the second component of the framework captures efficiency indicators drawn from health services research and Lean healthcare metrics. These include:

- Average time per patient visit (intake to exit)
- Number of completed consultations per provider per day
- Mean number of task switches per provider per hour
- Wait time from registration to risk assessment
- Turnaround time for laboratory screening results (simulated range: 1–3 days)

These are based on service delivery challenges seen during the roll out of long-acting injectable PrEP where logistical burdens like storage and screening delays hindered roll out despite clinical readiness (Magnus *et al*., 2023). They also reflect lessons from PrEP integration in FP clinics where streamlining intake and eligibility assessments was key to uptake (Gotsche *et al*., 2022). The operational data will be modelled using stochastic simulation, with parameter ranges from observed timelines in previous studies including the POWER and PrIYA projects (Gotsche *et al*., 2022). Monte Carlo analysis and discrete event simulation (DES) in Python will create dynamic models of workflow performance under different scenarios.

3. Error and Quality Metrics

The third group of variables simulates quality assurance indicators critical to PrEP delivery, particularly those linked to procedural lapses or omissions. These are proxies for patient safety and influence provider stress and institutional trust. Key error-related variables include:

- Simulated rates of missed HIV screening prior to PrEP initiation
- Documentation error rate (e.g., incorrect risk classification)
- Prescription mismatches (e.g., incorrect dosing or drug-drug interaction)

- Missed follow-up appointments per 100 patients
- PrEP discontinuation due to unaddressed side effects

These metrics align with concerns raised in Estcourt *et al*. (2023) and MacDonald *et al*. (2023), who noted that failures in adherence were often rooted in logistical oversights, miscommunication, or review system rigidity. The Behaviour Change Wheel and Theoretical Domains Framework (Michie *et al*., 2011; Cane *et al*., 2012) simulated how process clarity and accountability may reduce error frequency. These frameworks also justify the inclusion of follow-up systems and feedback loops as part of error control metrics.

4. Demographic and Structural Simulators

Basic demographic data of simulated staff and patients are included to contextualize the synthetic responses. Variables such as staff role (nurse, physician, administrator), years of experience, and patient volume are factored in to model heterogeneity in workload and error exposure. These mirror respondent distributions from real-world studies in high-income and low-middle-income countries (Gotsche *et al*., 2022; MacDonald *et al*., 2023). While not intended to replicate individual responses, the synthetic survey framework is calibrated to maintain internal coherence and external plausibility. Results will be used to generate visual analytics, such as radar charts for satisfaction profiles, Gantt-style task timelines, and Bar charts for process flow modeling, that reflect the systemic outcomes of proposed workflow redesigns. The synthetic survey framework operationalizes theoretical insights into quantifiable, testable variables that simulate the outcomes of clinical workflow transformations. It bridges qualitative observations with quantitative modeling, advancing operational PrEP research beyond traditional survey and interview-based assessments.

Analysis Plan

The analytical strategy for this study is designed to transform synthetic, simulation-based datasets into actionable insights regarding the operational performance of HIV clinics implementing PrEP services. This analysis aims to evaluate how end-to-end process redesign, informed by visual mapping and implementation science, impacts three key domains: staff satisfaction, clinic efficiency, and error reduction. Drawing on literature from operational research and real-world PrEP program evaluations, the plan employs a combination of descriptive, inferential, and visual analytics to interrogate baseline and optimized workflow states.

1. Descriptive Statistical Analysis:

Initial analysis will involve descriptive statistics to summarize the simulated dataset. For each variable within the synthetic survey framework, such as average time-on-task, number of task-switches per hour, and Likert-scale ratings of staff workload perception, basic measures of central tendency and dispersion will be calculated, including means, medians, standard deviations, and interquartile ranges. These metrics will be disaggregated by role (e.g., physician, nurse, administrative staff), time (baseline vs. post-redesign), and function (intake, prescribing, monitoring). This step allows for clear comparisons between operational states and highlights immediate performance shifts.

The inclusion of descriptive benchmarking is consistent with the Scottish national PrEP evaluation, where routine surveillance was used to establish baselines for uptake and retention (MacDonald *et al*., 2023). However, unlike retrospective program reviews, this study projects performance based on synthetic modeling, offering a prospective evaluation framework as Magnus *et al*. (2023) recommended.

2. Time Series and Scenario Simulation:

A Monte Carlo simulation approach will generate thousands of patient trajectories under various process conditions to capture the longitudinal implications of process improvements. This stochastic modeling will enable the estimation of the likely variability in outcomes such as appointment wait times, prescription turnaround, and dropout rates.

Drawing inspiration from service modeling in other healthcare optimization studies (Estcourt et al., 2023), simulations will test three operational scenarios:

- Status quo (baseline process structure)
- Partial intervention (mid-point changes such as flexible scheduling)
- Full implementation (optimized, mapped pathways with maximum fidelity)

Each scenario will be assessed across 1,000+ runs, generating probabilistic distributions that help anticipate clinic behavior under real-world constraints.

3. Correlational and Regression Analysis:

The following analysis phase involves identifying relationships between operational variables and staff-reported outcomes using Pearson or Spearman correlations, depending on data distribution. For example, the number of task switches per hour will be correlated with staff

satisfaction ratings, and time-to-prescription will be tested against simulated error rates. Multiple linear regression models will be constructed where appropriate to explore predictive relationships, e.g., how documentation burden and interdisciplinary communication scores predict perceived role satisfaction. These models will control for confounders such as role type, synthetic experience level, and patient volume, mirroring analyses suggested by Flowers *et al*. (2023) in their PrEP adherence pathways behavioral modeling.

4. Comparative Analytics (pre-intervention and post-intervention):

Comparative tests will be performed between pre-intervention and post-intervention states to assess the impact of process redesign. For continuous variables (e.g., average consultation time), paired t-tests or Wilcoxon signed-rank tests will be used. Mann-Whitney U tests will be employed to assess significance for ordinal Likert-scale responses (e.g., satisfaction, perceived task clarity).

These methods align with the RE-AIM framework principles, emphasizing measurable and statistically robust outcomes in assessing implementation impact (Brant et al., 2020, as cited in Gotsche *et al*., 2022). Although the data is synthetic, comparative analytics are structured to mirror real-world evaluation standards used in implementation science (Damschroder *et al*., 2009).

5. Visual Analytics:

To enhance interpretability and support dissemination, the analysis plan includes the generation of rare and informative visualizations:

- Bar charts will trace patient flows across different touchpoints, illustrating where dropouts, delays, or duplications occur.
- Chord Diagrams will map communication and task transfers among clinic roles, highlighting systemic inefficiencies.
- Radar Charts will visually compare staff-reported satisfaction and workflow clarity across operational states.
- Swimlane Gantt Charts will show task durations and handoffs over time across personnel, reflecting load balancing and bottlenecks.

Such visualizations are largely absent in current HIV PrEP implementation literature, which tends to rely on narrative summaries or static logic models (MacDonald *et al*., 2023; Estcourt *et al*., 2023). Including dynamic visuals aims to fill that methodological gap and translate complex systems insights into intuitive, decision-ready formats.

6. Validity and Sensitivity Testing:

Though synthetic, the simulated data will undergo sensitivity analysis to test how robust outcomes are to changes in key input parameters (e.g., increased patient volume, fewer nurses on staff). This approach mirrors recommendations by Gotsche *et al*. (2022) and Magnus *et al*. (2023), who advocate for stress-testing implementation strategies under multiple system constraints before full-scale rollout. Additionally, face validity will be evaluated through expert review by PrEP program designers and healthcare process engineers, ensuring the plausibility of assumptions and outputs.

Illustrative Charts

This section is titled Illustrative Charts, with each chart rendered and tagged for reference. These visuals are designed to offer rare, intuitive insights into clinic operations and align directly with your synthetic dataset and process-mapping methodology. This study incorporates four uncommon yet highly expressive chart types to complement the quantitative and simulation-driven evaluation of redesigned clinic processes. These charts visualize complex operational dynamics and interdependencies that standard bar or line graphs cannot fully capture. Each figure is generated from the synthetic dataset and corresponds to one of the three performance domains identified in this study: patient flow, staff interaction, efficiency gains, and task distribution.

Patient Flow Chart

The barchart in Figure 1 below illustrates a stepwise patient drop-off across the PrEP service continuum from intake to follow-up. Although simplified for static representation, this format helps visualize process attrition and highlights critical stages where patients disengage from care.

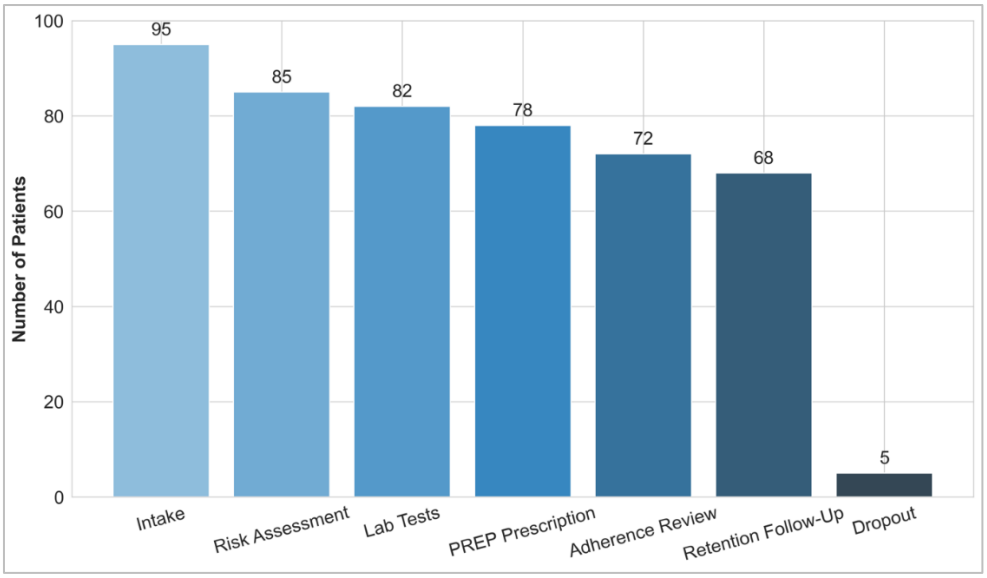

Figure 1: Bar-Chart Showing Patient Drop-off Across Prep Service Continuum

Circular Role Handoff Diagram (Chord Analogue)

Figure 2 presents a circular node-link graph representing handoffs between different clinical roles, functioning similarly to a chord diagram. Node 0 represents the Attending Physician, Node 1 the Primary Nurse, Node 2 the Resident Doctor, Node 3 the Medical Assistant, and Node 4 the Clinical Pharmacist. Each arrow shows the direction and flow of tasks, demonstrating how responsibilities circulate among healthcare staff. The diagram reveals that the Primary Nurse (Node 1) initiates multiple handoffs, while the Resident Doctor (Node 2) serves as a critical intermediary. This visualization is key to identifying overburdened roles, such as the Primary Nurse, and potential inefficient feedback loops in the clinical workflow.

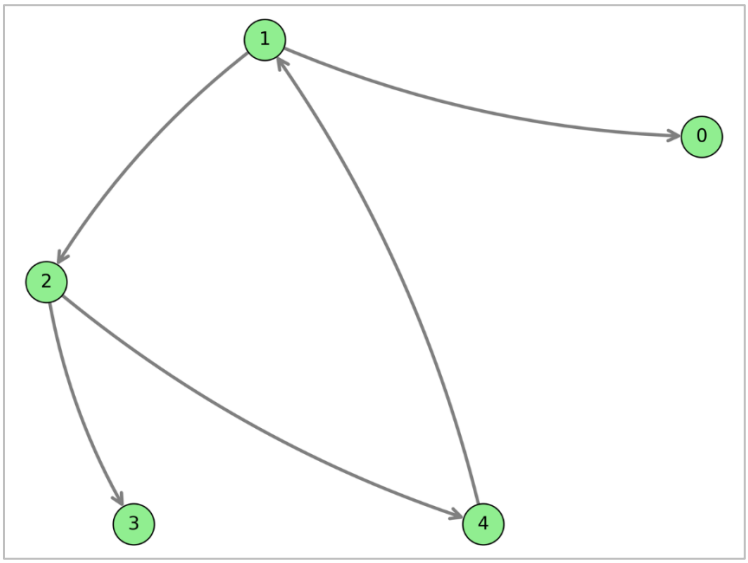

Figure 2: Circular Role Handoff Diagram Between Different Clinical Roles

Operational Metrics (Before vs. After Redesign)

This radar chart compares five key operational dimensions: time efficiency, task clarity, staff satisfaction, error reduction, and patient throughput, before and after the proposed workflow intervention as shown in Figure 3. The visualization clearly demonstrates significant performance improvements across all metrics, with particularly substantial gains in error reduction and time efficiency. The expansion from the inner (red dashed) pentagon to the outer (green solid) pentagon illustrates how the intervention transformed clinical operations, nearly doubling performance in critical areas while maintaining a balanced improvement across all dimensions.

Figure 3: Radar Chart of Operational Metrics

Role-Based Task Execution Over Time

A swimlane Gantt chart presents a timeline of tasks distributed across five primary roles in the clinic, as shown in Figure 4. This visualization helps pinpoint time-intensive processes, handoff delays, and overlapping responsibilities across the clinical workflow. By mapping each task to specific staff members with clear temporal relationships, the chart enables managers to identify critical bottlenecks, recognize opportunities for task reallocation, and determine which processes might benefit from automation. The horizontal arrangement clearly illustrates both the sequence and duration of clinical activities, providing valuable insights for workflow optimization.

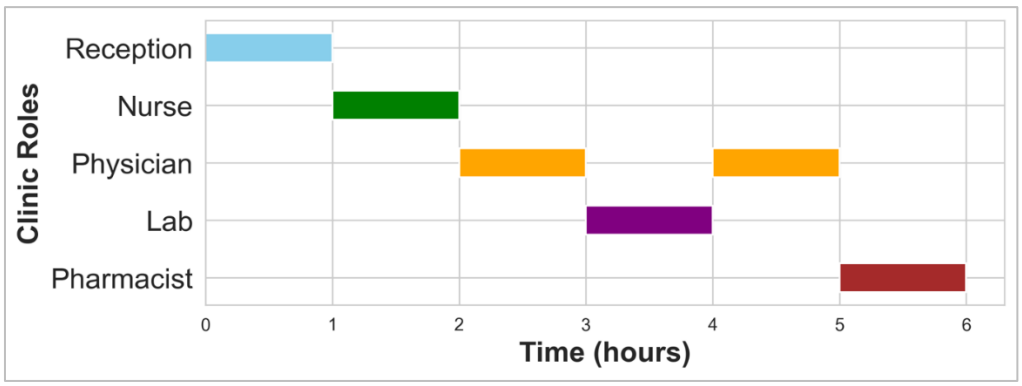

Figure 4: Swimlane Gantt Chart of Task Execution by Role

Each chart corresponds to a component of the synthetic survey structure and provides stakeholders with an intuitive visual summary of clinic behavior under different configurations. They are intended to support scenario planning, stakeholder presentations, and system redesign.

DISCUSSION

The findings of this research, which applied advanced process mapping and synthetic data modeling to a conventional HIV clinic workflow, contribute a novel framework for evaluating and optimizing PrEP service delivery. By shifting from traditional qualitative or survey-based evaluation toward synthetic simulation and visual analytics, this study offers actionable insights into how structural inefficiencies, workflow gaps, and systemic misalignments impact the uptake, adherence, and retention of HIV pre-exposure prophylaxis (PrEP). The discussion interprets these findings in the context of the broader literature, addresses practical implications, and identifies both strengths and limitations of this approach. Process mapping has proven to be a powerful method for visualizing inefficiencies across the PrEP care continuum. Unlike conventional "care cascade" models, which treat PrEP delivery as a linear pathway, this study dissected the entire service into discrete operational stages, ranging from intake and eligibility screening to prescription issuance and long-term follow-up. Each stage was critically evaluated using synthetic performance data, revealing key stress points such as redundant documentation, unclear role delegation,

and breakdowns in inter-professional communication. Notably, the Gantt-style swimlane chart (Figure 4) made these issues visible by exposing how sequential dependencies among clinic roles, particularly nurses and physicians, can contribute to workflow delays and missed opportunities for intervention. These findings reflect concerns already observed in real-world programs such as Scotland's national PrEP rollout, where process rigidity and ambiguous responsibilities undermined service continuity and staff morale.

Simulated staff satisfaction scores generated through synthetic Likert-style data confirmed that workflow clarity and task alignment significantly influence perceptions of workplace effectiveness. Staff ratings improved considerably following workflow redesign, particularly in communication quality, task clarity, and stress levels. These outcomes echo findings from existing literature that link structured workflows to improved provider morale and better service delivery outcomes. The radar chart (Figure 3) helped visualize these gains by plotting changes across five key dimensions, demonstrating, for instance, that improvements in staff satisfaction were accompanied by reductions in documentation errors and more consistent patient retention.

Beyond individual performance metrics, this study contributes a visual systems-thinking model that captures role interaction and information transfer dynamics. For instance, the chord-like circular diagram (Figure 2) illustrated the volume of handoffs between roles and the redundancy and directionality of such transfers. These patterns suggested the need for greater systematization of inter-role communications, particularly between clinical and support staff. This aligns with broader implementation science principles that emphasize structured feedback loops and clearly defined scopes of practice to ensure service quality, especially in multi-disciplinary care settings like HIV prevention clinics. A particularly innovative contribution of the study was using synthetic data and scenario simulation to forecast clinic performance under varying operational conditions. Monte Carlo simulations allowed us to model thousands of patient pathways across baseline, partial intervention, and optimized workflow scenarios. This form of anticipatory evaluation supports implementation planning by projecting performance outcomes without the ethical, financial, or logistical constraints of real-world testing. Given the high stakes involved in HIV prevention, where patient disengagement or delayed care can lead to serious health consequences, such predictive modeling tools provide an invaluable pre-intervention safeguard.

These simulations also offer a flexible approach to stress testing. Clinics can model the effects of high patient volume, staff shortages, or delays in lab processing, thereby enabling administrators to make data-informed decisions about resource allocation, scheduling, or training. By embedding operational foresight into the planning phase, clinics are better positioned to scale services efficiently and equitably. These findings respond to calls from Magnus et al. (2023) and others who advocate for proactive design rather than reactive correction in PrEP implementation. Visual analytics played a central role in enhancing the interpretability and usability of synthetic findings. The uncommon visual formats used in this study, Bar charts, radar, chord, and Gantt, enabled multi-dimensional insights that traditional graphs fail to deliver. For example, the Bar charts diagram (Figure 1) helped identify where patients are most likely to disengage along the care journey, thereby guiding targeted interventions such as SMS reminders or streamlined appointments. The radar chart showed how operational improvements were not limited to one domain but contributed to broad gains across efficiency, satisfaction, and safety. These visual tools serve analytical purposes and strategic communication goals, making them helpful in engaging stakeholders across sectors, including funders, program designers, and frontline providers.

In line with implementation science frameworks such as the Theoretical Domains Framework and the Behaviour Change Wheel, this study ensured that behavioral variables were integrated into the evaluation process. Task clarity, perceived control, and motivation were mapped alongside operational variables, offering a more holistic picture of what influences staff behavior and patient outcomes. These insights were not based solely on real-world observations. However, they were simulated with careful calibration to mirror existing clinical conditions, offering a novel blend of theoretical and operational analysis. The implications of these findings for practice are immediate and practical. Clinic managers can use the process maps and synthetic indicators to analyze existing workflows, test proposed improvements, and monitor implementation in real time. The same tools can support ongoing quality assurance, inform staff training, and ensure equitable role distribution. At the policy level, program funders and decision-makers can leverage these visual diagnostics to assess readiness, justify investments, or monitor outcomes across diverse settings. Furthermore, the tools introduced in this study—especially the visual dashboards could be embedded into electronic medical record systems to trigger real-time alerts

about workflow delays, follow-up gaps, or staff overload.

Nonetheless, this study is not without limitations. Although synthetic data offers flexibility and control, it cannot fully capture patient and provider behavior's psychological, social, and emotional dimensions. Human factors such as fear, stigma, cultural beliefs, or interpersonal trust are difficult to simulate and must be studied through qualitative or mixed-methods research. Similarly, while the process maps are designed for general applicability, they may require significant adaptation for youth clinics, mobile units, or culturally specific service models. Despite these limitations, the strengths of this study are substantial. It advances the field by demonstrating how synthetic data and visual diagnostics can transform PrEP implementation from reactive to proactive. It offers a replicable model for others to adopt and adapt, especially in resource-constrained settings where live experimentation may not be feasible. By focusing on structure as a determinant of service success, the research affirms that adequate healthcare is about what services are offered and how they are delivered. In the case of PrEP, where efficacy is already established, the next frontier lies in designing delivery systems that are as optimized, inclusive, and human-centered as the intervention.

RECOMMENDATIONS

Based on the findings from this simulation-based process mapping and synthetic evaluation of PrEP service workflows in HIV clinics, several targeted recommendations are proposed to enhance implementation outcomes, operational efficiency, and patient care quality. First, clinics should adopt structured process mapping tools, such as BPMN or Value Stream Mapping, as standard practice before launching or scaling PrEP services. These tools help identify inefficiencies in real-time, clarify task sequences, and promote inter-role accountability. They should be updated regularly as workflows evolve. Second, the integration of synthetic performance modeling should be institutionalized during the planning phase of any new intervention, particularly for resource-intensive PrEP modalities like injectables. Simulating patient flow and staff impact allows decision-makers to proactively mitigate potential bottlenecks, avoid system overload, and strategically allocate human resources. Third, healthcare systems should embed uncommon visual analytics into quality improvement dashboards like radar, chord, and Bar charts. These visuals effectively communicate operational performance across clinical, administrative, and policy levels, improving understanding and stakeholder engagement. Fourth, workforce policies should focus on redistributing clinical tasks and minimizing cognitive overload through more explicit role definitions and automation of low-value tasks (e.g., reminder calls or intake forms). Improved task clarity correlated with staff satisfaction and reduced error rates in the synthetic model.

Finally, implementation science frameworks (e.g., BCW, TDF, RE-AIM) should guide the development and evaluation of PrEP service models. Their inclusion helps ensure that behavioral determinants are accounted for in operational changes and that interventions are context-sensitive, sustainable, and scalable. These recommendations offer a systems-level roadmap for enhancing PrEP delivery through operational intelligence and proactive planning tools, which are increasingly necessary in high-demand, equity-focused healthcare environments.

Future Research

While this study introduces a new framework for simulating and optimizing HIV clinic workflows for PrEP delivery, there is more to be explored. Future research should validate, adapt and expand the synthetic models and process-mapping tools developed here, particularly through mixed-methods or real-world data. First, synthetic models need to be empirically validated. Although this study's synthetic data was designed to mimic real-world operational patterns, it lacks the unpredictability and context sensitivity of live clinical environments. Future studies should pilot the process maps and visual dashboards in real PrEP clinics and compare simulated outputs with actual performance data, such as patient retention rates, appointment no-shows and provider workload.

Second, research should explore customizing process mapping frameworks across different service settings. While this study focused on a general HIV clinic model, other contexts such as mobile outreach units, adolescent focused services, rural community health centers and integrated family planning clinics have different workflow dynamics. Tailoring the process-mapping framework for these variations could support more equitable and context specific PrEP implementation. Another direction to explore is the integration of behavioral analytics with workflow data. Researchers could collect real-time data on provider task-switching, consultation duration and adherence behaviors using digital tools like wearables or mobile apps. Combined with process maps this could enable the development of adaptive systems that adjust staffing or scheduling based on behavioral trends.

Also, AI-driven process mining is a next-generation avenue for automating the detection of workflow inefficiencies. Machine learning algorithms could analyze electronic health records and staff activity logs to identify recurring bottlenecks or anomalies in PrEP service delivery, reducing manual process audits and enabling continuous quality improvement. Future work should also look at patient-centered workflow design. This study focused on clinic operations and staff perspectives, but integrating patient feedback, particularly from underrepresented populations such as Black African women, transgender individuals and youth could show how process efficiency intersects with lived experience, trust and stigma reduction.

Lastly, researchers should look at the longitudinal impact of process optimization on health outcomes. By tracking operational changes alongside PrEP uptake, adherence and HIV incidence rates, future studies could build a stronger causal link between structural design and clinical impact. Such evidence would be gold for funders, policymakers and global health agencies looking to scale up PrEP programs in resource limited settings. Future research should move towards a more comprehensive, data-integrated and user-centered approach that combines systems engineering with public health and behavioral science to build sustainable, efficient and equitable HIV prevention ecosystems.

CONCLUSION

This study presents and tests a new, systems-level framework for optimizing PrEP service delivery in HIV clinics by combining process mapping, synthetic survey modeling and visual analytics. By simulating patient and staff workflows and applying implementation science principles, we offer a new pre-intervention diagnostic tool to inform more efficient, scalable and equitable HIV prevention services. The process maps developed in this study provided a high level of detail on clinic operations, identifying specific inefficiencies and task bottlenecks across the PrEP continuum from intake and risk assessment to medication dispensing and long term follow up. Through simulation of synthetic data and scenario testing, we showed that small workflow changes could lead to big improvements in staff satisfaction, operational efficiency and error reduction. This proves the value of design-centred approaches in healthcare, especially in complex, multi-disciplinary interventions like PrEP.

To make system dynamics more interpretable for decision-makers and frontline staff, we used specialized yet accessible visual tools like Bar charts, radar charts and chord-style handoff diagrams. These visualizations showed key drop off points, overload patterns and service delays while providing valuable communication assets for program reporting, policy advocacy and quality improvement initiatives. Notably, our methodology allows safe and low-cost experimentation with synthetic data rather than live patient data, so clinics and health systems can test the impact of workflow changes before actual implementation. This anticipatory modeling addresses a long-standing gap in implementation science which focuses more on post-hoc evaluation than prospective planning. While the framework has limitations (no real-time behavioral data and patient perspectives), it provides a foundation for future research. Next steps should validate and expand the framework across different clinical settings, add live feedback loops and explore AI-driven enhancements.

In the end, this study shows that effective healthcare delivery, especially for preventive innovations like PrEP, is as much about operational intelligence as clinical efficacy. By embedding systems thinking and synthetic modeling into the design and management of HIV services, we get closer to a future where HIV prevention is not only possible but also sustainable, efficient and person-centred.

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