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IMPLEMENTATION SCIENCE (E GENG, SECTION EDITOR)

Making Smarter Decisions Faster: Systems Engineering to Improve the Global Public Health Response to HIV

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Abstract

Purpose of Review This review offers an operational definition of systems engineering (SE) as applied to public health, reviews applications of SE in the field of HIV, and identifies opportunities and challenges of broader application of SE in global health.

Recent Findings SE involves the deliberate sequencing of three steps: diagnosing a problem, evaluating options using modeling or optimization, and providing actionable recommendations. SE includes diverse tools (from process improvement to mathematical modeling) applied to decisions at various levels (from local staffing decisions to planning national-level roll-out of new interventions). Contextual factors are crucial to effective decision-making, but there are gaps in understanding global decision-making processes. Integrating SE into pre-service training and translating SE tools to be more accessible could increase utilization of SE approaches in global health.

Summary SE is a promising, but under-recognized approach to improve public health response to HIV globally.

Keywords Implementation science · Systems engineering · HIV · Public health approach

Introduction

The last two decades brought significant scientific advances in biomedical interventions for HIV prevention, diagnosis, and treatment. Point-of-care HIV tests can provide accurate results within 15 min; first-line antiretroviral therapy (ART) is available in single pill formulations, and multiple viral load monitoring platforms have been developed. These interventions are cost-effective and affordable. Although ongoing technological advances will continue to increase effectiveness, reduce costs, and reduce barriers to testing and treatment, existing tools are sufficiently strong to support a public health approach to HIV diagnosis and management.

There is a global commitment to end AIDS; to this end, the UNAIDS 90-90-90 goals were developed. There has been significant progress towards these goals. An estimated 75% of the 36.9 million individuals living with HIV worldwide have been diagnosed, 79% of those are on treatment, and 81% of those are virologically suppressed [1]. However, there is significant geographic heterogeneity in progress. To close existing gaps and achieve these goals, it is necessary to not only address individual-level factors like drug resistance, adherence, and care-seeking barriers, but also optimize health system performance. The enormous technologic innovation, resource commitment, and rapid scale up of programs in well-resourced and resource-limited settings make HIV unique among infectious diseases. HIV funding has plateaued;

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efficiency and quality must improve to maximize the potential of technological advancements, align available resources with needs, and reach global goals.

A successful public health approach to HIV will optimally use limited resources for maximal population benefit, and recognize that delaying time-sensitive programmatic decisions costs financial resources and lives. However, decision-making within health systems is a complex process influenced by individual, organizational, and external factors [2–4]. Systems engineering (SE) provides a way to inform programmatic decision-making within complex systems by using diverse modeling tools to decrease uncertainty, and make smarter decisions faster. Systems engineering is distinctive in its combination of data-driven diagnostics and modeling to yield recommendations.

The purpose of this review is to (1) introduce an operational definition of SE applied to global health, (2) review recent applications of SE to HIV globally, and (3) identify challenges and opportunities for increasing the use of SE in low- and middle-income countries (LMIC).

Systems Engineering History

SE arose in the early 1900s with the emergence of complex industrial systems, first in telecommunications [5], and later in military, aeronautic, and other industrial applications [5–8]. Perhaps the most well-known application of SE is the Toyota Production System (Lean model) for process improvement and reduction of error rates within manufacturing systems. Current business applications often use intricate approaches and process improvement strategies like Six Sigma to identify and reduce sources of waste in complex systems. Theoretical models have emerged to describe management for system improvement (Deming's Theory of Profound Knowledge), to understand organizations and systems deeply in order to transform them [9], and to explain how and why innovations spread (Rogers' Diffusion of Innovation theory [10]). Diffusion of Innovation theory has been incorporated into modern approaches to dissemination and diffusion in the social sciences [11, 12]. SE has recently been applied to healthcare in industrialized countries, often incorporating quality improvement (QI) [13, 14•, 15–17], with fewer examples in LMICs. Recent analyses have suggested that global health projects budget an average of $< 3\%$ for operational research or SE, and often spend considerably less [18].

A 1956 survey among SE practitioners characterized the core principle of SE as the deliberate sequencing of five steps: planning, analysis, optimization, integration, and evaluation [5]. In this definition, developed by engineers operating in predominately closed manufacturing and operations systems, planning meant user needs assessment; analysis referred to a range of qualitative or quantitative analytic techniques; optimization entailed identifying some criterion or criteria to optimize through theory and experience; the step of integration entailed either implementing a change or advising others in implementation; finally, evaluation referred to observing performance of the built or modified system. Varying definitions have been proposed, as new analytic tools emerge and are incorporated into SE, often fueled by increasing computing power. The core principle of these definitions has consistently been the use of structured methods to analyze a complex system; model and optimize potential actions/decision options; choose an action or decision; make a change (i.e., integration); and evaluate results [5–7, 19]. SE is further characterized by applying this process across the various interconnected elements, components, actors, levels, and spaces within a system.

More recent articles on SE and its application beyond industry have focused on developing and adapting modeling tools for application to different sectors, such as health [14•], but have not generally proposed new or revised definitions of what SE fundamentally is. SE is an interdisciplinary field that overlaps with operations research; implementation science; quality improvement, statistics, and reliability; decision and risk analysis; human factors; operations management; and organizational theories. Indeed, definitions of these fields often sound similar to SE, such as a definition of operations research proposed by Pitt and Monk as "the discipline of using models, either quantitative or qualitative, to aid decision-making in complex problems" [20••, 21].

Systems Engineering Definition

We propose the following operational definition of SE for global health: an approach that uses data to improve decision-making within a given global health system by (1) diagnosing problems and identifying needs, (2) evaluating decision options to address a selected problem or need through modeling or optimization, and (3) translating optimized decision options into practical recommendations or actions (Fig. 1). Most SE definitions require implementing and evaluating an action, and SE applications to global health should include these steps whenever possible. However, we take a more liberal definition by considering initiatives that stop at practical, actionable recommendations to be SE. In health systems in which decision-making is complex and requires consensus—and decisions are often not made by those who would perform SE—actionable recommendations may be the most realistic SE output.

It is our position that strategies, interventions, and studies that lack one of these three steps may be useful for practice or academically important, but would not qualify as SE. We argue that initiatives that include one or two steps could be improved by including all three. Diagnosing needs through analysis of systems ensures that decisions target high-priority system leverage points. Skipping this step risks focusing efforts on lower-priority issues, or those with limited potential impact. Evaluating potential decisions ensures that subsequent recommendations and actions are efficient, effective,

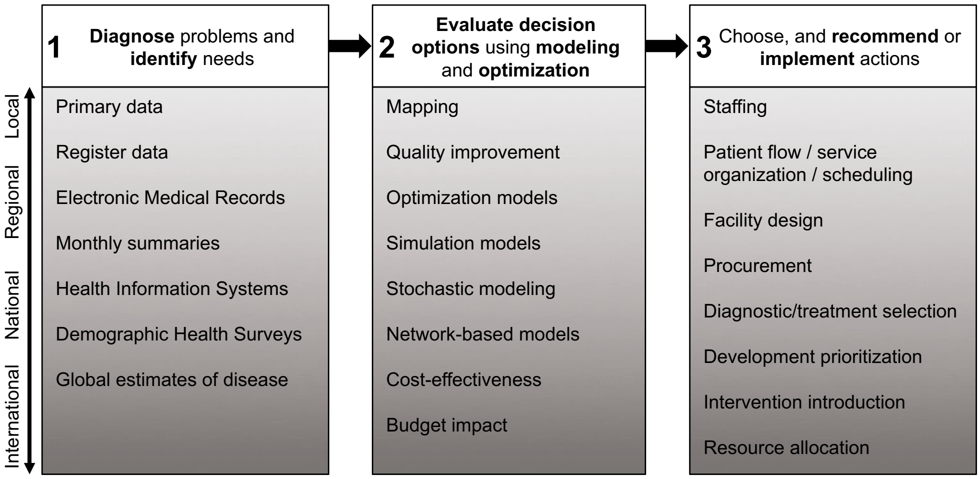

Fig. 1 Operational definition of systems engineering approach and tools used for decision-making at various levels in global health systems. Across the top, the 3 steps in our operational definition of SE are shown. From left to right, the first column notes data sources to support needs assessment; the second column notes the SE tools and methods for evaluating decision options; and the third column notes the types of decisions that SE can be used to evaluate

and best-matched to the health system. Proceeding to actions or recommendations without evaluating potential decisions risks implementing a well-intentioned action that is not suited to a given health system, or does not optimally use limited energy and resources. The act of translating optimized solutions to actionable recommendations links the analytical steps in SE to impact, without which the analysis remains a purely academic or theoretical exercise.

Steps 1 and 2 rely on collecting and analyzing multiform data, and generally use established SE methods and tools. Step 3 involves translating step 2 model outputs into recommendations and actions that are realistic and context-appropriate for a given health system, for example, considering financial and human resource limitations. Established methods for collaborative decision-making, diffusion, and dissemination exist and can support each step (particularly step 3) by systematically considering context and participation of health system stakeholders. These methods include human-centered design [22], stakeholder analysis [23], Delphi methods [24], qualitative methods [25, 26], and related contextual approaches. Figure 1 lists data sources that can support diagnosing needs (step 1), common methods and tools for evaluating potential decisions (step 2), and types of decisions that can be recommended or implemented (step 3), ordered by the level of health system for which they tend to be most relevant. Of course, these decisions may be made at different levels, and government structure and decentralization impacts at what level different types of decisions are made. Table 1 provides a glossary of specific SE tools and references of their application.

Health Systems and Decision-Making in the Global HIV Response

SE focuses on influencing and improving decision-making within *systems*. Properly applying SE to global health requires some discussion of the characteristics and complexity of global health systems, and the types of decisions that SE can improve. The World Health Organization (WHO) identifies six health systems building blocks: service delivery, health workforce, health information systems, medicines and technologies, financing, and leadership/governance [65•, 66]. These building blocks are complex, dynamic, and vary by setting. Complex systems include layered interdependencies—modifying one component changes others, and the obvious choice to target may not be the correct one because it induces blockages elsewhere in the system. SE is well-suited to these complex health systems, as it reflects and tames this complexity. SE may be applied at a local, regional, national, or international level; each level comprises different institutions, roles, and eligible types of decisions, thus the most appropriate tools also differ (Fig. 1).

Local-level (facility or clinic) decisions benefit most from tools that can represent the detailed patterns and constraints at that facility, including flow mapping (drawing physical maps of patient paths taken in a clinic), QI, cascade analysis (quantifying the relative improvement possible at each step of a cascade), discrete event simulation, and queuing methods (Table 1). Regional and national systems with multiple institutions may necessitate complex and flexible tools, including simulation, optimization, cost-effectiveness, and budget impact models. These may inform decisions about national health plan coverage, guideline development, or minimum staffing ratios. Finally, international decisions may require comparing large numbers of scenarios for similar outcomes over long time periods, requiring large mathematical models to inform recommendations regarding global prevention, testing, and treatment strategies (Table 1). Systems often interplay across these levels, so decisions may also cross levels.

Case Studies

The following case studies illustrate the value a diverse set of SE methods applied various levels has had for the HIV public health response (though not every case study fully meets our

Table 1 Overview of SE tools, tool definitions, and example health system improvement questions

SE tool/method	Tool definition	Steps	Example question	References
Flow mapping, value stream mapping, process mapping [a]	Frontline system operators create a visual map of the sequential steps taken by patients, samples, commodities, etc. within their system in order to identify physical or temporal system wastes and bottlenecks, and visualize reorganization of system	1, 2	How can services be reorganized at a facility to make it easier for patients to navigate?	[27, 28]
Quality improvement (QI)[a]	Approach to improving reliability and reducing failures within a system or process	1, 2, 3		[29]
- Failure Modes and Effects Analysis (FMEA)	Visual tool to identify all possible ways in which a failure might occur in a system, identify the source of failure, and plan system re-organization to avert failure	1, 2	What are the reasons that it is difficult to reach universal coverage in a particular clinic?	[30]
- Root cause analysis	Visual causal diagram to show deeper root cause of a specific problem	1		[31•, 32]
- Fishbone (Ishikawa) diagram	Visual causal diagrams to show cause of particular problem	1		[33, 34]
- Lot Quality Assurance Sampling (LQAS)	Random sampling methodology for identifying defects and promoting quality control	1	How frequently is HIV testing missed in routine clinic care?	[35]
- Time and motion	Measuring time spent by individual clients/samples at each step in a set process to identify bottlenecks	1	When in a patient's HIV care visit are they waiting the longest?	[36]
- Six Sigma	Set of statistical tools for process improvement, focused on increasing reliability and reducing variability and failures in a system	2	What small changes can help HIV testing reach universal coverage in a clinic?	[37]
- Lean approach/Toyota Production System	Approach to reducing waste within a system through process improvement	1, 2, 3		[38]
- Plan-Do-Study-Act (PDSA)	Sequential, iterative cycles testing small changes to optimize improvement of a system and its processes	2		[31•, 33, 34, 39–41]
- Statistical process control (run charts, control charts)	Visual tool, based in statistical methods, to track system performance over time and identify system failures	1, 2	Were changes observed when teams tried their ideas due to chance or reflective of real effects?	[42]
Optimization models [a]	Mathematical approach to maximize or minimize an objective function under constraints. The solution is the decision option that produces the optimal objective value; analytical solutions exist or can be approximated numerically; often utilized for resource allocation	2	What is the appropriate resource allocation between expanded HIV prevention and treatment services in interacting populations?	[43, 44]
Simulation models [a]	Mathematical approach to select best decision option from a set, based on criteria, using computer models to imitate the real system and obtain observations of its performance; typically analytical solutions do not exist	2		
- Cascade analysis	Mathematical approach to identify step within series of sequential steps with greatest potential for optimization; used to prioritize gaps and opportunities for improvement	1, 2	Which step in the HIV cascade, a series of sequential care steps, requires the most improvement?	[45–47]
- Discrete event simulation (DES)	Mathematical approach to simulate a sequence of events in discrete time; often used to study hospital operations and patient flow	2	Which changes best alleviate bottlenecks in clinic flow?	[48]
- Queueing model	Mathematical models to study waiting time; often used to simulate various waiting lines to estimate expected time	2	Can appointment times reduce patient waiting times in a HIV care clinic?	[49, 50]

Table 1 (continued)

SE tool/method	Tool definition	Steps	Example question	References
	in waiting and service; often used to improve hospital operations, patient flow, scheduling, and facility design			
- System dynamics models	Mathematical models using simulation to reflect dynamic behavior of complex systems with accumulation and feedback; often used to characterize interaction of various components within a system and project the long-term outcomes of policy change	2	What is the long-term health impact of an HIV treatment policy change?	[51]
Stochastic modeling (including Markov Decision Process) [a]	Mathematical models that examine inherent randomness in events and produce optimal actions under uncertainty; often used to model personalized healthcare intervention design, such as screening, monitoring, and treatment guidelines	2	Which specific treatment drugs should an individual patient be prescribed?	[52, 53]
Network-based models [a]	Mathematical approach to simulate contact, and the impact of contact, between individuals within a system or network; often used to simulate interventions delivered to an individual with an indirect impact on other connected individuals (e.g., sexual networks, drug use networks, social networks)	2	How do changes to concurrent sexual partnership affect the HIV incidence in a region?	[54–56]
Cost-effectiveness analysis [a]	Decision-analytic models that compare the additional costs and additional benefit of an intervention or change to the next best alternative	2	Which national HIV testing strategies are most cost-effective?	[57, 58••, 59–63]
Budget impact analysis [a]	Economic assessment that calculates total cost of delivering a chosen intervention to a given population, and determines the affordability of a chosen path	2	Is a particular national HIV testing strategy affordable within a set budget?	[64••]

References for each tool represent both applications of that tool as well as further reading on the methodology. Tools are organized from more local application at the top to broader application at the bottom

[a] SE tools highlighted in gray represent major categories of tools

definition of SE, addressed in Table 2). Table 1 provides additional examples of SE tools applicable to the global HIV response.

Systems Analysis and Improvement Approach

This case study shows a combination of the three SE steps, using a series of SE tools [27••]. The Systems Analysis and Improvement Approach (SAIA) intervention was originally applied to prevention of mother-to-child-transmission of HIV (PMTCT) and early infant diagnosis (EID) programs for HIV-positive pregnant women, and increased ART coverage and EID completion in a 36-facility cluster randomized trial in Kenya, Mozambique, and Cote-D'Ivoire [28]. SAIA identifies facility-level gaps in PMTCT performance indicators (HIV testing in antenatal care, ART initiation, infant prophylaxis, and infant HIV testing) using a cascade analysis tool (CAT) populated by routine registry data. The CAT helps health care workers (HCW) by using an optimization function to estimate the potential PMTCT cascade gain at their facility if each cascade step were fully improved. Frontline HCW then engage in flow mapping, to map their facility's patient care pathway and the complex inter-linked steps—including decision points—that exist in the current system. This helps identify potential modifications to address their facility's PMTCT cascade gaps. The SAIA intervention then evaluates system modifications using QI; unsuccessful modifications are adapted or abandoned and successful ones are adopted. System modifications include reorganizing services, educating patients, improving HCW communication, improving data quality, and strengthening existing norms. This SE application clearly includes the three key steps for SE: diagnosis and optimization using the CAT, flow mapping, and QI; and recommending and implementing system changes, taking into account practical considerations.

SAIA is currently being adapted to several other HIV and non-HIV related cascades, including pediatric and adolescent HIV, hypertension among people living with HIV, HIV testing in family planning clinics, cervical cancer screening in family planning, and mental health. While these SAIA adaptations are being trialed at the local level, delivery of the original SAIA PMTCT intervention by district health departments is currently being evaluated across an entire province in Mozambique.

Table 2 Core systems engineering components for five HIV case studies

Case study	Step 1. Diagnose problems and identify needs	Step 2. Evaluate decision options using modeling and optimization	Step 3. Choose, and recommend or implement actions
1. Systems Analysis and Improvement Approach (SAIA)	Cascade analysis to identify facility-level gaps in PMTCT performance indicators; flow mapping to identify inefficiencies and bottlenecks in patient flow at a facility-level	Model the effect of optimizing each PMTCT step on performance indicators, evaluate workflow changes using quality improvement	Adopt, adapt, or abandon workflow changes based on results of quality improvement
2. Waiting time and clinic flow	Time and motion studies to characterize patient wait and consult times, and identify potential sources of excessive wait times	Simulating impact of workflow modifications on wait times using discrete event simulation models	Assignment of client appointment times; staggering staff break times; scheduling staffing levels to match patient volumes
3. Assisted partner services	Efficacious intervention identified in Kenyan trial but testing data noted it was not being implemented	Cost-effectiveness and budget impact analysis	Staffing decisions for scale up made, considering task shifting
4. Oral PrEP roll-out	Kenya Ministry of Health identified heterogeneous HIV risk across counties necessitated county-specific plans	Estimation and Projection Package and SPECTRUM model to evaluate five pre-exposure prophylaxis roll-out scenarios	Roll-out of pre-exposure prophylaxis across Kenya's 47 counties with varying intensity informed by modeled HIV incidence reduction and financial costs
5. Point-of-care HIV diagnostics for early infant diagnosis (EID)	Mozambique Ministry of Health identified slow turnaround of infant HIV test results reduced retention of patients	Mathematical micro-simulation model to evaluate added benefit of an additional infant HIV testing time point versus optimizing system for existing time points	Optimizing existing infant HIV testing time points offered more immediate opportunity for improvement

Waiting Time and Clinic Flow

Patient wait times impact patient satisfaction and retention. Using time and motion studies, wait and consult times have been characterized in Kenya [36], South Africa [67], and other settings, representing step 1 of the SE process. However, without further evaluating decision options and proposing actionable recommendations, such studies would not meet our proposed definition of SE.

In contrast, a team in Kenya characterized wait times and perceived sources of excess waiting time in an HIV clinic. Their study met the operational definition of SE because they proposed actionable recommendations to address specific problems identified during their problem diagnosis and modeling, such as staggering staff break times, implementing patient appointments, and scheduling staff shifts to match projected volume [38]. A Zambian team offered further prioritization of actionable recommendations by collecting wait time data and patient flow patterns, building a discrete event simulation (DES) model, and simulating various workflow modifications, providing prioritized recommendations, ranging from adding staff to integrating only select healthcare services [48].

An Ugandan team took this approach a step further by conducting small-scale testing of strategies for improving efficiency at one clinic, observing a decrease in wait time for stable patients from 102 to 20 min [68]. Another Kenyan team conducted multiphase research to quantify wait times, identify pre-service wait time as problematic, and finally test a modified flow pattern in an individual-level randomized controlled trial. The team assigned client appointment times and demonstrated decreased waiting time (197 versus 65 min) and increased client economic productivity on clinic days [69].

These case studies demonstrate that simply using an SE tool to characterize a problem within a health system does not qualify as SE. Additionally, they demonstrate that there are a variety of SE tools that can be used to address the same problem, depending on the setting, scale, and ability of SE practitioners to enact change within a system.

Assisted Partner Services

This case study shows a national-level SE application, which quickly informed international guideline modifications. Assisted Partner Services (APS) for HIV is a form of contact tracing in which people newly diagnosed with HIV are asked to enumerate their sexual partners, who are traced and offered HIV testing. This approach is more efficient than blanket testing, and demonstrated increased testing and improved case detection in an observational [70] and randomized trial [71]. In anticipation of APS policy decisions following the efficacy randomized trial in Kenya, mathematical modeling revealed that APS was cost-effective and noted that task shifting could further improve cost-effectiveness [57]. This is a clear example of the three SE steps; data were used to identify a gap between evidence and practice, a model was used to evaluate potential policy decisions, and actionable recommendations were made. These results were considered by the WHO, and they endorsed APS in their 2016 HIV testing guidelines [72].

However, there are often gaps between WHO guidelines and national programs. A subsequent budget impact analysis considered the specific contextual factors and budget in Kenya. This analysis modeled various implementation decision options, including task shifting to community HCW and different rates of scale up, and made Kenya-specific actionable recommendations for intended recipients and staffing [64••]. This context-specific analysis using an SE approach accelerated adoption of APS in Kenya, where it has been incorporated into national guidelines and is currently being scaled nationally.

This case study demonstrates the potential of SE to expedite the translation of evidence into action. A review in 2000 found that just 14% of research results entered routine clinical practice, taking an average of 17 years [73], while APS trial results were published in 2017 and incorporated into WHO guidelines and Kenya's national policies within a year.

Oral PrEP Roll-out

This case study shows another national-level application of SE. Oral pre-exposure prophylaxis (PrEP) is an efficacious yet expensive intervention for reducing the risk of acquiring HIV that is cost-effective in certain populations. The Kenyan Ministry of Health (MOH) collaborated with a consortium of modelers and strategic analysts ("OPTIONS" consortium), and utilized an SE approach to determine which counties and risk- and demographic-based populations should be prioritized for PrEP in their national strategy, in the first public sector PrEP roll-out by an African country [74••]. HIV risk, and thus PrEP need, is heterogeneous within and between populations, and cost-effectiveness depends on gauging risk, creating a programmatic challenge. The MOH collaborative team identified a need for a county-specific plan, either a universal or population-targeted offer of PrEP.

The collaborative team evaluated five roll-out scenarios using the Estimation and Projection Package (EPP) and SPECTRUM model [75]. The team prioritized scenarios in which PrEP introduction would result in the greatest reduction in HIV incidence nationally. They then compared the financial impact (PrEP cost/person and population size) of the five scenarios to guide decision-making [76]. As a result, PrEP has been offered in 900 facilities across all 47 counties in Kenya as of 2018, with intensified efforts in selected counties [74••]. This set of decision-making tools was packaged into a user-friendly website with instructional modules and tools geared towards MOHs [77], and has influenced PrEP roll-out in South Africa and Zimbabwe.

Point-of-Care HIV Diagnostics for Early Infant Diagnosis

This case study illustrates the utility of different SE tools across the lifecycle of a problem in Mozambique. EID involves testing an HIV-exposed infant to determine their HIV status and initiate ART, if positive. Traditionally, EID has involved laboratory-based PCR, which has long turnaround times due to inefficient batching, transport, test performance, relaying results from the lab, and delivering results to the family.

The Mozambican National Institute of Health investigated a series of interventions to optimize timely EID using an SE approach. The team determined that turnaround delays reduced EID program retention, piloted a test result printer system to speed up results communication from lab to facility, and recommended expanding this technology [78]. However, turnaround time was still suboptimal, and the team tested introducing point-of-care PCR testing in a routine program setting to further optimize EID, focusing on operational outcomes (turnaround time) and clinical outcomes (ART initiation and retention). Dramatic results in all three outcomes, including a reduced turnaround time from 127 days to < 1 day, supported their recommendation to adopt this new technology [79].

This team and others considered optimizing EID further by introducing HIV testing at birth, instead of the typical 6 weeks later. Using a micro-simulation model (CEPAC), mathematical modelers are addressing the challenge of whether introducing HIV testing at birth or strengthening existing 6-week testing programs is better [58••]. This type of modeling is an excellent SE example; teams noted that infant HIV mortality was due to late detection and treatment, simulated and evaluated a range of possible decision options, and made context-specific recommendations. These modeling exercises are complementary to large-scale testing of decision options in a programmatic setting—they are faster, less ethically problematic, and cheaper, but are based on assumptions that may merit empirical testing to arrive at context-specific decisions.

Opportunities and Challenges for Operationalizing SE Within LMIC Health Systems

Health systems in LMICs present unique opportunities and challenges for SE application. Centralized health systems are common in many LMICs, particularly for HIV services. Staffing required to meet service demands are frequently insufficient, and donors' funding priorities influence national priorities. However, many global public health stakeholders make use of data and modeling in setting national priorities and strategic plans. For example, LMIC governments and global health organizations routinely use data to set program priorities, including census data, demographic and health surveys (DHS), disease and outbreak surveillance, and disease-specific surveys such as the AIDS Indicator Surveys (AIS) for HIV tracking.

Data are the foundation of SE and are influenced heavily by health systems structure, human resources, and donor and governmental priorities. International donor organizations have heavy, often burdensome, data reporting requirements for HIV programs that are tied to funding renewal [80]. These requirements have in some cases led to improvements in standardized routine health information system (RHIS) indicators that: are reported at regular intervals (often monthly); cover all health facilities; cover the full cascade of care necessary for optimal system performance; and enable the integration of data outside HIV programs such as budget allocation, staff effort and training, supervision activities, and supply availability [81].

These rich, hyper-local types of data are not always available, even in well-resourced settings. For example, the United States Centers for Disease Control does not have access to similar national HIV services data. However, RHIS HIV program data have challenges, including: numerator-denominator incompatibility yielding unreliable coverage estimates, data quality and validity concerns, data primarily for donor reporting yielding excessive indicators of varying value, and difficulty integrating facility-level RHIS data with community-level data [82]. When considering frontline HCWs, their massive data collection and reporting burden must be appreciated. Besides their responsibility for patient services, frontline HCWs often collect, summarize, and report registry data, often using entirely paper-based systems. PEPFAR alone has over 500 HIV program indicators [82], many of which are supposed to be collected, summarized, and reported monthly for every implementing facility. However, engaging HCW can improve data quality and utility [83].

Innovations in RHISs in LMICs will influence the expansion of SE. Many sub-Saharan African countries have electronic medical records (EMR) for HIV care, but not for upstream HIV cascade steps like testing and linkage to care. The District Health Information System (DHIS-II), used in > 60 countries provides monthly facility-level data for a wide range of diseases including HIV, but is limited as aggregate counts cannot be separated into relevant sub-strata. Electronic registers and unique identifier systems, such as biometric IDs, are being explored in settings with strong health information system infrastructure, such as Kenya [84]. However, enhanced RHIS adoption is often tied to donor funding or partner priorities. The most marginalized health facilities with poor health outcomes and low volumes may benefit less from improvements than high volume facilities with implementing partners, further limiting the ease of conducting SE at these facilities.

Given the varied data infrastructure in many LMICs, another consideration is whether operators in LMIC health systems are sufficiently trained to routinely utilize SE approaches. Many SE tools geared towards local-level decisions are already utilized by HCWs: flow mapping and QI are commonly practiced, intuitive, and do not require extensive training. Cascade analysis tools are implemented in various countries and have been recently implemented on mobile devices for PMTCT in Kenya and Mozambique [85]. These and other local-level decision-oriented methods could be integrated into pre-service training for various cadres of HCWs. More complex methods for regional to international decision-making require partnerships between context experts (HCWs, managers), and technical SE experts (industrial engineers, public health researchers). Partnerships that coordinate contributions from HCW and SE cadres need to navigate challenges related to expectations in roles and incentive structures within their organizations, but in doing so they can produce significant value [86]. However, any SE initiative must consider the many responsibilities of health sector staff it relies on for implementation, and endeavor to minimize inadvertent negative impacts of pulling health sector staff away from other activities [87].

Many traditional SE tools will require adaptation and translation to be accessible, easily operationalized, and relevant to public health. Examples of successful adaptation and translation include the Institute for Healthcare Improvement's trainings and tools to operationalize QI [39, 42]; as well as the Plan 4 PrEP tools created by OPTIONS, which massively simplify mathematical and health economics modeling to enable MOHs to make PrEP-specific decisions [77].

The ultimate goal of an SE approach is to improve decision-making. In order for SE applications to have broad impact in influencing decision-making, two perspectives on scale are useful. A "bottom-up" approach involves finding successful local-level SE procedures, whereby frontline HCW and managers are able to step back and view their work as a system of services delivery, then scaling them across health systems through coordination and hand-off to governments. A key challenge with the "bottom-up" approach is adapting the procedure so that it remains effective when scaled to many facilities, considering external validity of the procedures. A "top-down" approach involves some broader body using SE to inform national or international recommendations, then using policy, advocacy, financing, and training to advocate for adoption and promote fidelity to recommendations by local levels of government and frontline implementers. A key challenge with a "top-down" approach is adapting recommendations to be flexible to local context, both to influence adoption and fidelity and to maximize impact. This is well described in implementation science literature as distinguishing the essential core components from the adaptable periphery [3].

In addition to SE training and tool translation, realizing the full potential of SE to influence decision-making in LMIC health systems requires an understanding of how policy decisions are made and influenced by evidence and other technical inputs. Scaling up complex interventions may be most effective when evidence, knowledge, or model findings are translated into accessible and context-specific formats [88]—evidence suggests that technical reviews and evidence summaries typically do not influence policymaker decision-making [89]. There is ongoing research into strategies to increase research uptake to inform decision-making [90–92].

Strategic application of SE is a powerful tool towards achieving the UNAIDS 90-90-90 goals. The SE approach can help address the heterogeneity in performance across countries that are falling short of these goals, and within countries to address specific steps that require optimization or specific regions that require particular attention and support. There has been a recent global focus on health service quality including within the Sustainable Development Goals [93•, 94•, 95•]. While recent efforts have addressed quantity by focusing on service accessibility, future efforts should also focus on quality. The SE approach directly addresses quality—ensuring that the right services are in the right location at the right time. Ensuring that evidence-based interventions are routinely delivered in a safe and equitable way will require focusing on standalone quality metrics, and understanding and addressing the interplay between the building blocks of health systems—an SE approach will be integral in this endeavor.

Conclusion

SE is a flexible approach for making smarter decisions faster, and has an important role for delivering HIV services in LMICs. SE involves problem diagnosis, modeling and optimization, and actionable recommendations, and can be executed using diverse methods applied at different levels within complex health systems. Given the recognition of the role of quality in scaling health services in resource-limited settings, SE is an important approach to employ to systematize how HCWs, from local to national levels, review and analyze data to inform decision-making.

HIV funding is plateauing; the global health community will need to make well-informed decisions to improve efficiency of programs. SE directly addresses this need; by employing SE more broadly, we can achieve UNAIDS 90-90-90 goals in diverse settings more quickly, and improve program efficiency and coverage, promoting greater equity. As programmatic funding sources evolve to move beyond silos, SE can support integration of HIV services into primary health systems, and broader public health systems.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent All reported studies/experiments with human or animal subjects performed by the authors have been previously published and complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

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