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Abstract

Purpose – The purpose of this paper is to demonstrate how public health and systems science methods can be combined to examine the structure and behavior of Afghanistan's routine childhood immunization system to identify the pathways through which health system readiness to deliver vaccination services may extend beyond immunization outcomes.

Design/methodology/approach – Using findings from an ecological study of Afghanistan's immunization system and a literature review on immunization program delivery, the routine immunization system was mapped using causal loop diagrams. Next, a stock-and-flow diagram was developed and translated to a system dynamics (SD) model for a system-confirmatory exercise. Data are from annual health facility assessments and two cross-sectional household surveys. SD model results were compared with measured readiness and service outcomes to confirm system structure.

Findings – Readiness and demand-side components were associated with improved immunization coverage. The routine immunization system was mapped using four interlinking readiness subsystems. In the SD model, health worker capacity and demand-side factors significantly affected maternal health service coverage. System readiness components affected their future measures mostly negatively, which may indicate that the reinforcing feedback drives current system-structured behavior.

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Originality/value – The models developed herein are useful to explore the potential impact of candidate interventions on service outcomes. This paper documents the process through which public health and systems investigators can collaboratively develop models that represent the feedback-driven behavior of health systems. Such models allow for more realistically addressing health policy and systems-level research questions.

Keywords Public health, Health policy, Emerging healthcare delivery structures, Research methods, Vaccines or vaccination, Maternal and child health

Paper type Technical paper

Introduction

Evidence-based policy has repeatedly surfaced as a goal that is difficult to achieve (Machingaidze *et al.*, 2014; Newman *et al.*, 2017; Simmons, 2015). Even in resource-plentiful environments, it has been suggested that individual and organizational structural deficits limit the use of diverse forms of evidence particularly from academic research (Newman *et al.*, 2017). While health systems are known to play a critical role in achieving public health program and development goals (Evans *et al.*, 2008; Travis *et al.*, 2004), there is limited capacity to evaluate interventions designed to "strengthen" health systems (Adam *et al.*, 2011). Evaluation methods have not reflected the complex nature of health systems and have not accounted for non-linearity of effects (Adam *et al.*, 2012; Greenwood-Lee *et al.*, 2016; Shiell *et al.*, 2008).

This paper presents an example of a process involving methodologies from public health and systems sciences, combined to examine the relationship between a subsystem and its host health system. We chose to examine the routine immunization system and its relationship with non-immunization areas of service delivery in Afghanistan's health system in order to demonstrate the effect of immunization systems beyond immunization.

Background

Launched more than 40 years ago in 1974 (Lim *et al.*, 2008; Shen *et al.*, 2014; World Health Organization (WHO), 2011), the Expanded Programme on Immunisation (EPI) marks the beginning of one of the best-recognized and most successful health programs across the world (Lahariya, 2015). As a result of concerted international efforts, most low- and middle-income countries have developed national immunization programs based on the EPI scheme. Programs have since become increasingly complex with rising costs, added vaccines in the routine schedule, hard-to-reach populations, increased demands on cold-chain infrastructure and logistics, and exogenous threats like civil unrest and conflict (Shen *et al.*, 2014).

The immunization system

A system can be defined as a set of "things," interconnected in such a way that they produce their own pattern of behavior over time; the key to understanding their behavior is to examine their structure (Meadows, 2008). Health systems are defined as the combination of all people, institutions, resources, and activities whose primary purpose is to promote, restore, and maintain health (USAID, 2015; WHO, 2007). An immunization system can be defined in similar terms, with the understanding that it is created and maintained to support immunization-specific outcomes. In order to understand the effect of the routine immunization system beyond immunization, we examined the structure of the routine immunization system. Here, system structure may include infrastructure (e.g. buildings or transportation schemes), the organization of human resources, governing and regulating bodies, point-of-service-delivery norms and environment, and supplies, among other things.

Immunization and its host health system

The heart of the immunization system is routine immunization, defined as "the foundation through which countries provide access to lifesaving vaccines, aiming to control and eliminate threats of vaccine preventable diseases" (Shen *et al.*, 2014; Steinglass, 2013; WHO, 2011). Routine immunization is often portrayed as an integral part of a health system and represents a set of resources and activities that strengthen the health system. It has been described as a critical subsystem of the health system (Clements *et al.*, 2011; Wang *et al.*, 2013), as a health service delivery platform from which other services may be provided (Sodha and Dietz, 2015; Steinglass, 2013), and as being both dependent upon and strengthening of the health systems through which services are delivered (Shen *et al.*, 2014).

Routine immunization has a horizontal nature that spans several vaccine-preventable diseases and varying target populations. A horizontal approach (also known as integrated programs) is an inclusive service delivery strategy that spans multiple focuses on a wide health front through intentional long-term and permanent institution and systems building. Routine immunization also has vertical program characteristics that include vaccination campaign activities, content- and intervention-specificity, disease elimination targets, and specific target populations and diseases. A vertical approach is a service delivery strategy that has separate management, logistics, and reporting systems organized for its specific focus. Vertical characteristics are usually intended to circumvent the limitations of weakly structured systems.

Evidence suggests immunization-specific logistics and cold-chain subsystems can strengthen the movement of resources around the health system (Lahariya, 2015; Shen *et al.*, 2014). Trained human resources may bolster the healthcare workforce, and the sheer number of required encounters with the health system throughout the routine immunization schedule represents opportunities to interact with parents, educate them on vaccines, and build rapport (Cappelen *et al.*, 2010; Shen *et al.*, 2014; Sodha and Dietz, 2015). Community engagement for immunization could improve community ownership of health programs, build members' skills in planning, implementing, monitoring, and advocating, and foster environments for equity- and trust-building that permeate into generalized trust in other public services (Cappelen *et al.*, 2010; Gilson *et al.*, 2005; Ozawa *et al.*, 2016; Ozawa and Stack, 2013; Shen *et al.*, 2014; Varghese *et al.*, 2014).

System readiness: defining immunization service readiness

Readiness of a health system to deliver health services and products (capacity for effective service delivery, Ozawa *et al.*, 2016) is a primary focus of program development. Readiness for the immunization system consists of each of the components necessary to ensure that vaccination can be sufficiently provided. These components could be parsed into domains of health system performance such as those in a balanced score card (Edward *et al.*, 2011; Peters *et al.*, 2007), the six-block health systems framework (World Health Organization, 2007), or the immunization system framework for addressing immunization coverage (John Snow International, 2011).

Pathways to immunization and non-immunization outcomes

In general, service delivery capacity, consistency, and reach are important to address under-vaccination issues whereas caregiver awareness, attitudes, and beliefs as well as caregiver and household factors including health-seeking behavior are mostly linked to issues of being unvaccinated (Bosch-Capblanch *et al.*, 2012; Cappelen *et al.*, 2010; Favin *et al.*, 2012; Rainey *et al.*, 2011; Shea *et al.*, 2009). When considering pathways that extend beyond immunization, maternal health service systems may act synchronously with the immunization system. Whether the linked behavior produces tradeoffs (improvements in either/both immunization and maternal health service outcomes) is less well-known.

Families' healthcare-seeking behaviors for maternal health and for children's immunization (both of which are linked to mothers' health decisions) have been found to be related (Cardol *et al.*, 2005; Hu *et al.*, 2013; McGlynn *et al.*, 2015; Wado *et al.*, 2014). Maternal health services such as antenatal care (ANC) (Hu *et al.*, 2013; Mathew, 2015; McGlynn *et al.*, 2015; Sullivan *et al.*, 2010), tetanus toxoid vaccination (Bosch-Capblanch *et al.*, 2012), and skilled birth attendants present at deliveries (SBA) (Fernandez *et al.*, 2011; McGlynn *et al.*, 2015) have been linked to immunization services, to one another (e.g. ANC and SBA coverage in Afghanistan, Tappis *et al.*, 2016), and to appropriate care of child for fever and diarrhea (McGlynn *et al.*, 2015).

SD modeling

The pathways through which immunization systems interact with their host health systems are just starting to be examined using methods that allow users to account for complexity. Complexity is a technical term in health systems (and public health) research literature that indicates the importance of relationships and adaptive interactions of components in the emergence of the whole (system) (Greenwood-Lee *et al.*, 2016). Despite representing only one area of service delivery in a health system, the immunization system is an example of complexity.

Rooted in systems science (Lyon *et al.*, 2016; Mabry *et al.*, 2008; Sterman and Sterman, 2000), SD is a methodological approach capable of accounting for complexity. SD model development is an iterative process that allows for the modeling of complex behaviors of organizational and social systems (Homer and Hirsch, 2006). SD models are statements about system structure and the policies that guide decisions pertaining to the system, and they enable users to test alternative scenarios and translate the complex structure and behavior of systems into practical actions (Lyon *et al.*, 2016).

SD models make implicit assumptions explicit, identify gaps in knowledge and data, and highlight sensitive areas (leverage points) for system change (Meadows, 1999). These models can reliably determine the future dynamic consequences of how changes to one part of the system affect another part. Rather than simplifying systems to a series of linear pathways, an SD modeling approach allows for examining repeated interactions and feedback within and between subsystems over time (Homer and Hirsch, 2006; Lyon *et al.*, 2016). Feedback loops could increase, lessen, or otherwise change relationships in a system, producing new patterns of behavior that differ from how we may expect the total system to behave (Forrester, 2009). Examples of referencing feedback loops in systems are becoming more common (Ozawa *et al.*, 2016; Paina *et al.*, 2014; Varghese *et al.*, 2014), but few approaches can account for feedback quantitatively (Lyon *et al.*, 2016).

The two primary components of SD models are stocks and flows. Stocks represent quantities that accumulate or deplete over time. Stocks can represent tangible resources (e.g. number of facilities, amount of time given to an activity, number of recipients of a health intervention, etc.) or information (e.g. provider knowledge, provider skill, health messages, etc.). Flows, which are directed into and out of stocks, cause the levels of the stocks to change. In the immunization context, for example, increasing inflows (vaccination rates) may increase the vaccinated stock (number of individuals having received vaccination). To take two other examples, increased vaccine stock moving through the cold chain to health facilities (inflow) may increase the amount of vaccine stock available at health facilities for vaccination services (stock), or the rate of dose wastage (outflow) may decrease the amount of vaccine stock available at health facilities for vaccination services (stock).

As noted above, SD models can exhibit complex behaviors that cannot be modeled by a series of linear pathways. The most important constructs in SD models for representing such complexity are feedback loops. A feedback loop would cause effects from a flow to propagate through the system and return to influence this flow (Forrester, 2009). For example, an increase in the flow of vaccine may create an oversupply of a vaccine stock, leading to excessive dose wastage. A well-regulated system would have a feedback loop to reduce the inflow, so that the resulting stock of vaccine would meet demand with acceptable levels of dose wastage.

Methods

Research questions

We present an overarching country case study consisting of three component studies, each with its own set of methods. We designed the country health system tradeoffs case study to examine the impact of immunization-specific readiness to deliver immunization-related services on immunization- and non-immunization-service delivery performance in the health system of Afghanistan. We were interested in the association between the system's readiness to deliver immunization-related services and immunization service delivery performance (Study 1). Then, we focused on mapping immunization system components and exploring causal pathways that link the system's readiness to deliver immunization-related services to both immunization- and non-immunization-service delivery performance (Study 2). Lastly, we developed a quantitative, SD model for further examining the structure and behavior (Study 3). We did this by carrying out a system-confirmatory exercise through which we could visually examine the structure of the immunization system as well as explicitly and mathematically describe the system components, their relationships, and their anticipated year-to-year effect on immunization and non-immunization performance.

The primary predictors of interest in the country health system tradeoffs case study capture immunization-related readiness of the Afghan health system. Readiness was selected as a proxy for performance at the health facility, serving as an inclusive yet basic measure of supply-side performance in Afghanistan. Consideration was given to measures specific to vaccination delivery such as vaccine stock, cold-chain functionality, staff and clinicians for vaccination, information systems, and other infrastructure. Primary outcomes of interest are coverage estimates for immunization- and non-immunization-related services. Coverage is defined as the proportion of targeted population that has received a given service (e.g. vaccination, skilled birth attendants at delivery, etc.). As noted above, three component studies were carried out to complete the overarching case study.

Study 1

This ecological study linked household survey data to annual health facility assessment data. These data were collected during four annual National Health Service Performance Assessments in Afghanistan from 2008-2009 to 2012-2013 (Ministry of Public Health *et al.*, 2013) and during two household surveys in Afghanistan during 2007-2008 and 2012-2013 (the National Risk and Vulnerability Assessment (Ministry of Rural Rehabilitation and Development and Central Statistics Office, 2008) and the Afghanistan Health Survey (Afghan Ministry of Public Health *et al.*, 2012), respectively. Household surveys were used by the Afghan Government to periodically assess if changes have occurred to key health outcomes and to provide demographic information. The Institutional Review Board (IRB) at the Johns Hopkins School of Public Health (JHSPH), and the Ministry of Health Ethical Review Board in Afghanistan approved these studies.

We constructed the following immunization service readiness variables for health facilities: a vaccine stock (including expired inventory), cold-chain storage and transport functionality, number of health workers who provide vaccination services, health workers who have had vaccine-specific refresher training, management agency type, universal precautions capacity, management reminders (i.e. immunization schedule and IMCI chart are present), and laboratory capacity for vaccine-related diagnostics and surveillance. Readiness scores were constructed for laboratory, stock, precautions, management, and cold-chain readiness at facilities. Full description of sample sizes, data structure, variable creation, and model specifications can be found elsewhere (Peters *et al.*, 2007; Hansen *et al.*, 2008; Edward *et al.*, 2011; Ministry of Public Health, Johns Hopkins Bloomberg School of Public Health and Indian Institute of Health Management Research, 2013). Study 1 findings were used to inform Study 2.

Study 2

We completed Study 2 in three phases to develop qualitative maps of the immunization system in Afghanistan.

Literature review. A rapid review of literature from the past ten years on readiness to deliver immunization services in low- and middle-income countries (especially in fragile states) and immunization system structure was conducted using PubMed, Scopus, and Embase using combinations of key search terms including "immunization," "vaccination," "immunization programs," "delivery of health care," "health services," "systems analysis," and "maternal health services." We included articles and reports from previous works on vaccination services and programs. Findings on immunization program components, structure, and linkages to the health system and its performance were recorded. Immunization system components were further categorized and supported by context-, content-, and methodology-knowledge (Afghanistan, immunization programs in low- and middle-income countries, health service delivery, systems thinking, and modeling).

Causal loop diagram (CLD) development. Initial lists of subsystem-system components and definitions of relationships were refined based on the triangulation of the data from the different sources including empirical findings from Study 1. Themes were identified as emerging from common domains of service delivery (Edward *et al.*, 2011; Peters *et al.*, 2007; WHO, 2007) in health systems and within immunization systems (e.g. supply chain capacity, stock and inventory of supplies at different levels of the system/subsystem, human resources for delivering vaccination, surveillance (lab) capacity for case confirmation, demand capacity). We used these service delivery readiness domains to help define immunization subsystem boundaries. The main immunization outcome of interest was vaccination coverage of the third dose of the pentavalent vaccine (Penta3). The main non-immunization outcomes of interest were coverage estimates of the following health services: ANC, SBA, children with acute respiratory-infection-like symptoms who were taken to a health facility for treatment, and maternal tetanus toxoid vaccination.

We used CLDs to represent the structure of the system using nodes for the variables and directed arrows for causal relationships. CLDs were created using Vensim PLE (Ventana Systems, 2015) and were refined through five revisions. CLD development was supported by complex adaptive systems (CAS) theory, a paradigm that is useful for exploring factors influential in the immunization subsystem of Afghanistan as well as characteristics that support CAS behavior, like self-organization, adaptation, and learning from past experiences (Adam *et al.*, 2012; Paina and Peters, 2012; Varghese *et al.*, 2014). Using knowledge of CAS behavior (Paina and Peters, 2012), the first author, who has basic training in CLD building, field experience in Afghanistan, and consulting experience focused on immunization systems and demand at the WHO, created four subsystem CLDs that together depict the immunization system of Afghanistan. These subsystems focused on point-of-service-delivery health workers, functional cold chains, and vaccine supply, basic laboratory and surveillance capacity, and consumer health-seeking behaviors and characteristics.

The recommended notation from SD literature was used to label polarity, directionality of causal relationships, and feedback (Kim, 1992; Lane, 2008). To further help with CLD interpretation, an "O" was used to indicate a causal relationship of uncertain directionality. Green variables indicate a component that is a part of more than one subsystem. Red variables indicate a component that is a part of a system of care other than that of immunization (see Table I for full list of green and red variables). Feedback loops were labeled as "R" or "B" for their reinforcing or balancing nature (Rwashana *et al.*, 2009). Each loop was numbered for cataloging purposes. Loops were further categorized as stand-alone loops or loop variations. Loop variations exist where the majority of components in two loops are the same with the exception of a small but unique change in the proposed causal pathway. If loops shared the majority of common components with another loop and the only difference represented a minor alternative pathway, loops were then deemed variations and labeled with lower case letters (e.g. R1b represents a variation of the main loop R1a).

With each iteration, we were able to refine system boundaries by understanding the necessary and extraneous system components regarding our research aims and input by experts (next section).

Model validation and finalization. A validation process, similar to the process outlined by Ozawa *et al.* (2016), was carried out, soliciting feedback from methods, context, and content experts. This process was approved by the IRB at the JHSPH and deemed non-human subjects research. Initially, 13 experts were identified for their expertise in immunization and immunization programs, health service delivery systems and tradeoffs, immunization and health policy, and Afghanistan or developing country contexts of any of the previously mentioned areas. They represent private and public organizations, government and multi-lateral organizations, academic institutions, and local Afghan organizations and government with diverse backgrounds of expertise. These experts were asked to review and provide feedback on the four subsystem CLDs. Participants were contacted via e-mail or by phone and asked to answer a series of questions either by e-mail correspondence or by phone. Specific and open-ended questions were asked regarding the variables, connections, and structure of the subsystems represented in the CLDs.

Comments were consolidated and incorporated into the CLDs as the third, fourth, and fifth iterations of diagrams. We adjusted CLDs as expert feedback was received. Updated models were used for subsequent feedback surveys. In total, seven experts participated in the CLD review, after which the investigators considered the validation process "complete"

Table I. From Study 2: organization of subsystems: connector (green) variables as well as immunization and non-immunization outcome(s) of interest

	Subsystem (SS)			
Variable name	SS1	SS2	SS3	SS4
Connector (green) variables				
Good vaccine management	X		X	
Demand: children at facility for vaccination	X		X	X
Demand: decision to go to facility (for health services)	X		X	X
Vaccination service provision capacity [availability] at facilities	X		X	X
Vaccination service provision capacity [availability] for outreach	X		X	
Outreach activities	X		X	
Technical quality of service provision		X	X	X
Perceived quality of service provision			X	X
Community trust in system			X	X
Health worker knowledge and skill base at facilities		X	X	
Immunization outcome (green) variable of interest				
Vaccinated children	X			X
Non-immunization outcome (red) variables of interest				
ANC visits (pregnant women receiving antenatal care)			X	X
Skilled birth attendant at deliveries			X	
Tetanus toxoid vaccination of pregnant women			X	
Demand: child at facility for treatment of illness				X

based on saturation and quality of feedback. Review and discussion of the expert feedback, current evidence, future data needs, and the feasibility of SD model development supported model improvements.

Following the validation process, the CLDs were refined in order to better understand the structure of the system and what components and relationships may drive system behavior: that is, which areas of the system drive it to produce the immunization and non-immunization outcomes of interest. This process was used to prepare for creating SD models (Study 3) for a confirmatory exercise by completing the following steps: reducing each full subsystem (Figure 3, reduced from Figure 2) using principles of CLD structure (multiplying of relationships allows for reducing to a relationship to a single causal relationship) and by identifying main feedback loops that can be further supported with available empirical data; simplifying the feedback loops where pathways can continue through components that do not have available data; and joining the four reduced and simplified CLDs (Figure 4).

Study 3

Information sources and system components. The same variables created for Study 1 were used for Study 3. The immunization outcome of interest is the coverage estimate of the third dose of pentavalent vaccine among 12-23-month-old children (Penta3). Non-immunization outcomes of interest (for maternal health services) are coverage estimates of SBA and ANC among ever-married women age 12-to-49 years of age who have been pregnant with a live birth outcome in the past two years.

For Study 3, we used the same immunization service readiness variables developed for the analysis in Study 1, with the exception of health worker capacity scores (calculated using principal component analysis (PCA) (Jolliffe, 2002) from information on average health worker counts at health facilities (vaccinators, physicians practicing obstetrics and gynecology, nurses, mid-level clinicians, and general physicians). PCA was used to create a single demand-side factors component using percentage of richest households, percentage of mothers who have ever had a formal education, and percentage of currently married women aged 12-to-49 years who currently use a form of modern contraceptives (includes female sterilization, intra-uterine device, contraceptive pill, contraceptive injection, and condom).

Model building. Using Vensim PLE 6.4 (Ventana Systems, 2015) to develop a stock-and-flow diagram, a visual representation of the SD model was developed, referring to CLDs representing the Afghanistan immunization system (Study 2). Boxes in the model (Figure 1) represent stocks (quantities) of different forms of system readiness as well as coverage of different health services that change over time. Double-lined arrows represent inflows or outflows (rates) that change the level of stocks, and each flow is regulated by a valve (double, stacked triangles). Single arrows represent parameters that affect flows, and variables with no box represent auxiliaries (constants) that affect flows. Stocks of system readiness and coverage outcomes change from year-to year according to different model parameters, indicating that the model is dynamic. Using this setup, the flow of system readiness and coverage outcomes can be visually depicted. Feedback loops were label as "R" or "B" for their reinforcing or balancing nature (Rwashana *et al.*, 2009), and loops were numbered for cataloging purposes.

Base SD model. In order to continue with parameterizing the system, the first and third authors (representing public health and systems engineering expertise, respectively) collaborated to construct the model and generate output. The base model was created using Matlab (Math Works, 2016). The parameters of the model, including the rate constants for all of the flows, were identified using the multiple years of data for system readiness components (four years) and system coverage components (two years bookending the four

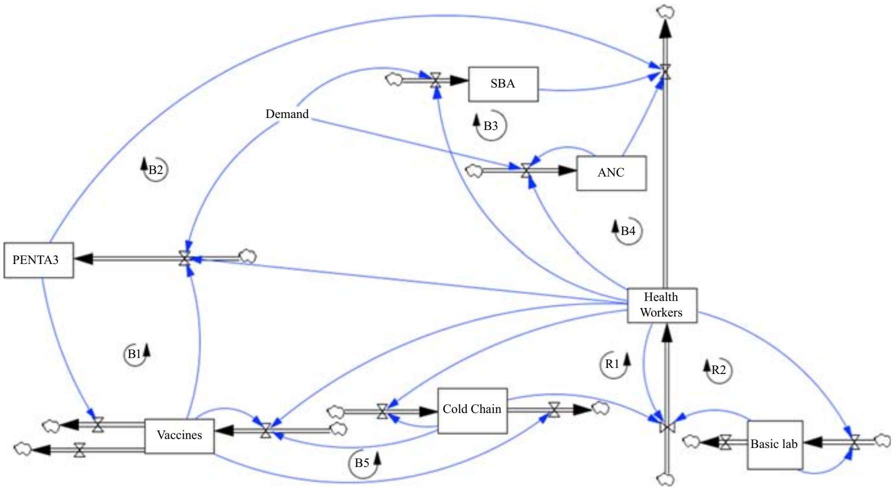


Figure 1. From Study 3: full system dynamics Afghanistan immunization system – maternal health service tradeoffs model

readiness years) (Figure 1) (single arrows). To begin the parameter identification process, regression lines were fitted for each stock in which there was data with multiple years. Then, the rate constants were determined by minimizing the sum of the squared differences between these regression lines and the levels of stocks predicted by the SD model. The constrained minimization function, fmincon, in Matlab was used in this analysis. The standard errors of the model coefficients and p-values were determined by using the statistical bootstrap procedure (Efron and Tibshirani, 1998).

General findings and discussion

In Study 1, vaccine-related laboratory and vaccine stock readiness scores were the main predictors associated with immunization coverage. Vaccine-related laboratory capacity may suggest other health facility strengths associated with improvements in immunization coverage, and experts found it difficult to discuss any direct mechanism connecting laboratory capacity and service delivery outcomes in Study 2. Also in Study 1, demand-side factors that may describe patterns of household health behaviors, such as exclusive breastfeeding practices and second dose of tetanus toxoid during pregnancy, were associated with immunization coverage as were women's education and household wealth status.

Across the four subsystem CLDs (full model example, Figure 2), demand-side and supply-side actors are a unifying theme. Each of the subsystems except SS2 includes a point of intersection between supply and demand (e.g. facility stockouts experienced by parents seeking vaccination in SS1, health worker motivation affecting technical quality and perceived quality of service provision, etc.). These may be pivotal points in the system where a service is or is not received (or decision for a future service is or is not made). The role of demand (the actions of deciding to have children vaccinated and seeking vaccination at health facilities) is a part of all but one of the subsystems. Despite having such a clear role in the immunization system, demand is difficult to define and measure (Informal Working Group on Vaccine Demand, 2015), and it is often viewed as a factor external to the immunization program (i.e. the balancing factor to immunization-supplied services).

When subsystem CLDs were reduced (example, Figure 3), the comprehensive system model (Figure 4) contained mostly reinforcing loops. Theoretically, one small improvement in readiness could vastly improve immunization outcomes over time; similarly, declining readiness could devastate the system over time. This system structure may have an effect

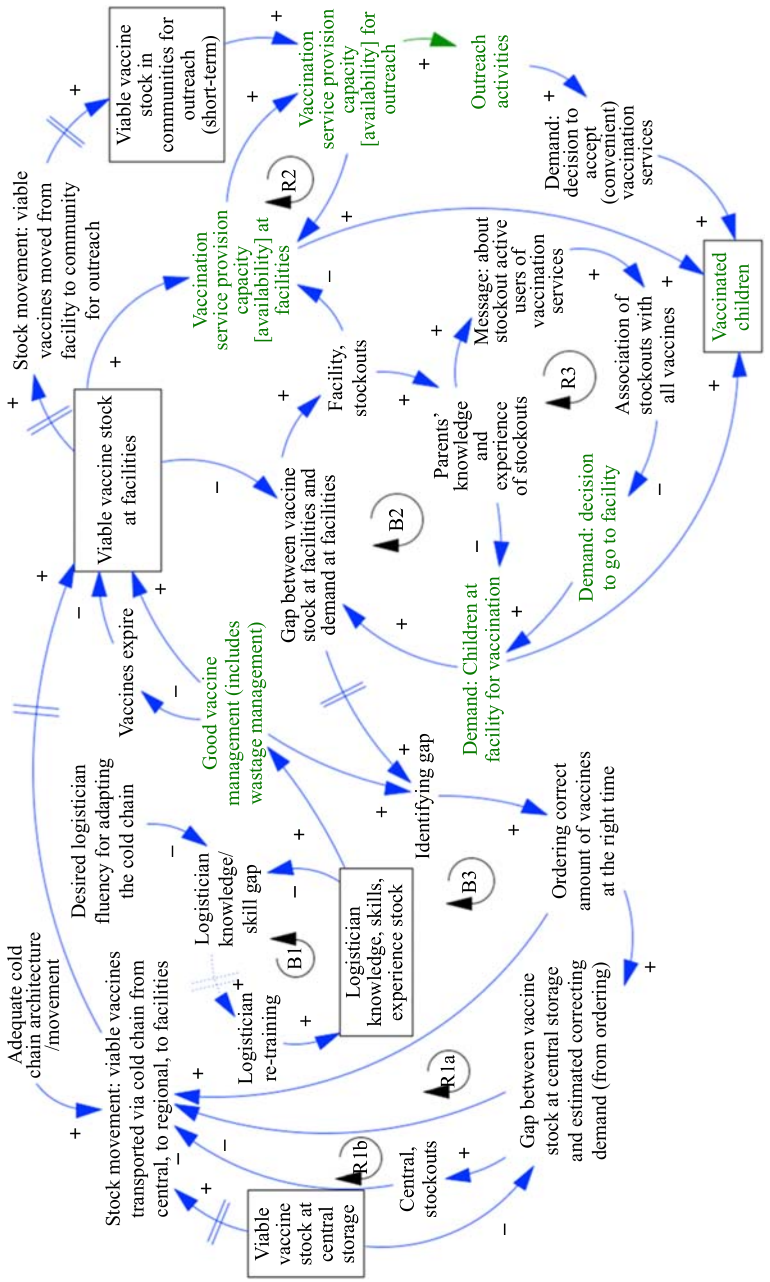


Figure 2.
From Study 2: subsystem 1, full: exploring the dynamics involved in cold-chain functionality and stock inventory and their relationship to vaccination coverage

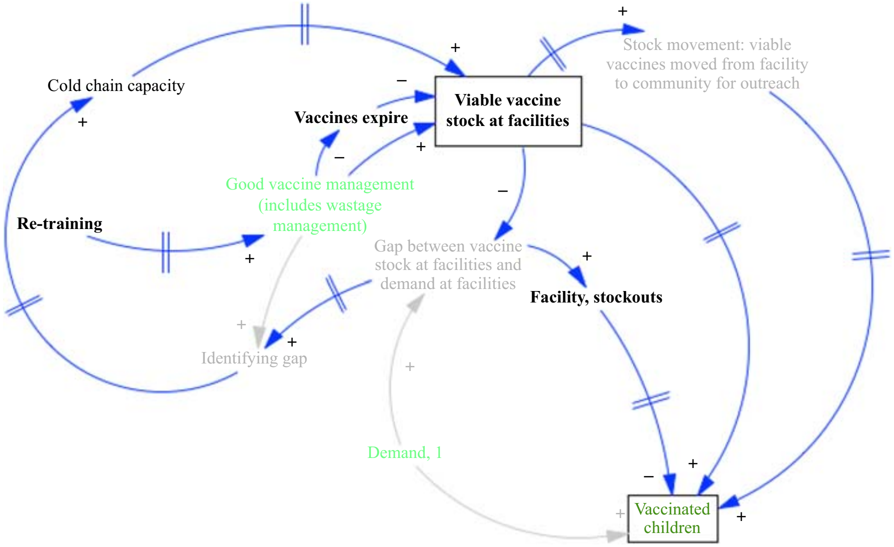
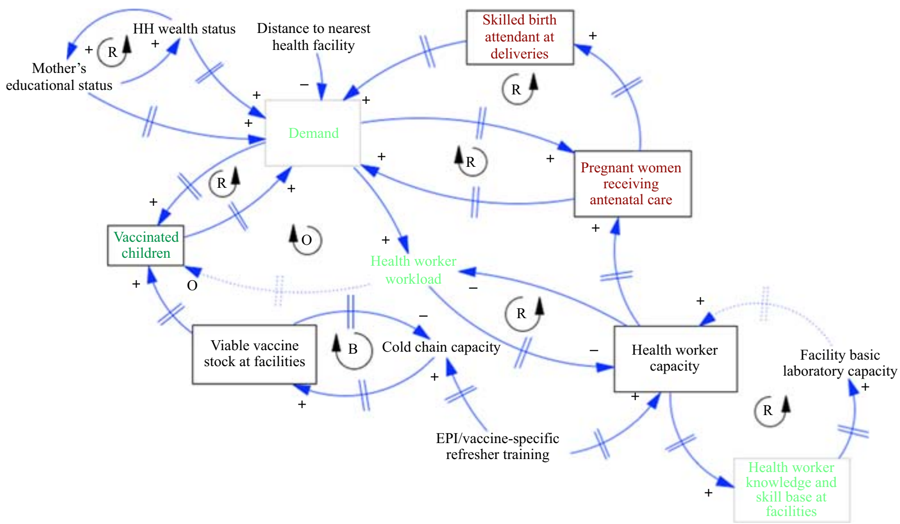


Figure 3.
Subsystem 1: reduced from Figure 2 (full SS1 system) showing components with available empirical data (bold) and connections



Note: In preparation for system dynamics modeling (Study 3)

Figure 4.
Immunization system in Afghanistan: combination of reduced four full subsystems (e.g. Figure 2), accounting for empirical data availability

on the parameterization of future SD models. Although the model in Figure 4 represents the original four subsystem CLDs that were extensively reduced and simplified, it contains components for which we currently have data for proxy measures (i.e. demand and health worker capacity stock). This has implications for knowledge and measurement gaps for not only our example of the Afghanistan context but also likely for other developing countries.

The SD model in Study 3 (Figure 1) produced similar results linking the demand component to maternal health service coverage (i.e. SBA coverage), vaccine stock availability to immunization coverage, the role of health workers with respect to maternal health service coverage (ANC), and the effect of past readiness upon future readiness. This model allowed us to visualize the flow of stocks throughout the system. Because of a limited amount of time to develop the SD model, we have not yet continued to a model exploratory phase for further calibrating the system structure and parameters. The collaboration between public health and engineering was a new experience for some, and a rhythm for the exchange of information and expertise took time to develop. Furthermore, there are currently no published quantitative SD models for simulating the impact of the readiness to deliver immunization services on health services outcomes. Hence, the base SD model introduced herein can serve as a working model for systems scientists who are interested in the dynamics of immunization systems and their effects that extend beyond vaccination service delivery outcomes.

Recommendations

Given the importance of immunization system actors (in this study, health workers and consumers of vaccination and maternal health services), future work should focus on their interaction with health service delivery systems. Models from this study could facilitate future exploration in behavioral economics of how system structure shapes actors' behaviors (area of study in behavioral economics, Cappelen *et al.*, 2010). For example, actors who seek and receive health services (i.e. part of demand for vaccination) could be examined in order to better understand their role in immunization systems. This likely requires attention not only to consumers of immunization and other health services but also to people who are a part of, or who contribute to, the societal structures that foster health-seeking behaviors. Approaches should account for the complexity of factors and pathways that influence health-seeking behaviors and examination of the points of intersection between system and demand. Such explorations may be more difficult in volatile environments like Afghanistan where system structure is continually adapting and thereby actor behavior (people's interaction with the system) is continually changing.

Based on our model, it is now possible to conduct a series of system exploratory exercises to assess how changes to one or a group of system components, such as increasing or decreasing vaccine stock readiness at health facilities, can influence not only immunization service outcomes but also service outcomes beyond immunization. For example, in a low-resource environment, an increase in vaccine stock readiness at health facilities may have an unanticipated adverse effect on maternal health service coverage so far as resources and efforts have been diverted from maternal health to vaccine supply chain and stock management. The base model is particularly useful in investigating system-wide changes, such as immunization policies or changes to system structure. In testing changes to system structure, the model may need to be reconfigured, and the base SD model would then serve as the foundation from which modifications can be made. Moreover, the model development process outlined above would serve as a guide in formulating the modifications, calibrating the parameters, and developing preliminary conclusions about the model results. Practitioners and those managing and governing immunization systems may suggest testing the effect of, for example, increasing or decreasing health worker capacity for vaccination service delivery, observing the intended and unintended effects of such a policy change on service delivery outcomes beyond immunization.

Conclusion

Health systems and subsystems are important objects of study in public health research. The understanding of their behavior can be improved by using methods that account for complexity. The approach presented in this paper offers a foundation for further testing of immunization policies and their effects on immunization and non-immunization performance when accounting for complexity. By partnering across disciplines like systems engineering and public health, knowledge and data gaps can be addressed using methods that can account for the complexity inherent to immunization and other health programs.

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