Article

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System dynamics approach to immunization healthcare issues in developing countries: a case study of Uganda

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This article critically examines the challenges associated with demand for immunization, including the interplay of political, social, economic and technological forces that influence the level of immunization coverage. The article suggests a framework to capture the complex and dynamic nature of the immunization process and tests its effectiveness using a case study of Ugandan healthcare provision. Field study research methods and qualitative system dynamics, a feedback and control theory based modelling approach, are used to capture the complexity and dynamic nature of the immunization process, to enhance a deeper understanding of the immunization organizational environment. A model showing the dynamic influences associated with demand and provision of immunization services, with the aim of facilitating the decision making process as well as healthcare policy interventions, is presented.

Keywords

causal loop diagrams, healthcare services, immunization demand, immunization healthcare, system dynamics, Uganda

Introduction

Stagnant and falling immunization rates in most sub-Saharan African countries have resulted in renewed international attention, and the effectiveness and sustainability of immunization programmes have become key issues of policy debate [1]. Increasing immunization coverage to prevent childhood diseases is an important developmental issue [2–5] and an area of critical research [6–11].

In a study to evaluate new trends and strategies in international immunization, Martin and Marshall [12] suggest that 'failure to immunize the world's children with life saving vaccines results in more than 3 million premature deaths annually'.

There is an urgent need to improve immunization coverage around the world. The World Health Organization has targeted measles for eradication in several regions of the world by the year 2010 but, despite an effective vaccine, there are still estimated to be 30–40 million measles cases and 800,000 deaths per year [13]. In Uganda, despite numerous immunization campaigns through the media, health visits and improved health services, coverage rates are generally still low (less than 60%) [13].

Various approaches have been applied to understand immunization coverage problems. However, there are still acknowledged deficiencies in these approaches, and this has given rise to research into alternative solutions, including the need to adopt new technologies to address the imbalance between immunization demand and provision of health services. Understanding of the immunization coverage system and its problems may be helped through system dynamics methods [14]. System dynamics provides us with tools which help to better understand difficult management problems such as faced by the immunization programme in Uganda.

Background to immunization coverage in developing countries

Preventable childhood diseases such as measles and premature deaths still occur, particularly in the developing countries, due to low immunization coverage [5]. According to the World Health Organization (WHO) [15], global coverage for measles immunization stands at 77 per cent. In 2005, 28 million infants worldwide had not been vaccinated with DPT3 (diptheria pertussis tetanus, third dose), with 75 per cent of these being in developing countries. Immunization coverage is lowest in poor countries and among poor populations such as Africa and Asia [16]. Globally, it was reported that the goal of fully immunizing 80 per cent of the world's children was reached in 1990; however, coverage in Africa for that year was 55 per cent. The United Nations Children's Fund (UNICEF) and the World Health Organization [17] further state that immunization coverage rose significantly since the launch of the expanded programme for immunization in 1974, from less than 5 per cent of the world's children in the first year to around 76 per cent by the end of 2003. Governments, donor agencies and projects have made contributions towards the improvement of immunization rates through the improvement of health infrastructure, financing, supplies, staffing and management of national immunization programmes.

Figure 1 shows the immunization coverage rates in Uganda over time. In Uganda, BCG immunization rates are higher than those of polio 3 (polio, third dose), measles and DTP3 due to the fact that BCG is administered at birth, while the rest are administered after some weeks as scheduled. There is a general upward trend in immunization coverage rates which is sustained by continuous campaigns to challenge negative responses towards immunization.

Research design

The study employed the dynamic synthesis methodology (DSM) developed by Williams Ddembe which combines two powerful research strategies: system dynamics (SD) and

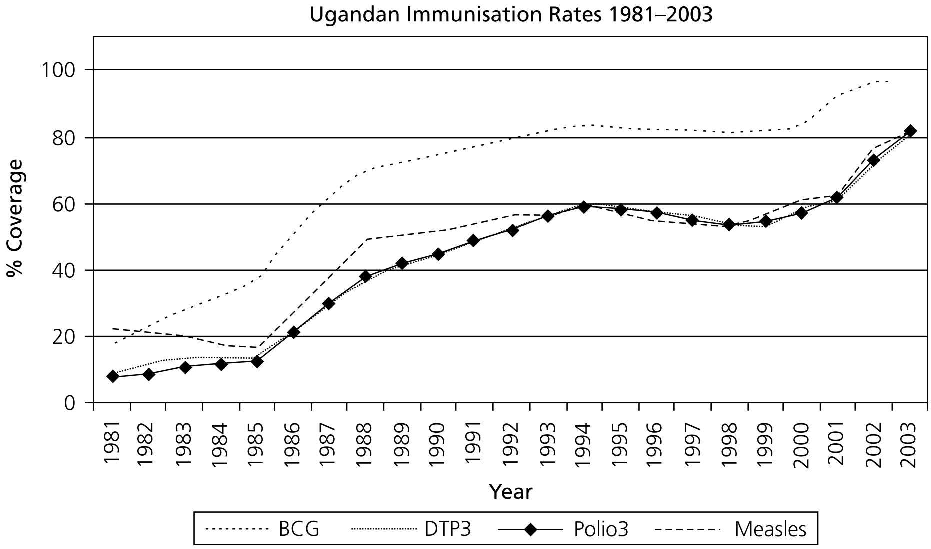

Figure 1 Ugandan immunization rates 1981–2003

case study research methods [18]. Combining simulation and case study methods is beneficial in that the case study enables the collection of on-site information about the current immunization system, owners and user requirements and specifications used to develop the generic model.

The system dynamics methodology illuminates key principal effects such as exogenous shocks, systemic feedback loops, systemic delays and unintended consequences typical of the immunization system as follows:

1 The immunization system presents exogenous shocks (factors external to the system), such as changes in demand for immunization (which may occur as a result of immigration) and the emergence of epidemics such as measles.

2 The immunization system contains feedback loops, communication paths and methods that impact behaviour. A feedback loop is a control system where the output of the system is fed back into the system [19]. For example, immunization knowledge enhances utilization of immunization services which in turn results in more knowledge.

3 The immunization system has systemic delays (time lags) which develop over time in response to internal and external influences. Examples of such delays are those arising from delivery of health services and cold chain maintenance (ensuring that vaccines maintain the right temperature during distribution), especially to rural communities, as well as delays in uptake of immunization.

4 Policy changes, feedback loops and behavioural changes in the immunization system result in both intended and unintended consequences which can be investigated using the SD methodology.

The problems faced by the nation's immunization system policy can be interpreted in terms of the information, actions and consequences which the system dynamics viewpoint presents [20–23]. The research design is shown in Figure 2.

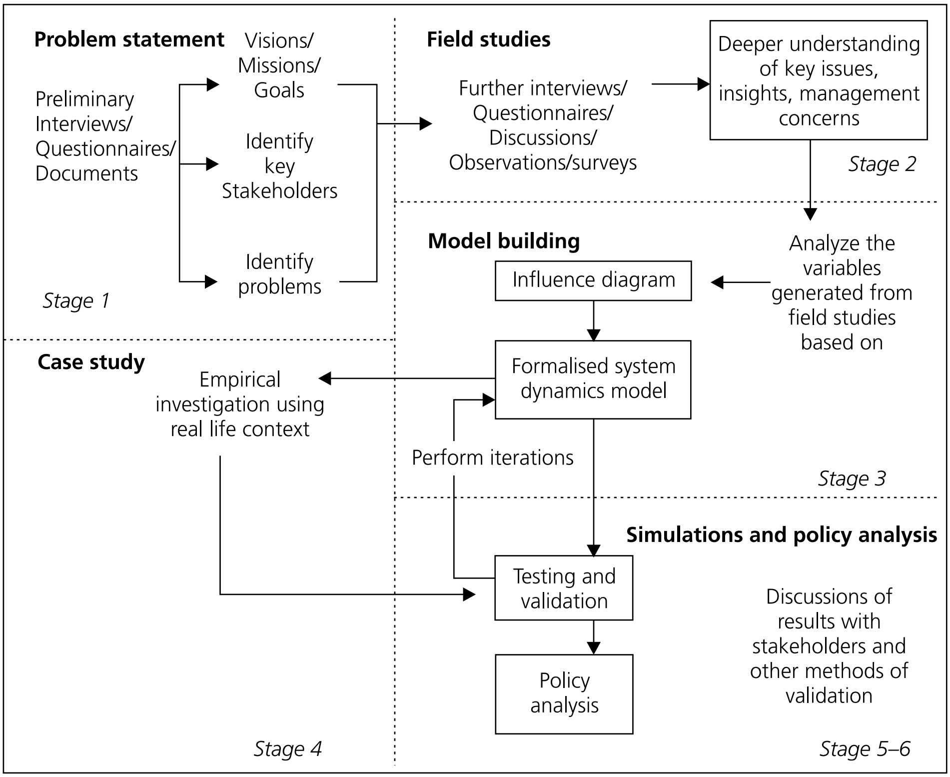

Figure 2 The research design (source: [28])

In order to understand factors that influence immunization coverage and their relationships, survey research supported by semi-structured interviews was conducted to understand the intricate information flows, delays and other competitive challenges. In stage 1 (Figure 2), information related to immunization issues and associated problems was initially collected from related literature and documents. Management and staff of the national immunization programme (UNEPI) and Mukono District Health Services were interviewed in order to establish the current problems faced by delivery and uptake of immunization services. Field studies were used to determine the full range of activities and challenges associated with immunization coverage (stage 2). Data obtained from the study were analysed with the SPSS statistical package (stage 3). The factors affecting immunization coverage, as well as national immunization policies used for immunization coverage, were critically analysed and used to develop causal loop diagrams (Figures 4 and 5) using Vensim modelling software.[1] The causal loop diagrams were presented to stakeholders for comments and improvements. Feedback from consultations was then used to develop the quantitative model. Stage 4 involved empirical investigation into the current Ugandan immunization healthcare services. Data obtained from the empirical investigation was used to populate the model. Stage 5 involved scenario modelling and testing of various policies as well model validation. Stage 6 involved the proposition of intervention strategies towards improvement of immunization coverage. Key information and processes required for immunization coverage improvement were derived.

Field studies

Field studies were carried out to determine the full range of activities and events that are associated with immunization coverage, and to examine the various acknowledged factors associated with the provision and utilization of immunization services [24]. The study was both qualitative and quantitative. The study was carried in Mukono district which lies in the central region of Uganda. Mukono was selected as the area of study since it has a good mix of both rural and urban populations. The people of Mukono district reside both on the islands (one county) and the mainland (three counties) and the population consists of more than 18 tribes. Data were collected through interviews using semi-structured questionnaires from various stakeholders interested in the current immunization system: mothers, health workers, district health officials, implementers of policy (UNEPI), policy makers (government) and community leaders. Field observation of some activities was also carried out, and other sources of data, especially those that would be able to highlight historical, social, political and economic contexts, were collected.

Mothers. In each county of the selected district, 200 mothers were interviewed. A multi-stage sampling method was used to define a target sample size of 800 mothers. The sample size was determined as follows:[2]
where:

- n is the required sample size.
- z is the standard normal deviation corresponding to the level or degree of confidence selected. Two confidence intervals normally used for the population mean are 95 and 99 per cent. This study selected the 95 per cent confidence interval as suggested by Hutchins et al. [25]. For 95 per cent confidence interval, $z = 1.96$.
- p is the fraction of population normally covered by immunization, i.e. 0.7.
- q is the fraction of population not covered by immunization, i.e. $(1 - p) = (1 - 0.7) = 0.3$.
- e is the error caused by observing a sample instead of the whole population or the permissible error which is less than or equal to 10 per cent.

Hence $n = 80.7$. Taking into account a non-response rate of 20 per cent, this gives a figure of 100 respondents. A design effect consideration resulted in 200 (100 × 2) respondents for each county, thus making the number of respondents in the four counties equal to 800. In each county, the planned number of interviews was at least 200 mothers. A structured questionnaire was used.

Health workers. Three private and five government health facilities were selected by simple random sampling from the district. Those that were selected included one government hospital and one private hospital, and the rest were health centres and dispensaries. At each sampled health unit, two people were interviewed, one vaccinator and one officer-in-charge of vaccines; this brought the total interviewed to 16.

Officials. At the district level, several meetings with various officials from the health and administrative services were held. Local community leaders and national officials, as well as consultants with UNICEF, were interviewed.

Data analysis

A thematic approach was used to compile and analyse the qualitative data. Socio-economic and demographic variables were treated as independent variables, while attitudes and knowledge were treated as both dependent and independent variables. The data were analysed using SPSS 10.0 for Windows. The analysis employed descriptive statistics, including frequencies, percentage distributions, cross-tabulations and correlations. Cross-tabulations were used to further analyse the data by considering a combination of information on two or more variables.

Analysis of the Ugandan immunization system

Healthcare services in Uganda, including immunization services, are provided through a decentralized system consisting of geographically spread health centres and regional hospitals which are categorized into health districts and health subdistricts. A system diagram, a high level map showing the overall architecture of the immunization system, was developed as shown in Figure 3.

The immunization system diagram shows four key subsystems which are explained as follows:

1. The *immunization management subsystem* is responsible for the management, monitoring and supervision of immunization services at the national level. Collaboration with the government/donor agencies effects proper budgeting and flow of funds. Management ensures that vaccines are ordered and delivered to the vaccines management subsystem for distribution.
2. The *vaccines management subsystem* is responsible for the management and delivery of quality vaccines to the healthcare service subsystem for distribution to the districts and health facilities. This involves maintenance of vaccine efficacy which is done by ensuring that the vaccines are kept at the right temperature.
3. The *healthcare service subsystem* is responsible for the provision of immunization services to the population. The health service is concerned with the management of resources (health workers, vaccines and equipment) as well as providing health education to the community.
4. The *community subsystem* represents the population that utilizes the immunization services. The community is obliged to take the children for immunization, follow the immunization schedule and report any incidences concerning immunization.

The key external agents (outside the boundary) include the *government and donor agencies* that provide the funds necessary to run the immunization programmes, the *vaccine manufacturing organizations*, and the *community leaders* who carry out mobilizations in the communities.

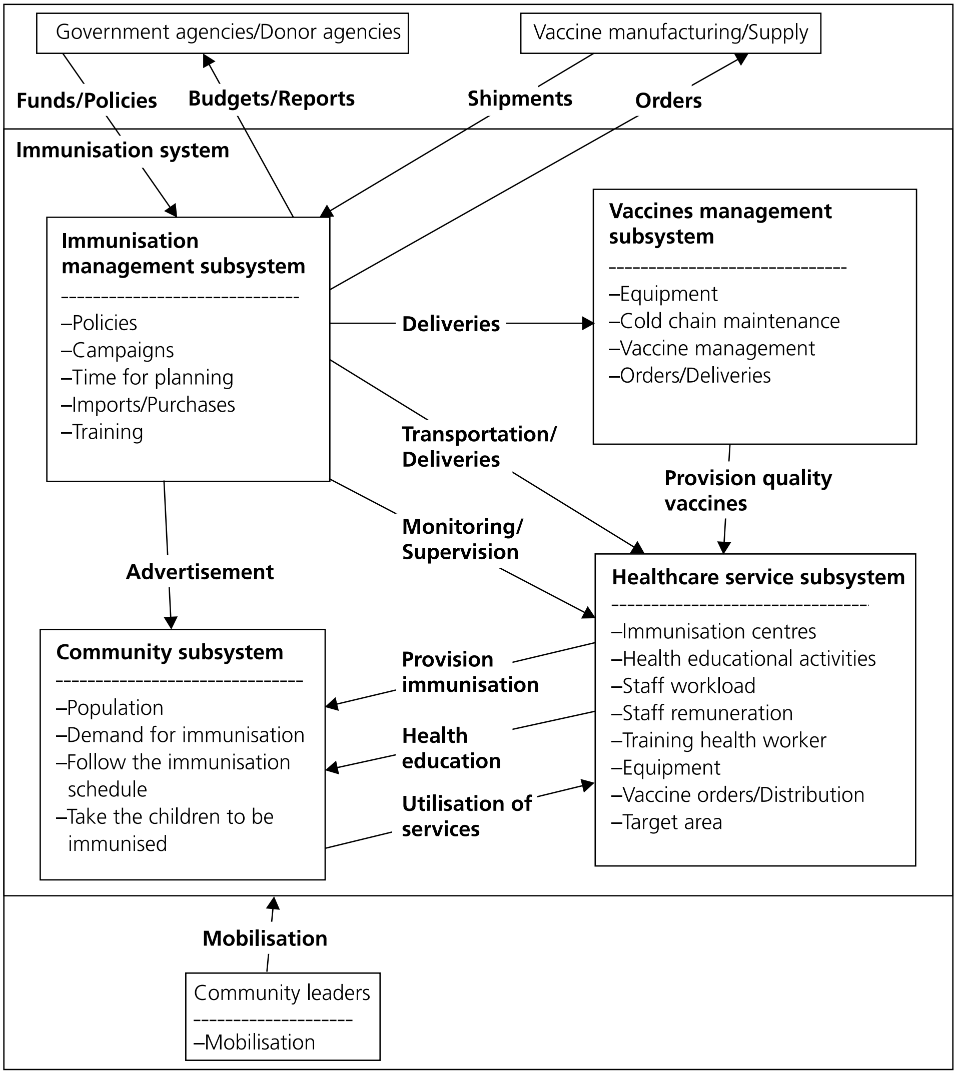

Figure 3 Immunization system diagram for Uganda

The system diagram conveys information on the boundary and levels of aggregation in the model by showing the number and type of different organizations or agents represented. Key processes and flows of information are shown. However, the diagram does not show the influences and causality which provide a deeper understanding of the immunization system.

Causal loop diagrams

Causal loop diagrams (influence diagrams) are circular chain diagrams of cause and effect which are used to represent relationships between variables which are often difficult to describe. A relationship between two variables is represented by an arrow showing the direction of influence. A positive sign on a link implies that a change in one variable results in a change in the same direction, whereas a negative sign denotes a change in the opposite direction. A feedback loop occurs when arrows connect a variable to itself through a series of other variables. A feedback loop may be reinforcing (R) or balancing (B). A reinforcing loop is defined as a positive feedback system that represents a growing or declining action, while a balancing loop is a negative feedback system that is self-regulating [26].

Findings from the field study, as well as immunization studies of other researchers [3, 5, 7, 27], are represented in the causal loop diagrams of Figures 4 and 5. The figures show the factors associated with demand for immunization and the provision of healthcare services, as well as the key issues that need to be taken into consideration.

Figure 4 illustrates the intricate and complex relationships among factors affecting immunization coverage from a parental participation perspective and a number of feedback loops which may help to explain different immunization coverage levels [28]. It is this feedback structure that gives rise to complexity, non-linearity and time delays in immunization coverage.

Figure 4 presents two balancing loops B1 and B2 and one reinforcing loop R1. Loop B1 is a balancing loop which shows that, with increased level of awareness, the demand for immunization increases, which increases the number of children immunized, thus creating a herd immunity which, in turn, results in fewer occurrences of epidemics [27]. Increased epidemic occurrences, on the other hand, result in an increased disease burden; this necessitates more awareness campaigns which, in time, lead to increased awareness levels.

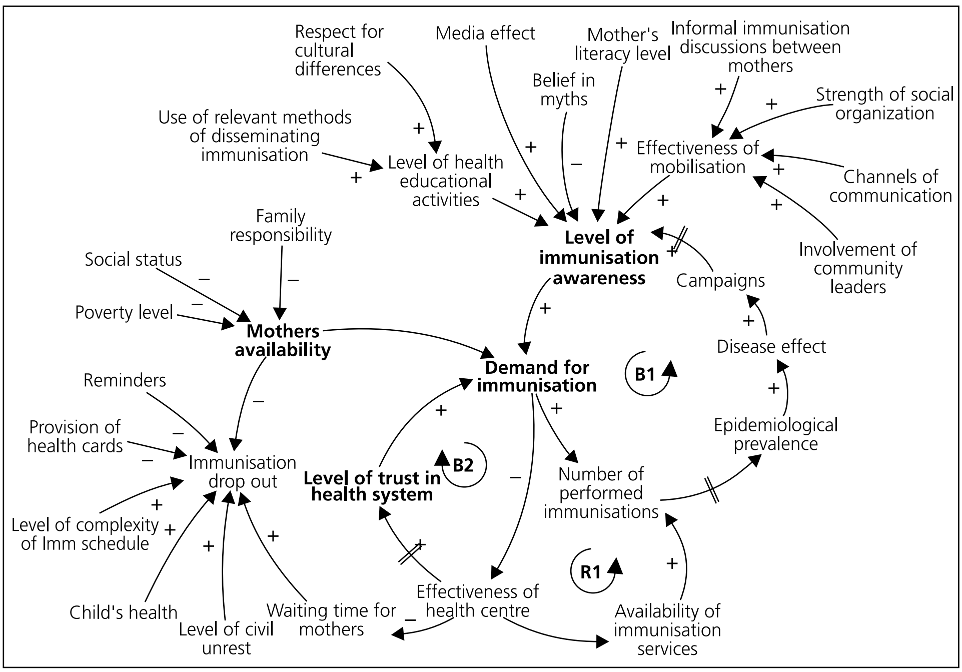

Figure 4 Causal loop diagram for demand for immunization dynamics

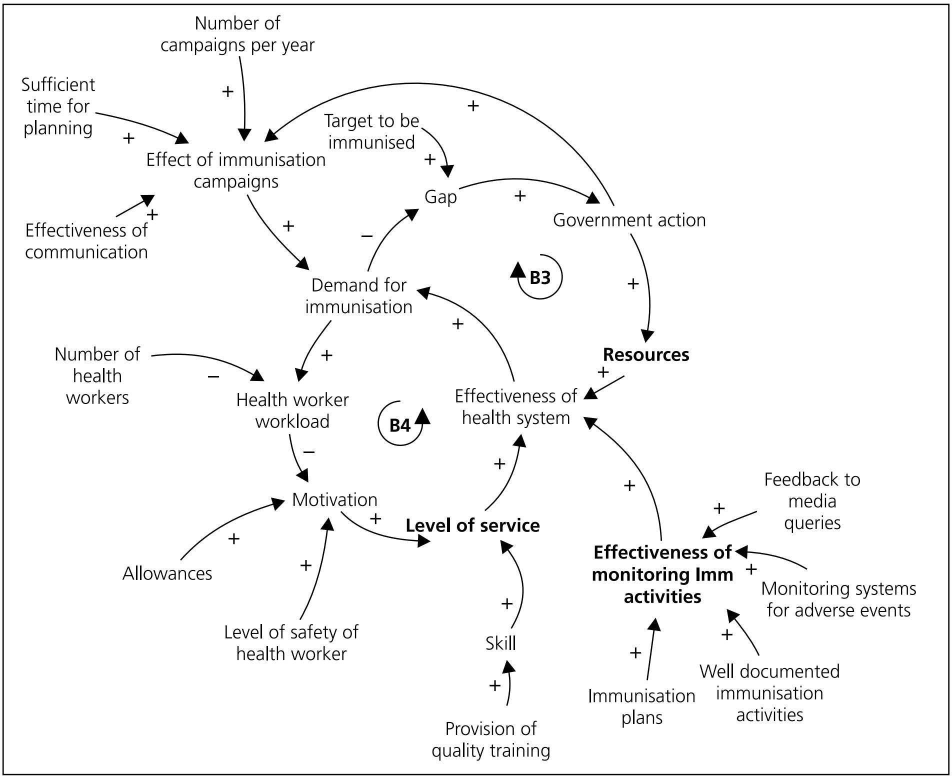

Figure 5 Causal loop diagram for healthcare service provision

Loop B2, a balancing loop, represents the dynamics involved in the effectiveness of healthcare systems. With a time delay, increased effectiveness results in increased level of trust, thus increasing the demand for immunization services. However, as the demand for immunization services increases, the resources are depleted and the workload increases, thus causing a reduction in the effectiveness of the health systems. Loop R1 is a reinforcing loop which shows a growing decline in the number of immunizations performed due to inadequate provision of immunization services. As the number of children to be immunized increases, there is need to increase the capacity of the healthcare services.

Figure 5 presents two balancing loops B3 and B4. Loop B3 seeks to achieve the set immunization targets by focusing on health service delivery. The difference between the targeted number of children and the actual number of children immunized creates a gap which triggers an increase in government funding for immunization programmes. An increase in funding results in increased resources and health centres which, when coupled with a high level of service, will increase effectiveness; this, in turn, improves the demand for immunization.

Loop B4 is a balancing loop, which represents the limiting factor resulting from increased demand as far as the effectiveness of the healthcare system is concerned. An increase in demand results in increased workload which reduces health worker motivation, resulting in reduced level of service, which affects the provision of healthcare services.

The effectiveness of the health system can be achieved through a combination of factors such as availability of resources (health centres, vaccines, transport), level of service of health workers (skills, workload) and effectiveness of monitoring systems.

Insights from the causal loop diagram

From the causal loop diagram, a broad integrated view of the system is provided for stakeholders to prioritize and set policies. The different policies and interventions that need to be developed for the improvement of immunization coverage can then be generated from a clear understanding of the complexity of the system.

Parental participation subsystem

The parental participation subsystem is based on the case study that was undertaken and the immunization studies of other researchers [7, 27, 29, 30]. From the study, the key issues that affect parental participation are grouped under the following, as shown in the causal loop diagram in Figure 4:

- Effectiveness of health centres results in increased availability of immunization services to mothers, which in turn increases the number of performed immunizations.
- Mothers' availability is associated with family problems (single parenting, number of children in the household), high poverty levels and social status (mothers' work, work schedule).
- Level of trust in the health system is increased as the effectiveness of the health centres increases. Increase in level of trust results in a change in attitude towards increased demand in immunization. Issues that are associated with the effectiveness of health centres include hygiene, levels of injection safety, number of health workers at the health centre, and health workers' response to the mothers.
- Level of immunization awareness is associated with mothers' level of literacy, belief in myths, effect of media, level of education and effectiveness of community mobilization.
- Immunization dropouts (infants who take initial doses but do not complete the immunization schedule) are associated with the level of civil unrest (presence of wars), children's health, level of complexity of immunization schedule, provision of health cards and reminders.

Healthcare subsystem

The healthcare subsystem is based on field studies carried out in a number of health centres in the Mukono district and various other studies. The key issues associated with the healthcare system are grouped under the following, as shown in the causal loop diagram of Figure 5:

- Level of service is associated with health worker motivation resulting from the provision of allowances, level of safety and workload. Increased skill level resulting from the provision of quality training increases the level of service which in turn increases the effectiveness of the health system.

- Effectiveness of monitoring of immunization activities involves the following: monitoring systems for adverse events, documentation of immunization activities, display of immunization activities, reporting of immunization activities and reviews of immunization plans.
- Effectiveness of immunization campaigns is affected by the number of campaigns in a year, availability of allowances, sufficient time for planning and effectiveness of communication.
- Efficiency of health facilities is affected by the availability of resources (finance, equipment, logistics) as well as monitoring of immunization activities.

Validation

The initial causal loop diagram generated from the field studies was presented to various stakeholders for their comments and feedback on understanding of immunization coverage problems. Thereafter, specific interviews were conducted with health workers, district health workers and mothers to improve the resulting causal loop model, and further qualitative analysis led to refinement of Figures 4 and 5.

Conclusions and future work

Systems dynamics has been used to capture and analyse complex interactions between behavioural, technical, policy and cultural issues. This provides a broad integrated view of the immunization system which facilitates communication and caters for the different stakeholder viewpoints. The synthesis of the various theoretical concepts through the use of causal loop diagrams facilitates the understanding of the immunization system which enables agreement on different policies and priorities. Examining causal loop diagrams enables decision makers to focus on the root causes of shortcomings and not the symptoms alone. It is through such understanding that effective decisions and policy interventions that are suitable for communities such as those in developing countries can be designed.

Ongoing work involves development of the quantitative model and applying simulation modelling to test different healthcare policies using 'what if' analysis, with the aim of improving policy analysis in immunization coverage. The causal loop diagrams are converted into stock and flow diagrams which are defined by mathematical equations where variables are given initial numerical values emanating from historical data. The aim of developing the model will be to show the relationships, trends and effects of key variables by testing various scenarios.

Notes

1 http://www.vensim.com/software.html.
2 How to determine a sample size: http://www.extension.psu.edu/evaluation/pdf/TS60.pdf.

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