System Dynamics Modeling in Healthcare: The Ugandan Immunisation System

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The paper develops a system dynamics simulation model to understand the dynamics of immunisation with the aim of aiding decision making process by proposing policies that would enhance immunisation utilization. The model is designed with the intent to show how particular variables influence immunisation demand and coverage rather than predict immunisation coverage rates. The paper applies system dynamics modeling and field study research methods to capture the complex and dynamic nature of the immunization process, to enhance the understanding of the immunization health care problems and to generate insights that may increase the immunization coverage effectiveness. The model is divided into four sectors interacting with one another. The paper suggests key leverage points which could substantially improve immunisation demand, effectiveness of the health system as well as vaccine management.

Key Words and Phrases: Immunization coverage, Immunisation utilization, System Dynamics, Simulation modeling in healthcare

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1. INTRODUCTION

Simulation modeling has become an important area for strategy implementation, policy analysis and design in many application areas including health care management. Some of the health care management systems include billing, administrative, staffing, patient management, hospital management, pharmacy, consulting systems, disease screening, and emergency care among others. Computer models are used extensively in many areas of systems management to provide insight into the working of a system. This is particularly useful when the system is complex and / or when experimentation is not possible. Simulation modeling has been applied in a number of health care situations [Bayer et al., 2007; Cody et al., 2007; Haslett, 2007; Chu et al.,2003; Fitzpatrick et al., 1993; Dexter et al.,1999; Dittus et al.,1996] and clearly has the potential to play a role in health care decision making at all levels. The availability of a variety of simulation software has significantly expanded the role of simulation modeling in healthcare research, policy making and operational decisions [Fone et al., 2002; McAleer et al., 1995].

Simulation models provide quantitative information that provides a clear understanding of the problem thus enhancing decision making. Computer simulation provides a powerful tool that can be used to model and understand complex systems from the macro systems level to the micro genetic level [Hethcote et al., 2004]. The availability of a variety of simulation software has significantly expanded the role of simulation in research, policy making and operational decisions [Dexter *et al*., 1999; Dittus *et al.*, 1996; Fitzpatrick *et al.*, 1993; McAleer *et al*., 1995].

1.1. Background

Preventable childhood diseases such as measles, polio and premature deaths still occur particularly in the developing countries due to low immunisation coverage [WHO, 1999]. According to WHO/UNICEF [2006], the global coverage for measles stands at 77 per cent, 28 million infants worldwide had not been vaccinated with DTP3 in 2005 with 75% of these belonging to developing countries. In a study to evaluate new tendencies and strategies in international immunisation, Martin and Marshall [2002] suggest that *"failure to immunize the world's children with life saving vaccines results in more than 3 million premature deaths annually"*. In resource constrained countries, despite numerous immunisation campaigns over media, health visits and improved health services, immunisation coverage are still low [WHO/UNICEF, 2006]. In Uganda, a nationwide survey showed that 46% of the children (12-23 months) had received all the recommended vaccines [UBOS, 2007].

Various approaches have been applied to understand immunisation coverage problems, however, there are still acknowledged deficiencies in these approaches and this has given rise to research efforts for alternative solutions including the need to adopt new technologies to address some of these problems. The immunisation system like many health care systems is very complex with many stakeholder (clients, doctors, nurses, managers, policy implementers) viewpoints that are difficult to manage. Due to increased pressure to reduce costs, increase efficiency and raise standards, health policy makers internationally have introduced a wide range of changes to healthcare in the quest for improved performance thus requiring System Dynamics techniques that have the ability to enhance the generation of knowledge in health services. Health care services like any other business involve a lot of transactions such as importation and delivery of medicines; construction of hospitals and clinics; hiring and deploying staff; processing and payments of staff salaries, purchase and delivery of food for patients; collecting and analyzing disease spread data, and educating the community [Wasukira et al., 2003]. Some of the issues that are faced by the health services include deficiencies in service delivery, growing gaps in facility and equipment upkeep, inequity of access to basic health services by the communities, inefficient allocation of scarce resources and lack of coordination among key stakeholders [Fraser and McGrath, 2000].

System Dynamics is highly applicable to the dynamic simulation of the immunisation system since it has a number of key attributes involving strong feedback loops thus requiring the systematic approach. Creation of a complex and sufficiently rich description of the immunisation system helps to analyze and study the dynamics associated with policy implementation in immunisation coverage.

1.2. Research Aim and Scope

The authors initiated this study with aim of understanding the immunisation health care problems, generate insights that may increase the immunisation coverage effectiveness, develop and simulate a healthcare policy design model by applying the System Dynamics (SD) modelling approach. This research covered the activities, strategies and policies associated with immunisation coverage. Modelling techniques as well key activities employed in health care modeling processes were investigated. Explorations of the relationships, dynamics and processes of the current immunisation system were done to establish how these factors influence insufficient demand and poor immunisation coverage. Vaccine management, health care service provision and the programme management at both national, district and village levels were examined. Specific in-depth investigations of the issues pertaining to immunisation demand were carried out in Mukono district.

2. RESEARCH METHODOLOGY

The study employed the Dynamic Synthesis Methodology (DSM) which combines two powerful research strategies; System Dynamics and case study research methods [Williams, 2000]. Combining simulation and case study methods as proposed by the Dynamic Synthesis Methodology is beneficial in that the strength of the case study enables the collection of data in its natural setting. Case study enables the collection of on-site information of the current system, owners and user requirements and specifications used to develop the generic model.

The System Dynamics methodology illuminates three principal effects which are systemic feedback loops, systemic delays and unintended consequences. The SD methodology is more suitable to solve the problems presented by the immunisation system as illustrated below:-

- Models benefit decision makers by identifying data that should be available but is not being collected.
- The immunisation system presents exogenous shocks (come from sources outside the system they affect) such as changes in demand for immunisation and the emergence of epidemics such as measles.
- The immunisation system contains feedback loops, communication paths and methods that impact behaviour such as the following illustration : immunisation knowledge enhances utilisation for immunisation services which in turn results in more knowledge.
- The immunisation system has systemic delays within its structure 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 especially to the rural communities as well as delays in uptake of immunisation.
- The different policy changes, feedback loops and behavioural changes in the immunisation system result in either/both intended and unintended consequences which can be well investigated using the SD methodology.

The vast problems faced by the nation's immunisation system policy can be interpreted in terms of the information, actions and consequences which the system dynamics view point presents. Figure 1 presents the research design framework used to conduct this research. This framework consists of six stages and was developed based on the Dynamic Synthesis Methodology by Williams [2000].

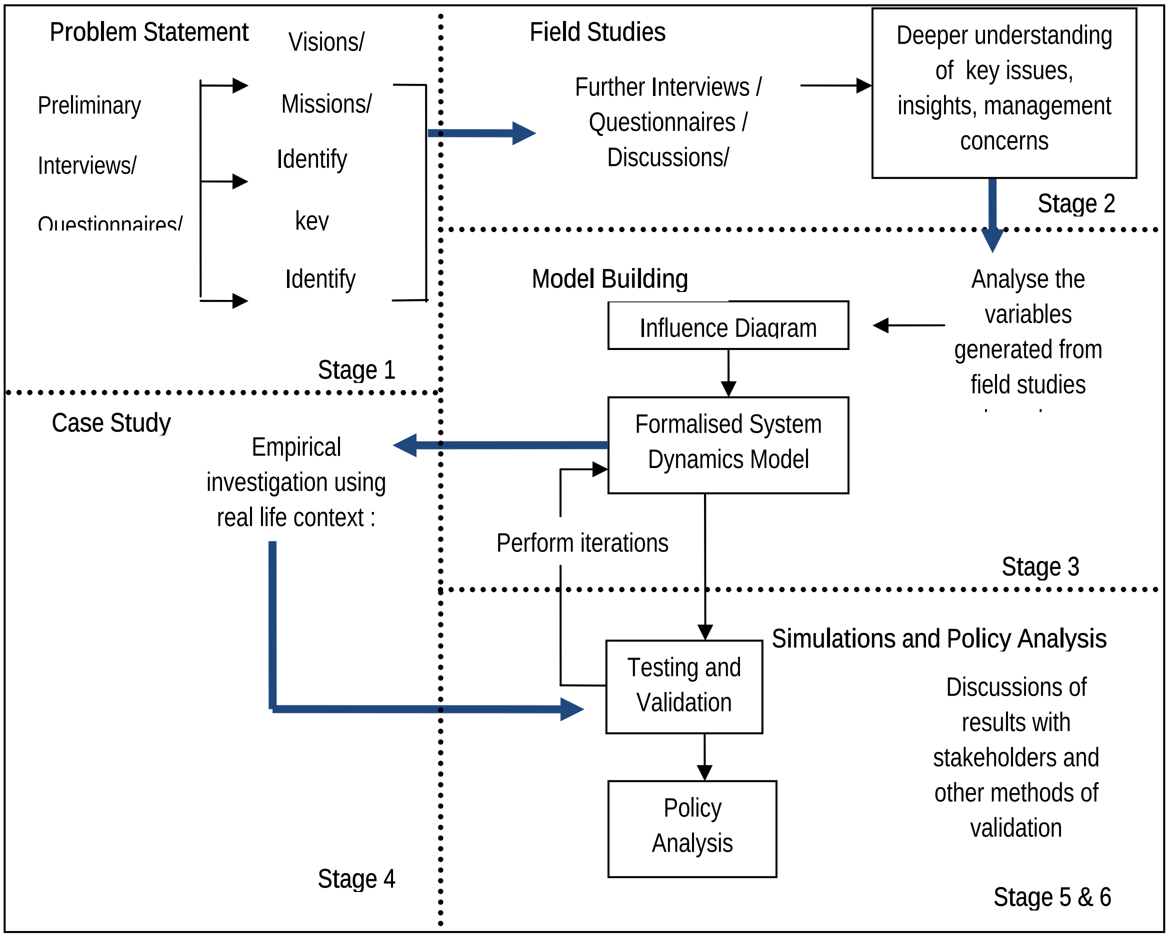

Fig. 1. The Research Design

In the first stage, preliminary interviews were done to identify problems and key stakeholders. Field studies were used to determine the full range of activities and challenges associated with immunisation coverage. Factors affecting immunisation coverage as well as national immunisation policies used for immunisation coverage were critically analysed. The model was built based on the field study results which provide a descriptive model on which the SD conceptual feedback structure is developed. The feedback structure model was developed with the help of Causal Loop Diagrams. Preliminary causal loop diagrams generated from the field studies were presented to various stakeholders for their comments and feedback on understanding of the immunisation coverage problems. Causal loop diagrams were converted to stock and flow diagrams which form a quantitative model of the problem in question. Mathematical relationships between and among variables which enable the simulation of the model were defined after which simulations of the key variables were run.

3. THE IMMUNISATION POLICY ANALYSIS MODEL

Immunisation coverage focuses on the supply and delivery of immunisation services, while immunisation demand is reflected through the parent's acceptance and the child's attendance according to the immunisation schedule. The immunisation simulation model was constructed so that it could be used to investigate deeper dynamic issues that are of concern to management and provide varying scenarios with different structures and policies. The immunisation model was built based on the analysed data that was collected through literature and field studies.

Demand is interplay of factors arising from the supply of immunisation services (healthcare factors) as well as population characteristics (socio-economic factors and background factors). The immunisation model was divided into the four sectors (population, immunisation demand, immunisation operations and vaccine stock management) and simulated over a 15-year period to evaluate potential policies development and debate in health care management.

3.1. The Population Sector

The population sector shows the dynamics that are involved in the various population categories (see Figure2). The population sector has a Population Ageing sub-model with four stocks which represent the four different age groups namely infants (below 1 year), children (above1to 14years), reproductive age group (15-49years) and adults above 50years. Infants (below1year) are particularly separated from the children because this is the age group that receives immunisation.

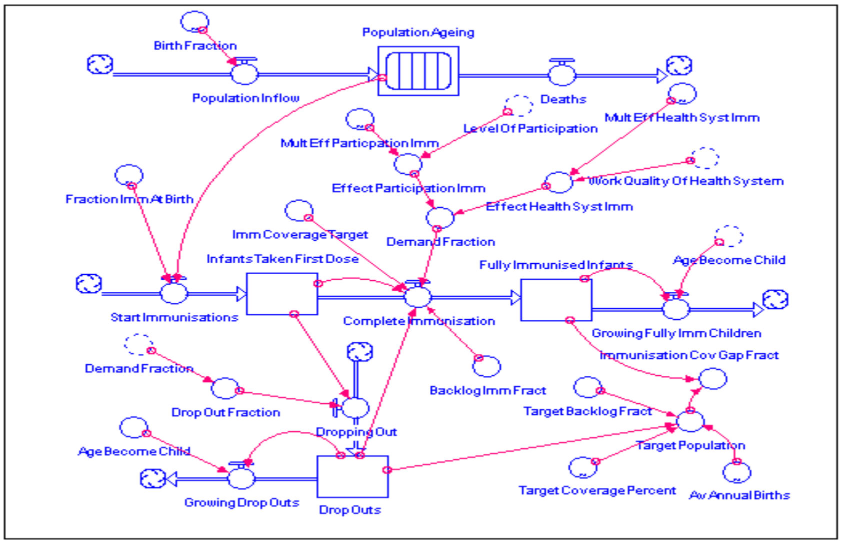

Fig. 2. The Population Sector

The population categories that are generated in this sector are *InfantsTakenFirstDose*(infants who have received the initial dose (at birth)), *FullyImmunisedInfants*(fully immunised infants who have completed the immunisation schedule by taking all the required doses) and *DropOuts* (infants who take initial doses but do not complete the immunisation schedule or take all the required doses of immunisation).

3.2. The Immunisation Demand Sector

The immunisation demand sector captures and models the dynamics that are associated with level of parents' participation in immunisation activities which affects the demand (see Figure 3). The output of the immunisation demand is the level of participation in immunisation activities and the key factors that were found to affect the level of participation are:

- Immunisation awareness which can be obtained through effective campaigns (media-radio, newspapers, films, television) coupled with high level of literacy provides knowledge concerning the importance of immunisation which increases the level of participation. Loss of immunisation awareness occurs after sometime and this can be accelerated by belief in myths.
- Accessibility to health facilities which makes it easier for the parents to take the children for immunisation without incurring extra costs.
- A high socio-economic status level increases the parents' availability thus enabling them to take off sometime and take the children for immunisation.
- Areas that have civil unrest reduce the parents' level of participation.
- Reminders sent to the parents of the immunisation schedule were found to tremendously increase the level of participation towards immunisation activities.

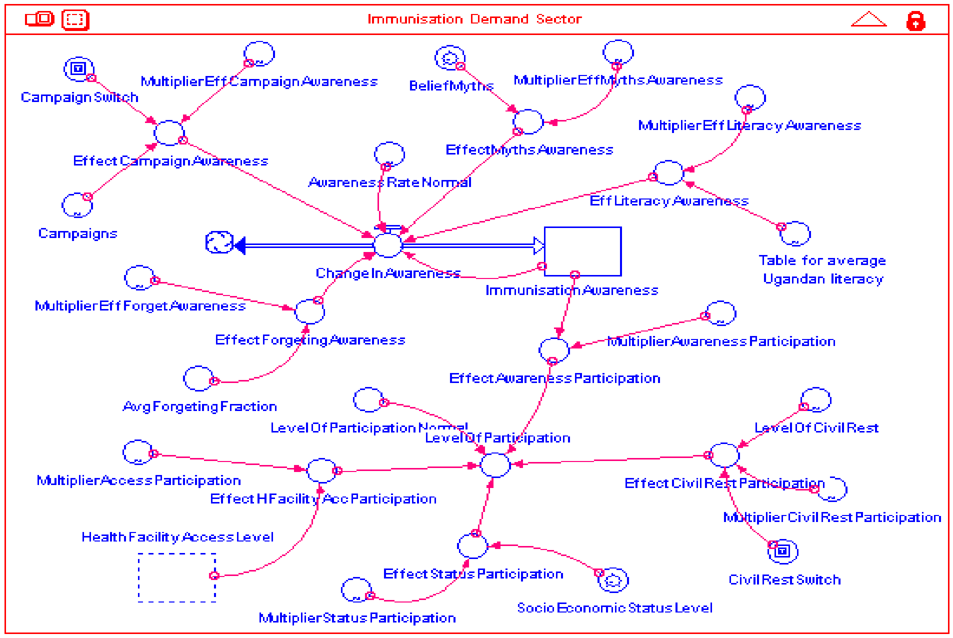

Fig. 3. The Immunisation Demand Sector

The above are soft variables which can not be quantified but are represented as level on scale ranging 0-1 with 1 as the highest level and 0 as the lowest level. The level of participation is an aggregate of the effects of awareness on participation (*EffectAwarenessParticipation*), civil rest (lack of civil wars) (*EffectCivilRestParticipation*)on participation, socio-economic status (*EffectStatusParticipation*), access to health facility (immunisation services) (*EffectHFacilityAccParticipation*). Each of these effects is derived by first assessing a multiplier effect for each of the variables. The multiplier effect are graph representations of the behaviour of the level of participation based on the changes of that variable.

3.3. The Immunisation Operations Sector

The effectiveness of health systems is vital to the immunisation coverage. The immunisation operations sector presents the dynamics involved in the provision of immunisation services (see Figure 4).

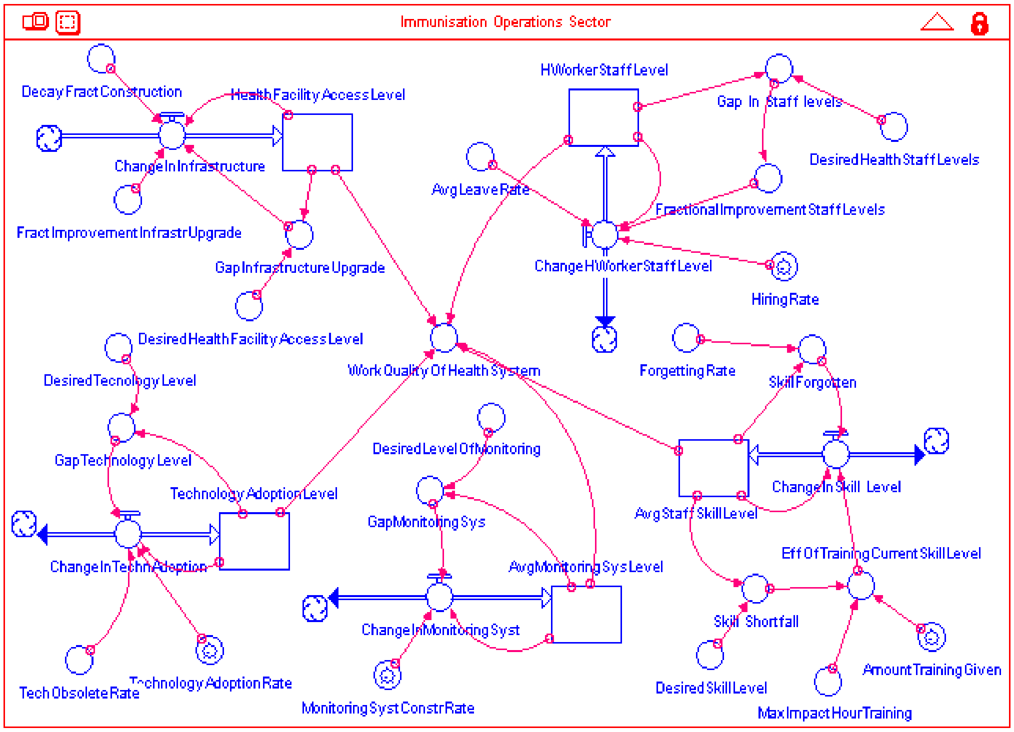

Fig.4. The Immunisation Operations Sector

Some of the key issues in the quality of health system include the following:

- Health facility infrastructure level (*HealthFacilityInfrustrLevel*) refers to the fraction of parishes that have hospitals, clinics or dispensaries where immunisation services are being provided. The construction of new health facilities is influenced by the gap between the actual quality of service and that which is desired.
- Health worker sta level (*HWorkerStaffLevel*) refers to the fraction of the number of health workers (nurses) involved in the government immunisation programme compared out of the required level.
- Health worker skill level (*AverageStaffSkill*) refers to the level of staff skill in the various health centres. Change in skill levels can be brought about through the amount of training provided coupled with the impact of the training. Increased skill levels provided efficiency in the health centres which improves the quality of service.
- Technology adoption levels (*TechnologyAdoptionLevel*) refers to the fraction of health centres that has adopted the use of technology in their operations. Change in technology adoption is influence by various factors which this model does not take care of.
- Level of monitoring systems (*LevelMonitoringSys*) refers to the levels of monitoring of immunisation activities. The level of monitoring systems in health centres and hospitals greatly a ects the quality of health system.

There are various factors such as payment of salaries and allowances for health workers which are left out of this model since these are done by the public service and not necessarily handled by the immunisation system.

3.4. Vaccine Management Sector

Vaccine management is the key to the success of immunisation programmes. There is need to monitor the management of vaccines as well as have them replenished regularly in order to prevent over and under stocking which may lead to expiry of vaccines and low coverage respectively. This sector represents the dynamics involved in the management of stocks with the aim of minimising wastage and avoiding stock out situations. Vaccine wastage is the proportion of vaccine supplied but not administered to the recipients (see Figure 5).

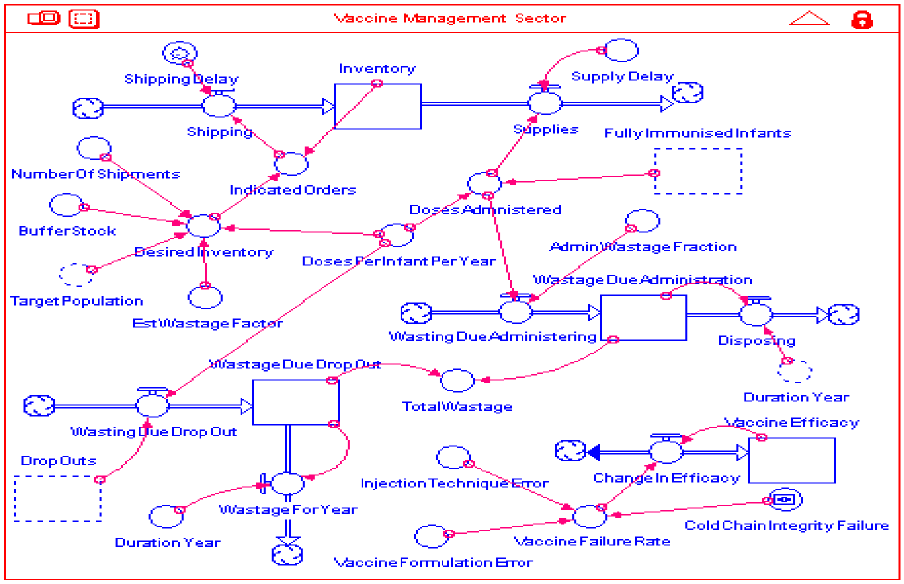

Fig.5. The Vaccine Management Sector

Barenzi *et al.*(2000) predicted the vaccine wastage rate for period 2000-2004 to be 60%. Factors associated with vaccine wastage are :-

- Administrative factors which arise during the delivery of vaccines. Vaccines are not fully utilised when being administered (e.g. only 16 or 17 doses are obtained from a 20 dose vial).
- Break down of cold chain management which reduces the potency of vaccines
- Stock management problems which result in expiry of vaccines resulting from short expiry dates provided by the manufacturers. Vaccines such as the measles vaccine with a shelf life of 5 months have to be distributed as soon as possible by following the Earliest Expiry First Out principle (EEFO).

Vaccines are administered to the infants to boost their immunity thus enabling them to have a higher survival probability even when they are infected. Vaccine e cacy is the strength of the vaccine and is vital in providing the immunity for a period of time. Change in vaccine e cacy is a ected by the vaccine failure rate (*VaccineFailureRate*) is an aggregate of the factors below which are quantified by considering levels of 0-1 :-

- Injection technique errors arising due to lack of skill in administering the injection.
- Cold chain integrity errors arising due to poor maintenance of cold chain from the manufacture to the end user.
- Vaccine formulation errors arising due to poor formulation of the vaccine while mixing it.

The model was populated with data from various census and health reports of Uganda from the year 2001-2007.

3.5. Reference to other model structures

This section highlights some of the models that were referred to during model development. Subramanyam and Sekhar [1987] in a vaccine optimal distribution system, used inputs based on population, growth rates, birth rates, infant mortality and calculated the target population based on the growth rate alone and does not take into account the drop outs who return for missed doses which this new model considers. The developed model uses vaccine failure rates resulting from vaccine formulation, cold chain integrity and injection techniques similar to those used by Tobias and Roberts [2000] in a prediction and prevention of Measles Epidemics model. The model developed by Maani and Stephenson [2000] highlights provider incentives, strategy fragmentation and parents' role as the key factors impacting immunisation rates. In the new developed model the key factors associated impacting immunisation rates are parents' role, quality of healthcare system, vaccine management, programme funding and social factors which a ect the community.

4. RESULTS AND DISCUSSION

Policy experiments refer to how a manager uses information about the system in the formulation and design of policies [Maani and Cavana, 2000]. With the help of screens the model is developed into a tool that can easily be used by policy makers of the immunisation system. This section provides snapshots of the output and a few scenarios of the model simulations.

4.1. Scenario 1 : Adjusting conditions of immunisation demand

This scenario allowed a user to adjust the conditions of the mother (level of immunisation awareness, socio-economic status and (health centre penetration) distance to the health centers under normal conditions of the healthcare system.

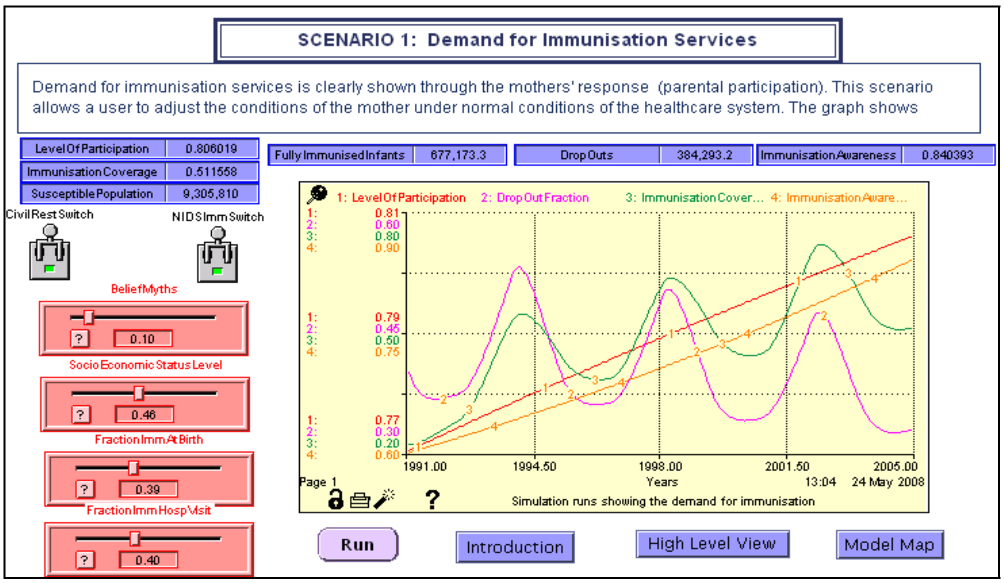

Fig. 6. Screen shot of the model

Figure 7 demonstrates the behavior of the model in the absence of campaigns. The immunisation coverage rates move gradually over time and do not reach high levels compared to Figure 6, where the rates rise close to 0.80, which implies that the absence of campaigns negatively affects awareness which affects participation in immunisation activities.

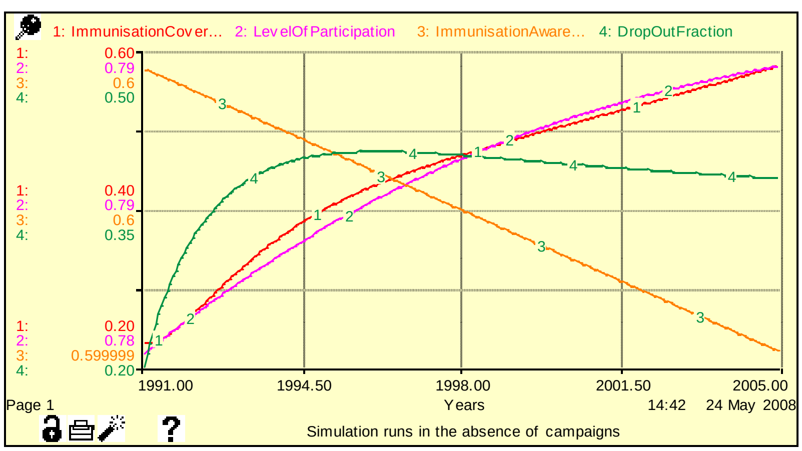

Fig. 7. Simulation Runs In The Absence Of Campaigns

Simulation runs showing the effect of Socio Economic Status of the people on immunisation response are presented in Table I.

Table I. Variation of Socio-Economic Status

	Variable	Normal rates	Increase by 0.1	Decrease by 0.1
Inputs	Socio Economic Status	0.46	0.56	0.36
Outputs	Immunisation coverage	0.518	0.523	0.511
	Level of participation	0.818	0.834	0.797
	Fully immunised infants	682,518	685,496	678,796
	Drop outs	370,006	354,968	388,784

Results of the simulation in demonstrate that an increase in socio-economic status of the mothers results in an increase in immunisation coverage rates, the level of participation in immunisation activities and the number of fully immunised infants while a decrease results in lowered rates. An increase in socio-economic status results in lowered drop out rates, while a decrease in socio economic status depicts an increase in drop out rates. Table II presents results of simulation runs in the presence of civil wars.

Table II. Effect Of Civil Wars on Immunisation Demand

Variable	Normal rates	Presence of civil wars
Immunisation coverage rate	0.518	0.49
Level of participation	0.818	0.75
Fully immunised infants	682,518	585,333
Drop outs	370,006	377,544

The presence of civil wars significantly lowers the immunisation coverage rates, the level of participation and the number of fully immunised infants thus increasing the drop outs as shown in Table II. This demonstrates that there should be peaceful environment that enhances parental participation in immunisation. Results of the simulation show that in order to increase the number of fully immunised infants as well as reduce the number of drop outs, the mothers should have immunisation awareness, good social economic status, absence of wars and have a health centre in the community.

4.2. Scenario 2: Adjusting conditions of healthcare service

This scenario allowed a user to adjust the conditions of the healthcare service (staff levels, skill levels, health facilities, stock availability) under normal conditions of the mothers conditions. Results of the simulation showed that in order to increase the number of fully immunised infants as well as reduce the number of drop outs, the quality of the healthcare service provision should be maintained at a high quality. The health workers should be motivated and each health centre should have a sufficient number to avoid overloading which lowers the motivation. Results of the simulation show that in order to increase the number of fully immunised infants, the healthcare services have to be improved and maintained bearing in mind the growing population.

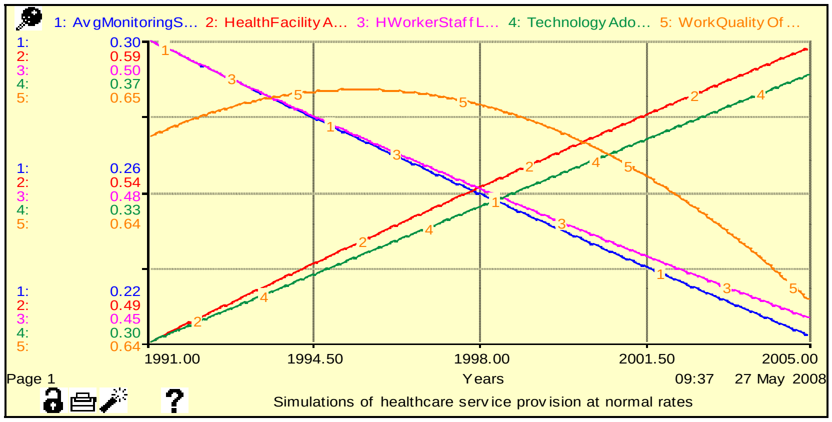

Fig. 8. Simulation Runs At The Normal Growth Rate In The Healthcare System

Figure 8 demonstrates a decline in the goal seeking behavior of the level of staff and level of monitoring systems which implies that the corrective action being taken is not sufficient to counteract the current trend. This contributes to the gradual decline in the work quality of the health service provision.

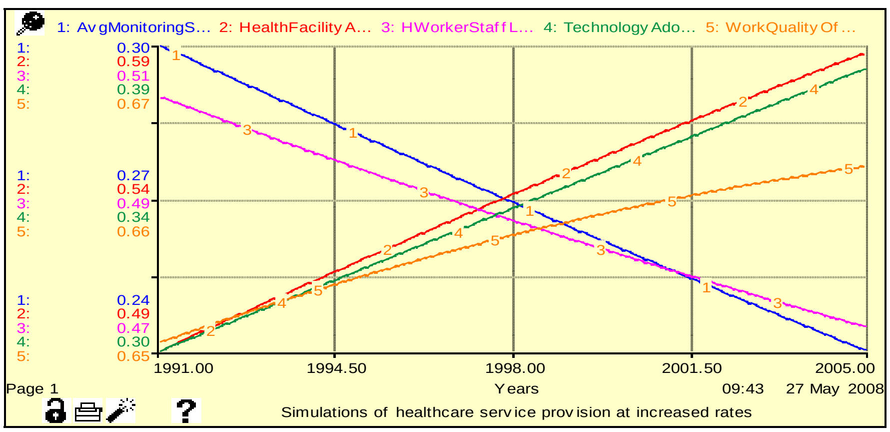

Fig. 9. Simulation Runs with Increase in the Healthcare System

Figure 9 demonstrates that the quality of health service must be increased to achieve greater coverage and more fully immunised infants. For example, an increase in the health service components (technology adoption rate, hiring rate, monitoring systems rate) increases the fully immunised infants by over 4,000.

A comparison between Figure 8 and 9 illustrates that when the healthcare system is not upgraded (hiring new health workers, building more hospitals, adoption of new technologies and increasing the skill level of health workers), the work quality of the health system deteriorates and immunisation coverage rates drop.

Results of the simulation in Figure 9 illustrate that in order to increase the number of fully immunised infants and as reduce the number of drop outs, the quality of health care service provision should be maintained at a high level. The number of health workers should be motivated and each health centre should have a sufficient number to avoid overloading which lowers the motivation.

Table III. Healthcare System Scenarios

	Variable	Normal growth rate	Decreased growth rate	Increased growth rate
Inputs	Technology adoption rate	0.05	0.04	0.06
	Hiring rate of health workers	0.02	0.01	0.03
	Monitoring systems growth rate	0.03	0.02	0.04
	Amount of training	0.08	0.07	0.09

Outputs	Work quality of health systems	0.643	0.640	0.657
	Immunisation coverage rates	0.464	0.463	0.470
	Fully Immunised infants	648,385	647,427	652,298
	Susceptible population	9,389,132	10,226,954	9,379,880

A comparison of Figure 8 and 9 shows when the healthcare system is not upgraded (hiring new health workers, building more hospitals, adoption of new technologies and increasing the skill level of health workers), the work quality of the health system deteriorates and immunisation coverage rates drop.

5. PROPOSED INTERVENTION STRATEGIES

Maani and Cavana define leverage points as actions or interventions that can have lasting impact on the system in terms of reversing a trend or breaking a vicious cycle. Leverage points can have substantial effect on the system by providing a fundamental and long term changes to the system as opposed to dealing with symptoms of the problems. This section highlights the key leverage points which could substantially improve immunisation demand, effectiveness of the health system, vaccine management as well as reduce immunisation costs. The proposed interventions include both short term and long term strategies as explained below:

1. *Level of participation*. The level of participation of mothers (caretakers) is key as far as immunisation coverage is concerned. The level of participation can be enhanced by considering short term and long term strategies. In the model (Figure 7), the absence of campaigns, the level of immunisation awareness declines which eventually results in lowered levels of participation in immunisation activities after some delay. This demonstrates the long term effect such a policy decision would have. Table II also demonstrates that the presence of wars in a region would tremendously impact the level of participation which is reflected by the fully immunised infants and the infants dropping out of immunisation. Some of the short term strategies include continued immunisation campaigns, increasing accessibility to health care services through the use of mobile clinics as demonstrated in Figure 9 and Table III. Some of the long term strategies include increasing the literacy levels, improving the livelihood of the people by lowering the poverty level (Table I) and minimising civil wars in the communities (Table II).
2. *Upgrade of immunisation healthcare system*. The model shows that the current level of access of healthcare services is not sufficient to meet the growing population. The level of accessibility of healthcare services currently at 49% should be increased. The nurse to patient ratio at 1: 3,065 should be increased to meet the required standard of 1:125 nurse to patient ratio (Musoke *et al*., 2006). The level of monitoring of health services should be increased through the adoption of technologies to improve the quality of immunisation services. The model reveals that there is need to increase the hiring rate of the healthcare staff as well as address issues pertaining to the rate of attrition which results in a decline in the staff levels (Table III and Figure 9). The model reveals that access to health services would improve participation in immunisation activity. The model demonstrates that an increase in infrastructure upgrade would increase immunisation coverage.
3. *Design of relevant health information systems*. The research suggests that in order to have well suited immunisation community based health initiative in developing countries, there is need to develop community health monitoring information systems that have procedures that track individuals by recording events and needs as services are extended to the communities (Rwashana and Williams, 2007). The success of a health information system depends on whether it meets the requirements of the stakeholders, which necessitates a deeper understanding of the organisational environment such as the one provided by the System Dynamics. A broad integrated view of the immunisation system provides an analysis of the complex interactions between behavioural, technical, policy and cultural issues which fosters communication among the stakeholders by linking up the non-technical view and technical view of the designers and programmers of information systems there by capturing the requisite information.
4. *Management of resources*. The immunisation system uses various resources to provide services to the communities. There is need to develop automated resource ordering and tracking systems in order to minimise stock out situations as well as overstocking which may lead to losses due to expiry of drugs.

6. CONCLUSION

The model focuses on the dynamic aspects that may be potentially within control by the stakeholders involved in the immunisation process. The model helps to generate insight to policy development as far as immunisation and healthcare is concerned and generates deeper insight of the issues that are associated with immunisation coverage. The research demonstrates the benefits of using systems thinking methods in facilitating the understanding of healthcare system.

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