Modeling the Dynamics of Immunization Healthcare Systems: The Ugandan Case Study

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Due to low immunization coverage, epidemics such as measles still occur in many countries in the world. 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 efforts for alternative solutions. To better understand immunization health care problems and to generate insights that may increase the immunization coverage effectiveness, the paper applies system dynamics modeling and field study research methods. Causal loop diagram representing the immunization system is presented out of which a model is designed with the intent to show how particular variables influence immunization demand and coverage. The paper builds on earlier papers by the same authors. Model analysis demonstrates the need to upgrade the health system in proportion to the growing population, and how this can lead to improved immunization coverage rates. The paper suggests key leverage points which could substantially improve immunization demand and the effectiveness of the health system as well as vaccine management.

***Key words and phrases**: Immunization coverage, Immunization utilization, System Dynamics, Simulation modeling in healthcare*

1. Introduction

Simulation models provide quantitative information that forms the basis for 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).

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. Although system dynamics models in health systems have been developed for almost 40 years, research has not been widely applied at the regional and national health systems level where integrated policies can be effectively modeled for dramatic health system improvements (Koelling and Schwandt, 2005). Although there are already other studies in the wider area of immunization coverage (Edmunds *et al.*, 2002; Grenfell and Anderson, 1989; Hethcote, 1997; Rohani *et al*., 1999; Subramanyam and Sekhar, 1987), System Dynamics based simulation modeling has not been widely applied to immunization coverage investigation.

1.1 Background

The World Health organisation has targeted measles for eradication in several regions of the world by the year 2010, but despite an effective vaccine there is still estimated to be 30-40 million measles cases and 800,000 deaths per year (WHO, 2002;1999).
Various approaches have been applied to understand immunization coverage problems, however, there are acknowledged deficiencies in these approaches. This is clearly demonstrated in resource constrained countries, where despite numerous immunization campaigns over media, health visits and improved health services are still low (WHO/UNICEF ,2006). 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. For example the coverage rate in Uganda is generally still low (less than 60%)(WHO, 2001). Despite a significant level of access to immunization services as reflected by DPT1 coverage, the drop out rate 27% (DPT1 -DPT3) in more than 70% of the districts is still very high (WHO, 2001). Due to low coverage, epidemics such as measles still occur in many countries in the world.

Recent literature on immunization coverage problem (Edmunds *et al.,*2002; Grenfell and Anderson, 1989; Rohani *et al.,*1999; Subramanyam and Sekhar, 1987), states that there are fluctuations in demand for immunization, vaccine supply and immunization coverage coupled with inherent delays between successive vaccine stock distributions. Exploring the effects of these fluctuations from a feed back viewpoint may shed light on the real cases of problems of immunization coverage.

System Dynamics is highly applicable to the dynamic simulation of the immunization 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 immunization system helps to analyze and study the dynamics associated with policy implementation in immunization coverage.

1.2 Research Aims and Scope

The authors initiated this study with aim of understanding the immunization health care problems, generate insights that may increase the immunization 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 immunization 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 immunization system were done to establish how these factors influence insufficient demand and poor immunization 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 immunization demand were carried out in Mukono district.

2. Research Methodology

The study employed the Dynamic Synthesis Methodology (DSM) proposed by Williams (2000). DSM uses a research design that combines two powerful research strategies namely: the qualitative (case study research method) (Galliers, 1984; Mason and Mitroff, 1973; Yin, 1984) and quantitative (System Dynamics Modelling)(Forrester, 1961; Richard-son and Pugh, 1981; Sterman, 2000)) techniques to provide solutions to problems. 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 vast problems faced by the nation's immunization system policy can be interpreted in terms of the information, actions and consequences which the system dynamics view point presents. The research design undertaken is shown in Figure 1 below :

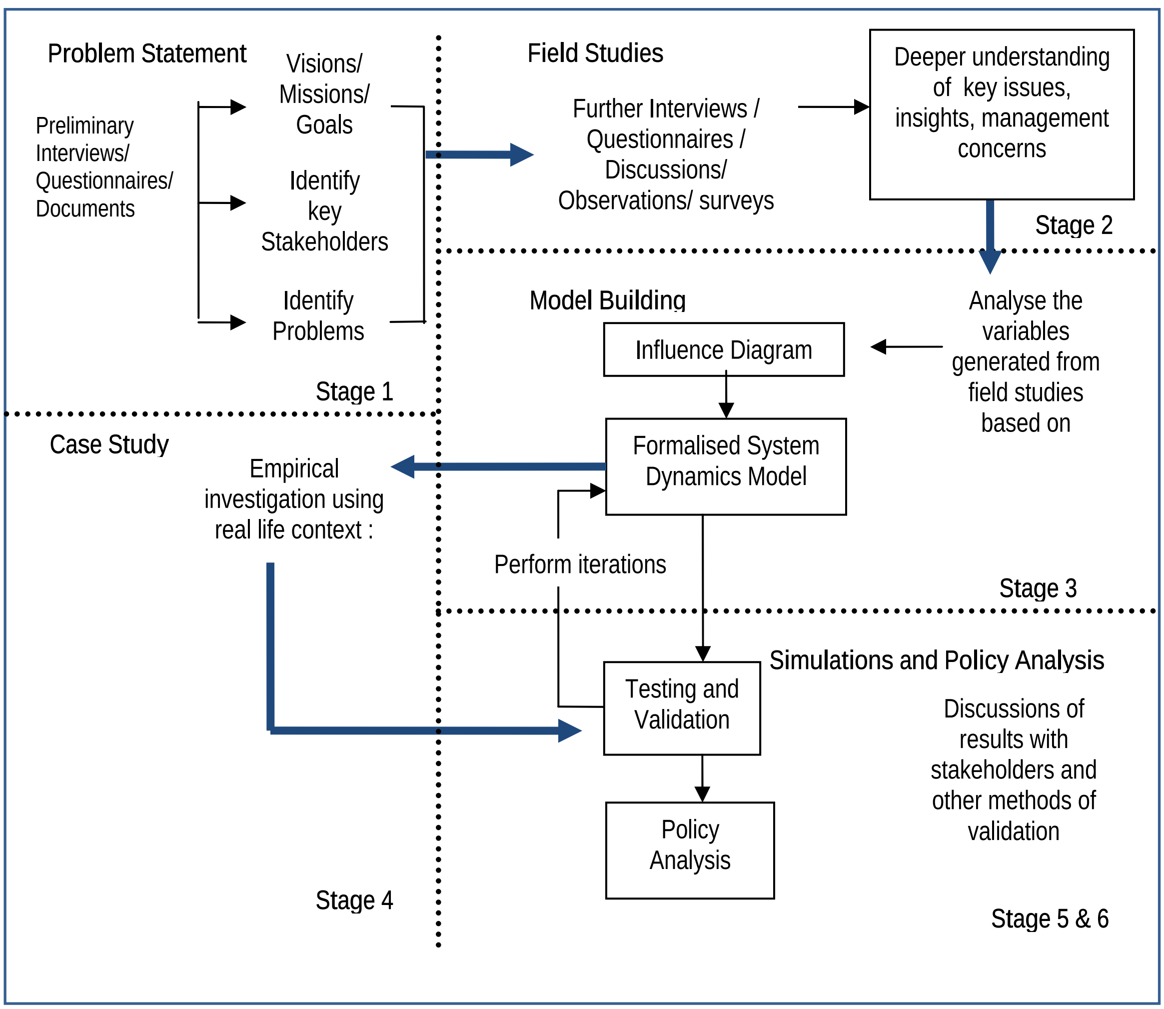

Figure 1. The Research Design

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 immunization coverage. Factors affecting immunization coverage as well as national immunization policies used for immunization 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 data collected from the field studies were presented to various stakeholders for their comments and feedback from which a final causal loop diagram was developed (refer to Figure 2).

3. The Causal Loop Diagram

Figure 2 presents the causal loop diagram of the immunization system. Figure 2 presents five balancing loops and one reinforcing loop. *Loop B1 (Resource Decline loop)* shows that as the actual number of infants being immunized increases, the health service delivery declines in terms of resources, thus presenting a need for improved services. An increase in the level of service delivery on the other hand is likely to increase the number of infants being immunized. Loop B2 *(Funding loop)* seeks to minimize the gap between the number of children targeted to be immunized and the actual number of children that are immunized through increased programme funding and upgrade of health service delivery. *Loop B3 (Immunization awareness loop)* seeks to increase immunization awareness through effective mobilization which in turn results in increased attendance of immunization thus narrowing the gap between the target and actual number of children immunized.

Loop B4 (Epidemic control loop) seeks to control the occurrence of epidemics through health service provision and attendance of immunization sessions to reduce infections. An occurrence of epidemics, however, results in the need for more programme funding. *Loop B5 (Trust in health system loop)* represents the dynamics involved in the parents' level of trust in the health system. With increased service delivery, more parents are likely to participate in immunization activities which depletes the health service thus reducing their trust in the system. *Loop R1 (Awareness-Participation loop)* represents a growing action that arises as mothers attend immunization sessions. An increase in attendance results in increased immunization awareness which in turn contributes to increase in attendance.

Figure 2 shows that the key factors that lead to increase immunization and utilization (the number of children immunized), are the level of parent participation and health service delivery. The level of parent participation is associated with the following key variables: level of immunization awareness, accessibility to health centres, socio-economic status (poverty level), trust in the health system and level of civil rest in the community. The key factors associated with the level of health service include: effectiveness of monitoring immunization systems, levels of health worker motivation (skills and workload), availability of quality vaccines (cold chain management, transport and management of orders) and technology adoption and infrastructure upgrade.

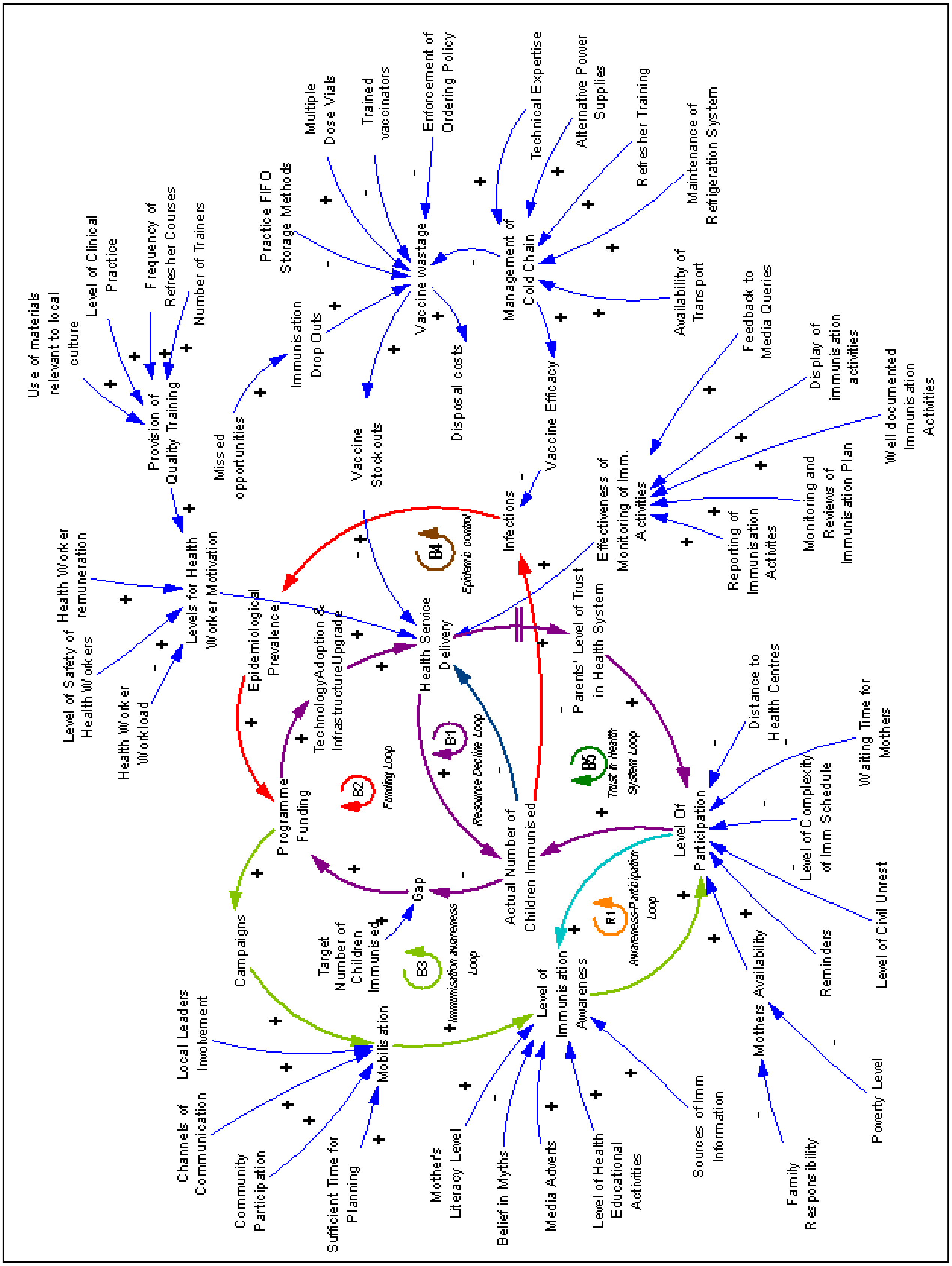

Figure 2. Causal Loop Diagram for the Immunization System

The key factors presented in Figure 2 were translated into stock and flow diagrams using STELLA modeling software to make the immunization model.

4. The Model

Immunization coverage focuses on the supply and delivery of immunization services, while immunization demand is reflected through the parent's acceptance and the child's attendance according to the immunization schedule. The model was designed with a clear purpose to aid the decision making process by proposing policies that would enhance immunization utilisation. The immunization model was built based on the analysed data that was collected through literature and field studies.

4.1 Reference to other model structures

Some parts of the model (relationships) such as the epidemic sector and the population sub-model are based on common existing models. 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 immunization rates.

4.2 The Model Sectors

The immunization model was divided into the five sectors (population, immunization demand, immunization operations, vaccine stock management and epidemics) and simulated over a 15-year period. The variables that appear in italics are model variable names.

4.2.1 The Population Sector

The population sector shows the dynamics that are involved in the various population categories. 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 14 years), reproductive age group (15-49 years) and adults above 50 years. Infants (below 1 year) are particularly separated from the children because this is the age group that receives immunization. The population categories that are generated in this sector are infants who have received the initial dose (*InfantsTakenFirstDose)*, fully immunized infants who have completed the immunization schedule by taking all the required doses *(FullyImmunizedInfants*) and infants who take initial doses but do not complete the immunization schedule (*DropOuts)* (refer to Figure 3) .

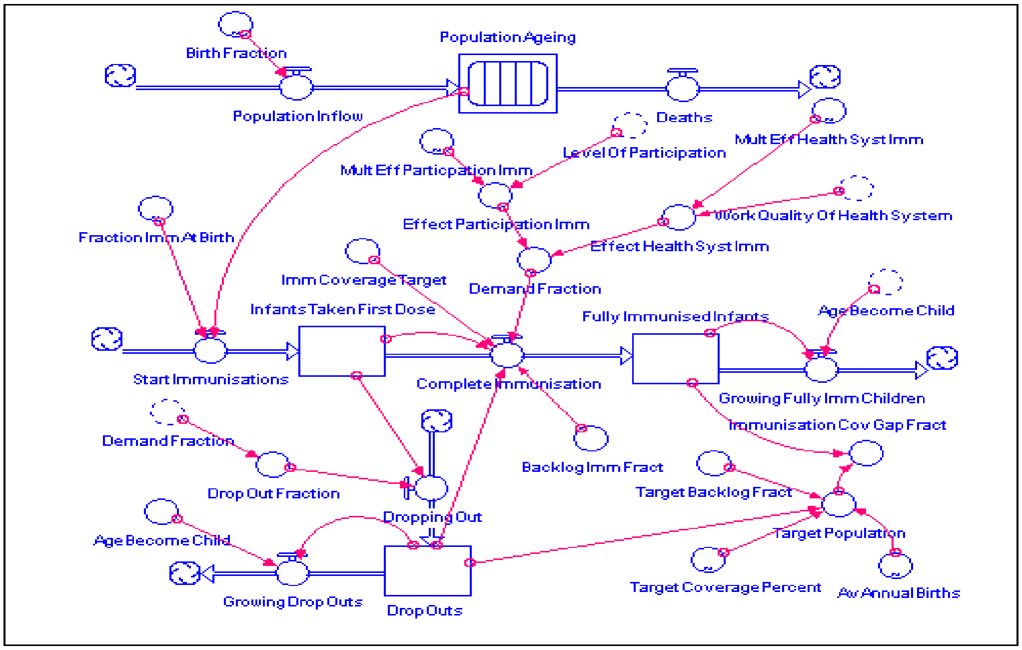

Figure 3. The Population Sector

4.2.2 The Immunization Demand Sector

The immunization demand sector captures and models the dynamics that are associated with level of parents' participation in immunization activities which affects the demand (refer to Figure 4). The output of the immunization demand is the level of participation in immunization activities and the key factors that were found to affect the level of participation are:

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

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*) and access to health facility (immunization 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.

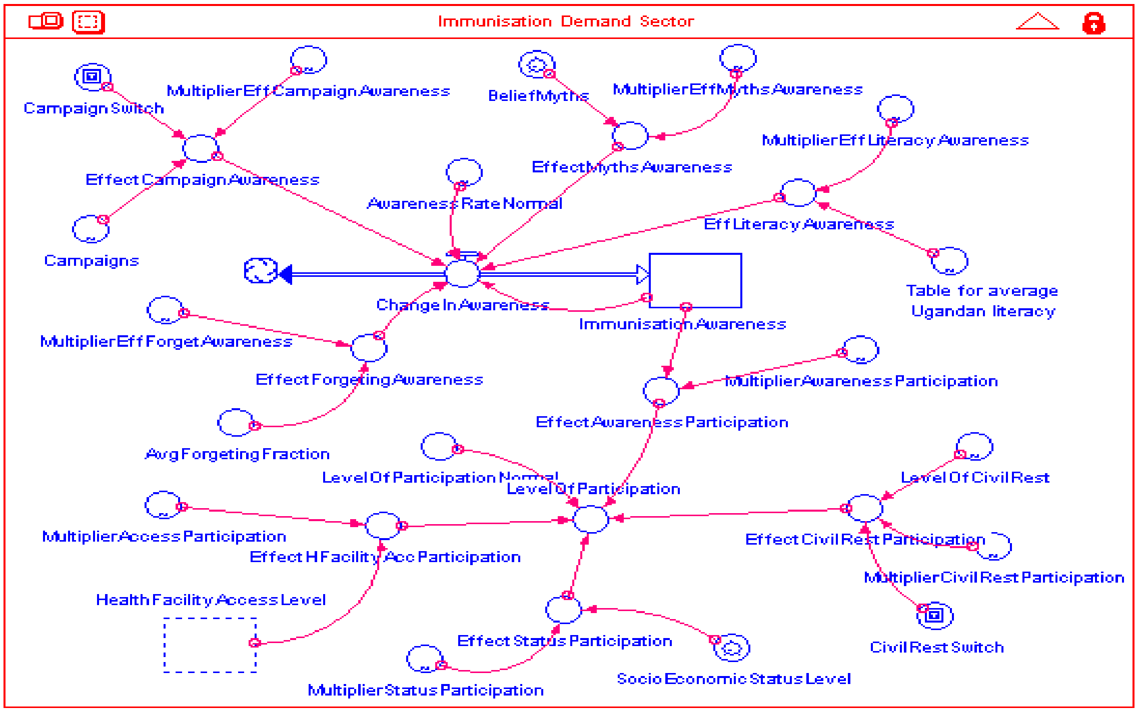

Figure 4. The Immunization Demand Sector

4.2.3 The Immunization Operations Sector

The effectiveness of health systems is vital to the immunization coverage. The immunization operations sector presents the dynamics involved in the provision of immunization services (refer to Figure 5). 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 immunization 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 staff level (*HWorkerStaffLevel*) refers to the fraction of the number of health workers (nurses) involved in the government immunization 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 immunization activities. The level of monitoring systems in health centres and hospitals greatly affects the quality of health system.

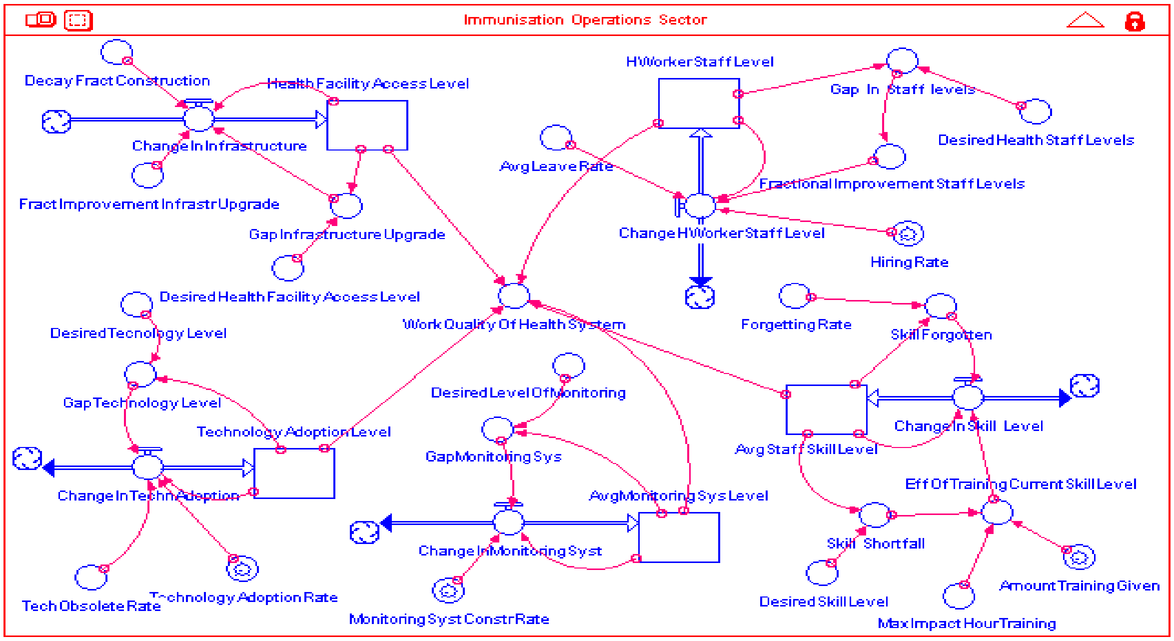

Figure 5. The Immunization Operations Sector

4.2.4 Vaccine Management Sector

Vaccine management is the key to the success of immunization 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 (refer to Figure 6).

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).

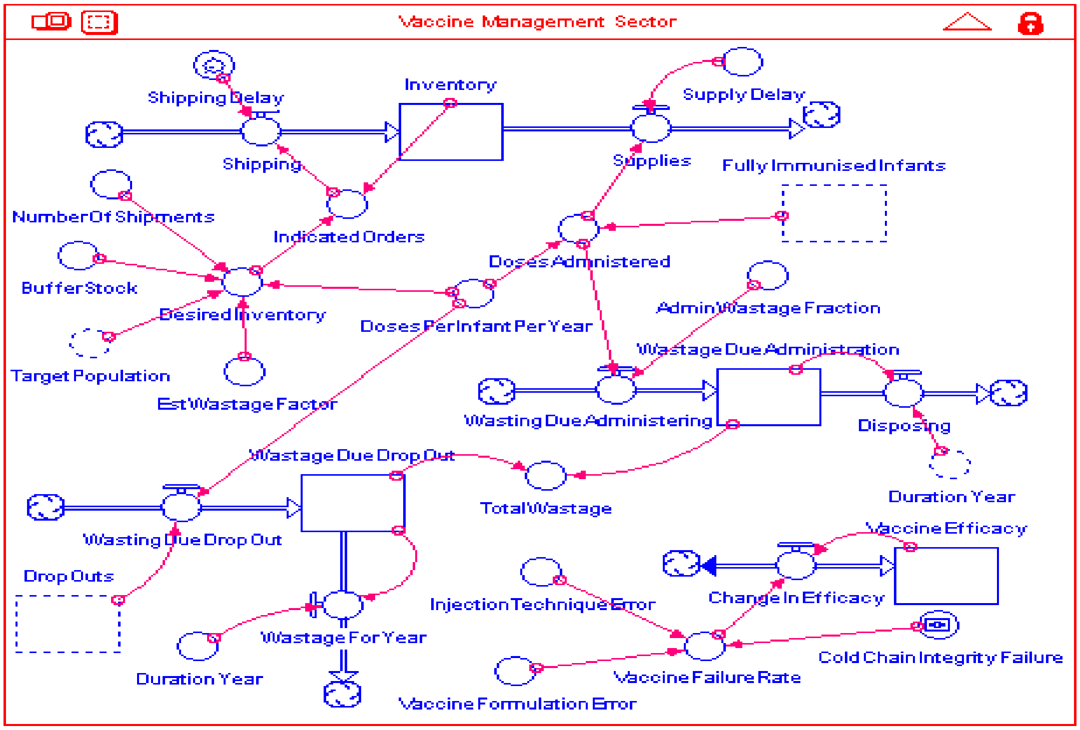

Figure 6. Vaccine Management Sector

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 efficacy is the strength of the vaccine and is vital in providing the immunity for a period of time. Change in vaccine efficacy is affected by the vaccine failure rate *(VaccineFailureRate*) is an aggregate of the factors below which are quantified by considering levels of 0-1:-

a. Injection technique error (*InjectionTechniqueError*)-errors arising out of lack of skill in administering the injection.
b. Cold chain integrity error (*ColdChainIntegrityFailure*)-errors arising out of poor maintenance of cold chain from the manufacture to the end user.
c. Vaccine formulation error (*VaccineFormulationError*)-errors arising out of poor formulation of the vaccine while mixing it.

4.2.5 Epidemics Sector

This sector represents the dynamics involved in the event of an epidemic (refer to Figure 7). Some parts of this sector are based on existing models by Sterman (2000). Unlike Sterman's model, this model incorporates the aspect of immunization. The sector presents the population into five stocks: susceptible population (*SusceptiblePopulation*), infected population (*InfectedPopulation*), sick population (*SickPopulation*), the recovered population (*RecoveredPopulation*) and the deaths resulting from the epidemic (*DeathsDueEpidemic*). When the infected population comes into contact with those who are susceptible, the infected population increases while the susceptible population decreases. The infectivity rate (*InfectivityRate*) is the probability that a person becomes infected after being in contact with an infectious person. The contact rate (*ContactRate*) is the rate at which people in the community are contacted per person per unit time.

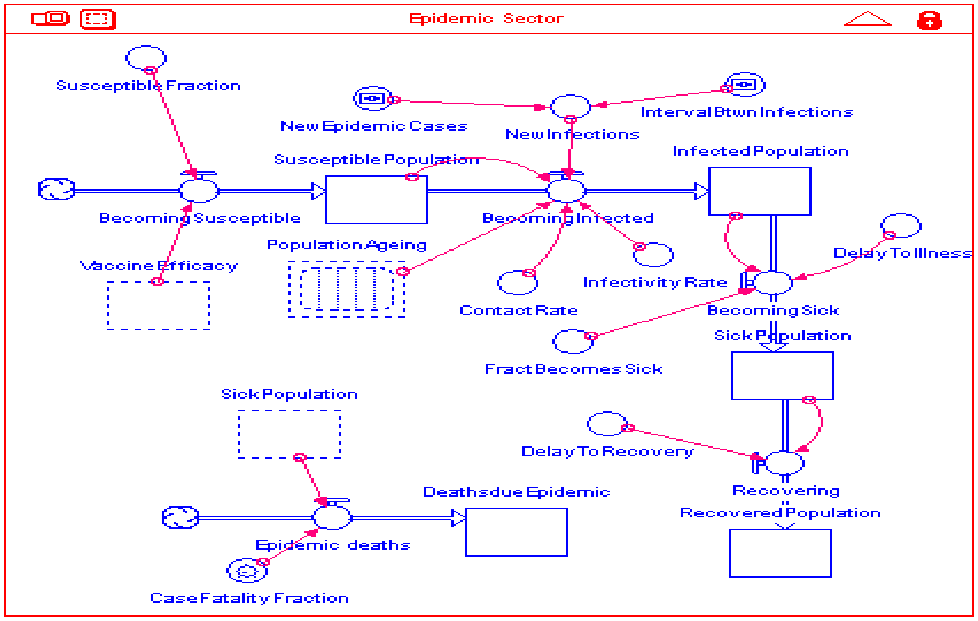

Figure 7: Epidemics Sector

The probability that a randomly selected encounter is an encounter with an infected individual is defined by this formula (*InfectedPopulation/Population*). Only a fraction of those who have been exposed to the virus get infected. The initial value of the susceptible population is calculated by considering the immunized and unimmunized population. The new population that is becoming susceptible is based on the new births less the infants who are fully immunized. The efficacy of the vaccine (power to produce desired effect) is not 100%. Immunization with the vaccine is only effective to a certain extent (90%) implying that out of those who are immunized, 10% are still likely to get infected.

When susceptibles get the virus, they become exposed (infected but not infectious) Anderson and Mary (1982). After the latent period, the exposed become infectious and can infect new susceptibles until they recover. Those that recover do not become susceptible once again. The infected population in increased by the population that is being infected and decreased by the population that becomes sick. The contact rate is the number of contacts with another person per unit time. The contact rate varies throughout the year and depends on one's environment.

The model was populated with data from various census and health reports of Uganda from the year 1991-2006.

5 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 was developed into a tool that could easily be used by policy makers of the immunization system. This section provides snapshots of the output and a few scenarios of the model simulations. Figure 8 presents the first screen shot of the model which contains buttons that lead to the model scenarios and screens.

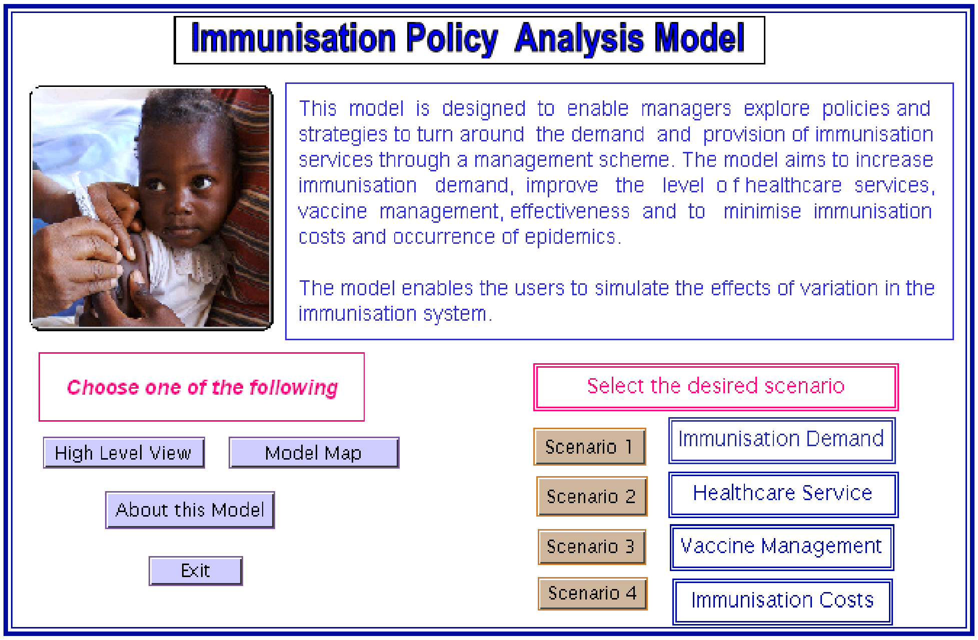

Figure 8. Screen shot of the model

5.1 Scenario 1: Adjusting conditions of immunization demand

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

Figure 9 shows the behaviour of key variables (immunization coverage, drop out fraction , level of participation and immunization awareness) under the normal rates. Simulation runs presented in Figure 9 show the behaviour of the level of participation in immunization activities, drop out fraction, immunization coverage and level of immunization awareness. Immunization coverage rates overshoot the targets for coverage and then undershoot. This kind of behavior arises from the presence of significant time delays (Sterman, 2000). Time delays cause corrective actions continue to act on the system after the targets for coverage have been reached. Delays in the system may result from delayed perceptions by management of the decreasing rates and the time it takes to initiate corrective actions such as campaigns. The drop out fraction, on the other hand demonstrates oscillating behavior with a downward trend. As immunization coverage improves, the drop outs reduce accordingly. The level of parental participation and immunization awareness demonstrates a linearly increasing behavior resulting from immunization campaigns and advertisement.

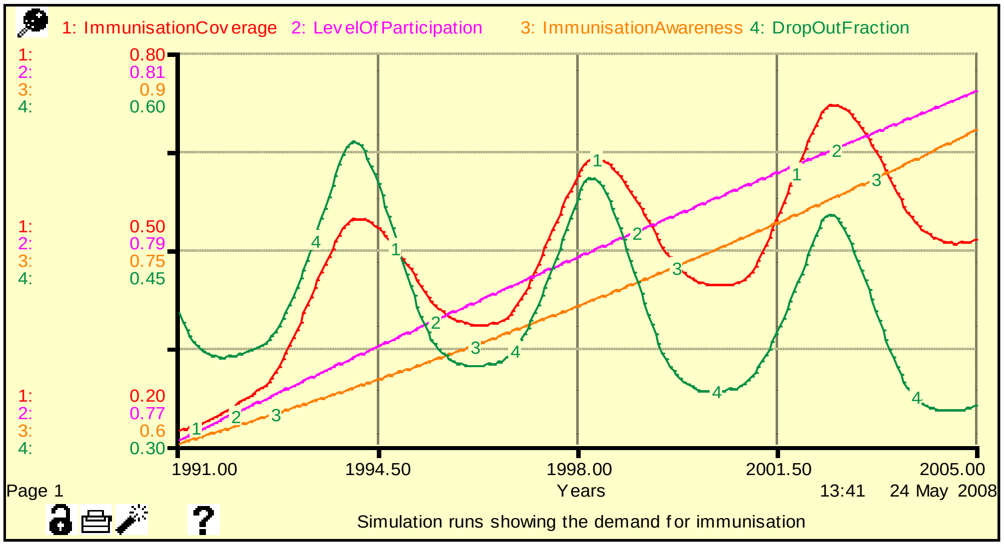

Figure 9. Simulation runs showing immunization demand under normal rates

Simulation runs showing the effect of Socio Economic Status of the people on immunization response are presented in Table 1. Results of the simulation in Table 1 demonstrate that an increase in socio-economic status of the mothers results in an increase in immunization coverage rates, the level of participation in immunization activities and the number of fully immunized 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 1. 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	Immunization coverage	0.518	0.523	0.511
	Level of participation	0.818	0.834	0.797
	Fully immunized infants	682,518	685,496	678,796
	Drop outs	370,006	354,968	388,784

Figure 10 demonstrates the behavior of the model in the absence of campaigns. The immunization coverage rates move gradually over time and do not reach high levels compared to Figure 9, where the rates rise close to 0.80, which implies that the absence of campaigns negatively affects awareness which affects participation in immunization activities.

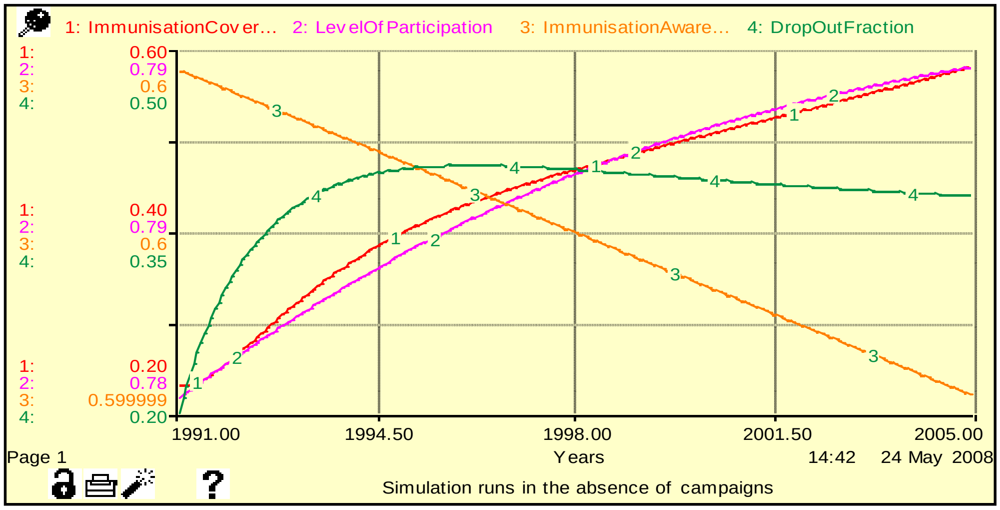

Figure 10. Simulation runs in the absence of campaigns

Table 2 and Figure 11 present results of simulation runs in the presence of civil wars.

Table 2. Effect of Civil Wars on Immunization Demand

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

The presence of civil wars significantly lowers the immunization coverage rates, the level of participation and the number of fully immunized infants thus increasing the drop outs as shown in Figure 11 and Table 2. This demonstrates that there should be peaceful environment that enhances parental participation in immunization.

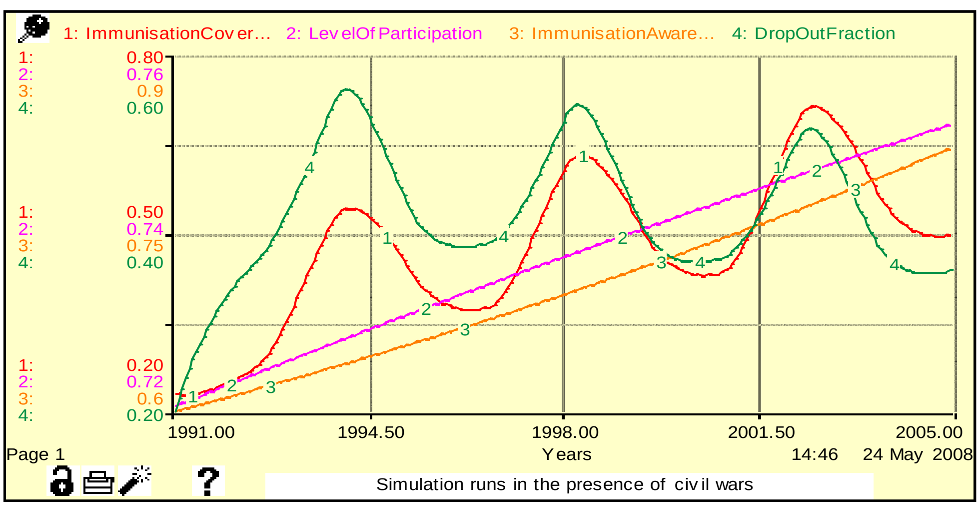

Figure 11. Simulation runs in the presence of wars

According to this model, increase in demand for immunization is demonstrated through the level of participation to immunization activities, immunization coverage rates and drop out rates. Results of the simulation showed that in order to increase the number of fully immunized infants as well as reduce the number of drop outs, the mothers should have immunization awareness, high social economic status, absence of wars and have a health centre in the community. This implies that there is need to intensify efforts towards increasing parental participation by improving the livelihood of the population, providing a free war environment, and increasing immunization awareness (literacy levels and campaigns).

5.2. Scenario: Adjusting conditions of healthcare service

Figure 12 provides a screen that enables a user to adjust the conditions of the healthcare service (staff levels, skill levels, health facilities, stock availability, and health centre penetration) under normal conditions of the mother.

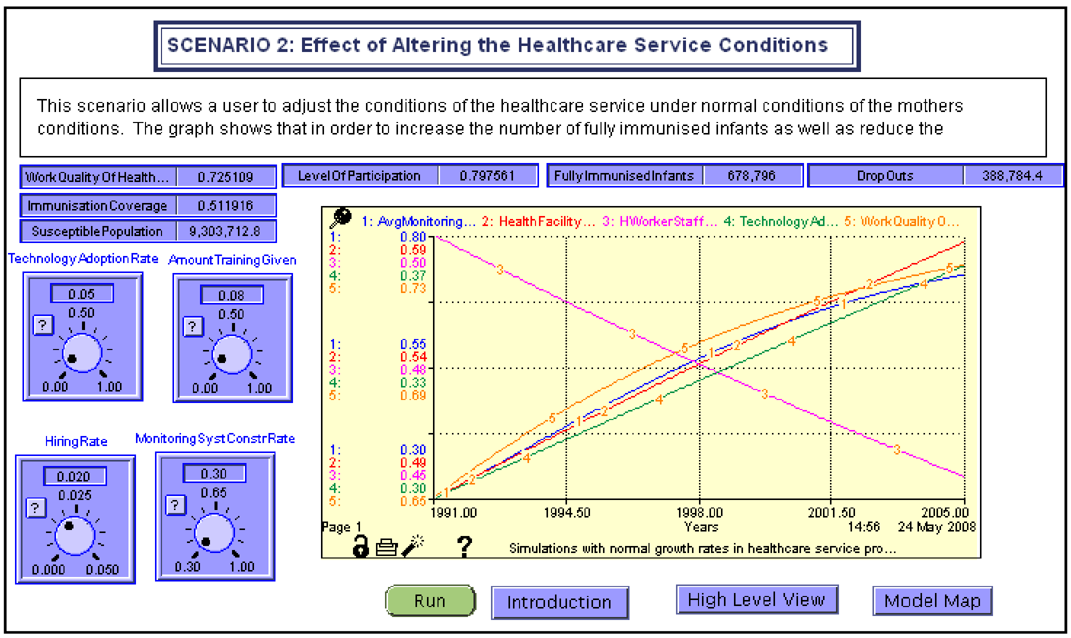

Figure 12. Screen showing the level of Healthcare Service Provision

Results from Figure 12 demonstrate that there has been progressive improvement in some of the key variables of the healthcare service provision namely: level of technology adoption, amount of training and upgrade of infrastructure upgrade. The healthcare system exhibits goal seeking behavior where the current level of health service provision is compared with the desired level. Corrective action such as building more health centres, adoption of new technologies and recruitment of health workers is taken to reach the desired goal. This however is not easily attainable due to financial constraints. An increase in the level of service provision results increases the number of infants being immunized which lowers the population susceptible to disease.

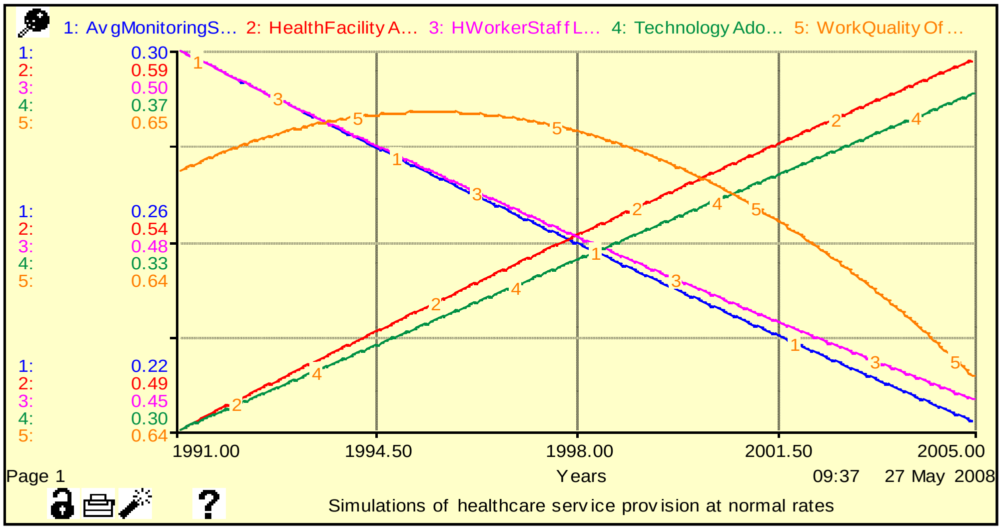

Figure 13: Simulation runs at the Normal Growth Rate in the Healthcare Service Provision

On the other hand, Figure 13 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. Mothers' response which is demonstrated by the respondents' response

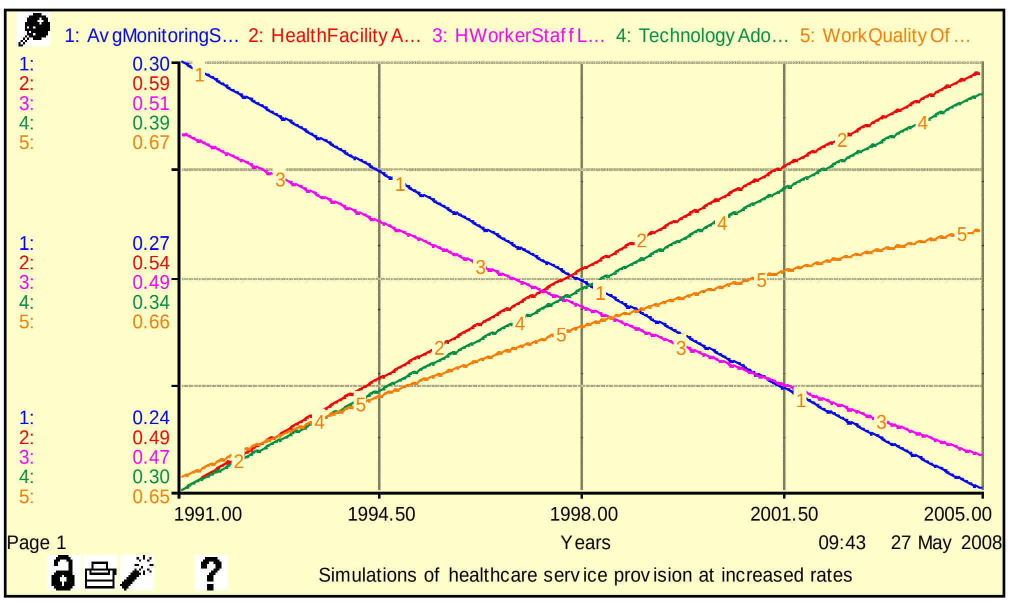

Figure 14: Simulation runs with increase in Healthcare Service Provision

Figure 14 demonstrates that the quality of health service must be increased to achieve greater coverage and more fully immunized infants. For example, an increase in the health service components (technology adoption rate, hiring rate, monitoring systems rate) increases the fully immunized infants by over 4,000.

A comparison between Figures 13 and 14 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 immunization coverage rates drop.

6 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 immunization demand, effectiveness of the health system, vaccine management as well as reduce immunization 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 immunization coverage is concerned. The level of participation can be enhanced by considering short term and long term strategies. Some of the short term strategies include continued immunization campaigns, increasing accessibility to health care services through the use of mobile clinics. Some of the long term strategies include increasing the literacy levels, improving the livelihood of the people (lowering poverty levels) and minimising civil wars in the communities.

2. *Upgrade of immunization 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 currently 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 immunization services.

3. *Design of relevant health information systems*. The research suggests that in order to have well suited immunization 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, 2007a). 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 immunization 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 immunization 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.

7 Conclusion

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

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