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Simulation tools for developing policies for complex systems: Modeling the health and safety of refugee communities

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Abstract The U.S. Committee for Refugees and Immigrants estimated that there were over 33 million refugees and internally displaced persons (IDPs) in the world at the beginning of 2005. IDP/Refugee communities behave in complex ways making it difficult to make policy decisions regarding the provision of humanitarian aid and health and safety. This paper reports the construction of an agent-based model that has been used to study humanitarian assistance policies executed by governments and NGOs that provide for the health and safety of refugee communities. Agent-based modeling (ABM) was chosen because the more widely used alternatives impose unrealistic restrictions and assumptions on the system being modeled and primarily apply to aggregate data. We created intelligent agents representing institutions, organizations, individuals, infrastructure, and governments and analyzed the resulting interactions and emergent behavior using a Central Composite Design of Experiments with five factors. The resulting model allows policy makers and analysts to create scenarios, to make rapid changes in parameters, and provides a test bed for concepts and strategies. Policies can be examined to see how refugee communities might respond to alternative courses of action and how these actions are likely to affect the health and well-being of the community.

Keywords Refugees · Agent-based modeling · Simulation · Policy analysis

1 Background and objectives

The U.S. Committee for Refugees and Immigrants [1] estimated that there were more than 33 million refugees and internally displaced persons (IDPs) in the world at the beginning of 2005. Over two million of these refugees are from Afghanistan alone. The UN Refugee Agency [2] budget as of July 1, 2005 was $1.35 billion. According to the World Refugee Survey, the United States and the European Commission contributed more than $700 million U.S. dollars annually to nongovernment organizations (NGOs) for refugee aid worldwide in 2004.

Since the end of World War II, global conflicts have generated an increasing number of refugees and IDPs, resulting principally from conflicts within states. An analysis of events and conditions that have led to refugee flows in the last quarter of the 20th century suggests that the numbers of refugees per conflict have been increasing and that certain regions of the world with countries experiencing high levels of violence are producing the majority of refugees and IDPs [3]. While during this period the traditional countries that have accepted refugees have increased the number of refugees accepted for resettlement, there is increased domestic pressure within these receiving countries to limit admissions of refugees [4]. At the same

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time, the Institute of Development Studies has raised questions as to whether refugees should be integrated into the local population and relief programs should work through local welfare agencies [5].

Policy responses to influxes of large numbers of refugees and IDPs vary considerably from country to country [6]. The consequence of providing humanitarian aid to refugees creates problems for the country receiving them. Reports of the United Nations High Commissioner for Refugees to the UN Economic and Social Council [7] and Amnesty International [8] documented the fact that military and armed attacks on refugee camps have increased. Consequently, the report calls for international protection of refugees especially women and girls, who constitute the majority of the refugee population. In addition to security, a second major problem for refugee communities is the provision of health care [9, 10]. Studies have found Hepatitis B, malaria, and tuberculosis prevalent among refugees to the U.S. and the U.K. [11]. Migrants to Spain from sub-Saharan Africa were found to be carriers of Hepatitis B [12].

Most refugee camps are located in areas afflicted with factional wars, border disputes, and other crises making it difficult to carry out effective humanitarian aid efforts. IDP/Refugee communities behave in complex ways making it difficult to make policy decisions regarding the provision of humanitarian aid and health and safety. International, national, institutional, organizational, and human factors interact in dynamic ways making it difficult to predict the outcomes of policy decisions [6]. Moreover, in situations such as refugee communities, the system is neither directly observable nor subject to unifying organizational theories. Decisions involve a number of stake-holders with conflicting values [13]. Currently there is a need to view the refugee problem as a reoccurring phenomenon with identifiable features rather than as individual historical events [14].

One approach to modeling refugee communities is to use computer-assisted reasoning in policy analysis [15]. Simulation can provide a way past some of the difficulties in modeling these communities. A simulation model represents a theory of how a particular system works. The model can be used to analyze the forces that are driving refugee flows and conditions. The impacts of government policies can be examined and used to conduct policy experiments to see how refugee communities might respond to alternative courses of action. By executing the computer model with different initial values for its parameters and inputs, patterns and regularities can be discerned from the results.

This paper describes an agent-based simulation model that was developed to examine policy options regarding the provision of humanitarian aid to refuge communities. Agent-based modeling (ABM) was chosen because the more widely used alternatives that utilize systems of differential equations, statistical decision theory, or operation research methods impose unrealistic restrictions and assumptions on the system being modeled such as linearity, homogeneity, and normality [16–18]. Also traditional models apply primarily to aggregated data.

In the following sections we briefly describe the rationale for choosing agent-based modeling to study refugee communities. This is followed by a description of the model and the rules that govern individual agents' behavior. We next present the results of computational experiments undertaken to better understand the effects of policy decisions on the health and well-being of a refugee community.

2 Methods

2.1 Agent-based modeling

Many social systems such as refugee communities are inherently nonlinear. That is the effects of independent variables representing policy decisions on dependent variables or outcomes are not proportional and directly predictable. Such nonlinear systems are difficult to model because they cannot be understood analytically [19]. The behavior of the system cannot be predicted from a set of equations. The only effective way of exploring the behavior of nonlinear systems is by building and running simulation models. Two different approaches to modeling nonlinear systems have been developed, system dynamics and agent-based modeling. The two approaches, while quite different, are complimentary. System dynamics models are based on a set of differential equations representing complex feedback loops among aggregate state variables representing the system. The feedback structure is what makes a system adapt over time [20, 21]. In contrast, agent-based modeling examines the global consequences of interactions among individual agents. Properties of the system emerge from a small set of rules governing interactions among agents [22].

Agent-based models are capable of modeling the complexity of social systems because they utilize the rich data and knowledge that are available about behaviors, motivations, and relationships among social agents. The purpose of agent-based modeling is to determine the global consequences of individual interactions in a given space. Agents are viewed as generating emergent behavior by interacting with one another according to a small set of rules. These interactions among agents give rise to the system's complex behavior. The overall behavior of the system of actors cannot be derived directly from the rules governing individual behavior of actors. Emergence then is viewed as a property of complex systems [23].

We chose to use agent-based modeling of refugee communities because it overcomes one of the major difficulties associated with policy analysis at this level, namely the scarcity of comparable and generalizable models of these communities. An agent-based synthetic environment allows us to generate an understanding of the collective behavior of refugees and IDPs through computational experimentation. This form of modeling provides insights into how macro level phenomenon emerges and attains equilibrium and stability over time from micro level behavior. In summary, agent-based simulation allows: (1) virtual simulation of the consequences of decisions, (2) integration of multiple theories regarding the phenomenon under investigation, (3) representation of agents with multiple decision strategies, and (4) modeling of heterogeneous actors who can modify their behavior over time [24].

The research process involves modifying the rules, the environmental parameters, and/or the decision parameters, and analyzing the resulting outcomes regarding the emergent behavior of the overall system. The purpose of the analysis is to determine leverage points in complex systems on which to base policy decisions [25, 26].

Systems Theory provides a theory of modeling that can be used for systems that are neither directly observable nor subject to a unifying organizational principle. A system is defined as a collection of interacting objects assumed to have multiple modes of responding based on the observed input–output relations over time. As long as the system is nearly decomposable, variables that move together over time can be aggregated statistically [25].

The types of objects that can influence the health and well-being of a refugee community system are refugees and IDPs; government, nongovernment, and social organizations that provide humanitarian aid; medical centers; and hospitals. Inputs to the system include numerous aiding actions by multiple organizations that affect the availability of food and water, medical supplies, and medical personnel as well as levels of security and sanitation. Within the refugee community system, classes of outputs include the number of refugees who are sick, dead, or healthy.

2.2 Model description

A number of platforms and methods exist that can be used for agent-based modeling [27]. For this study we used the Synthetic Environment for Analysis (SEAS)—computational experimentation environment [28]. This platform provides an environment that can be used to construct a virtual model of a refugee camp. The SEAS software has been used to create a small-scale artificial society which includes the health care system of a refugee community.

This model is one of several used in concert within the synthetic environment to conduct computational experiments in order to explore the effects of policy decisions regarding the provision of humanitarian aid, health and safety for refugees The model is based on several social science theories, namely certain fundamental or experimentally developed theories are explicitly encoded in the agents, for example., well-being [29, 30], set point theories from psychology [31], and production and consumption theories from micro economics. In the next section, agent's attributes are described as well as the inputs to and outputs of the model.

2.2.1 Agent specification

Individual refugees are constructed as a proportional representation of the social makeup of a refugee camp. Each individual agent consists of a set of static and dynamic traits. For example, there are three "income" classes for IDP/Refugees: Elite, Middle, and Weak. These designations correspond to the agent's Basic Needs level of low/medium/high and affect an agent's likelihood of becoming sick. Other traits modeled in each refugee agent include religion, ethnicity, social networks, and ideology.

Dynamic traits include the refugee's subjective well-being and health status. The refugee agent's subjective well-being is based on the work of Kahneman [30]. The agent's well-being consists of eight needs: basic, political, financial, security, religious, educational, health, and freedom of movement. A refugee agent's behavior is primarily driven by his/her traits and well-being. Information reaches the agent via traditional media sources and rumors spread by other agents.

Initially each agent's *desire* of each need is based on the socioeconomic class of the citizen. Further, we also identify *weights* that identify the relative importance of the fulfillment of each need to the citizen. Each citizen forms a perception of the level of fulfillment of each need from several information sources such as social groups, leaders, organizations, and media. Each agent then identifies deprivation of each need as the gap between the perception of a need and his/her desires for the need. By weighting the deprivation of each need, each citizen identifies their overall deprivation.

Citizens adjust their *weights* as certain needs become more significant due to conditions in the environment. Citizens focus on needs that they are most deprived of and attach less significance to those needs that are fulfilled. Organizations, Leaders, and Media can influence a citizen into adjusting weights by attaching significance to certain issues. Citizens are also influenced or coerced by their social groups in the needs to which they attach most significance.

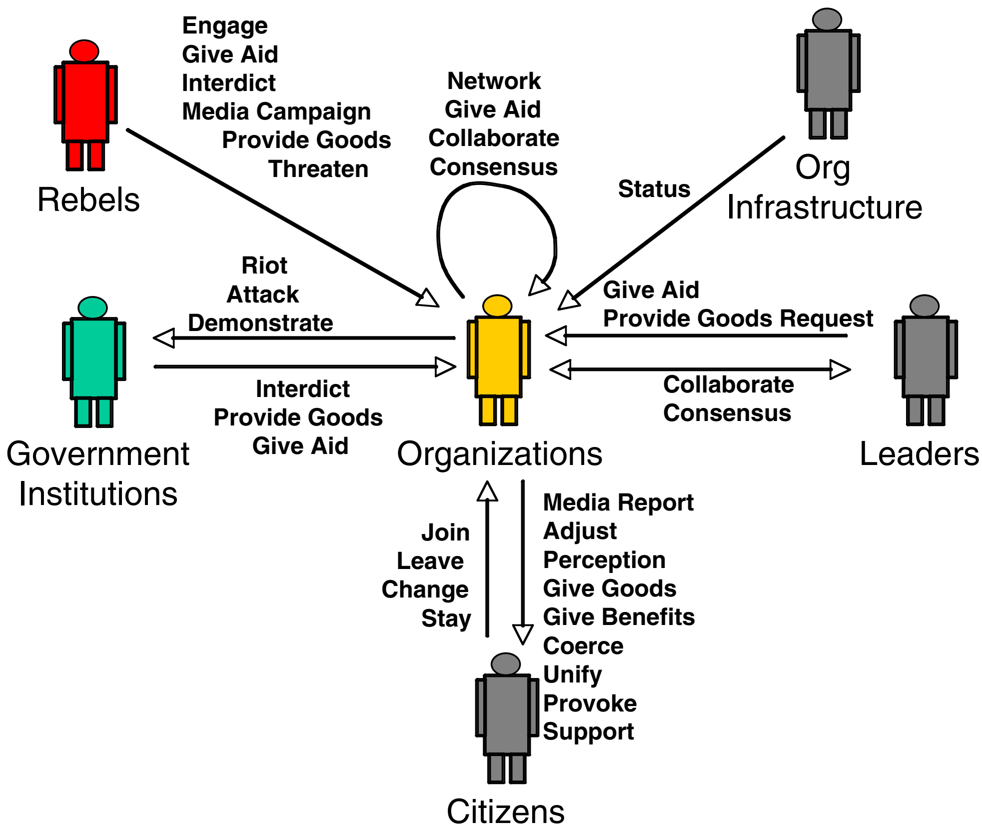
The *leader* agent is encoded with influence levels that reflect his/her power within the group, organization, or institution. A leader agent is categorized as social, religious, and/or political and has a repertoire that is larger than that of citizen agents and includes additional traits such as power base, ideology, and his/her stance on economic, political, and social policies. These agents are able to affect the political and social climate of the synthetic environment and impose their stances upon citizens and organizations to promote their respective goals. The goal of leader agents is to set the agenda of the organization or institution in which they reside and persuade the citizen/member agents to make decisions that favor those positions.

An *organization* is comprised of a structured group of artificial human citizen and leader agents. Citizens that subscribe to an organization make up the member population, and the combined behaviors and interactions of members and leaders results in the behavior for the organization. Organizational leadership constantly seeks maintenance and growth of the organizational membership by providing tangible and intangible benefits, and citizens subscribe based on a perceived level of benefit that is received from the organization. Leaders attempt to influence the organization to align with their ideologies by framing issues and attitude sharing. Members also influence each other's attitudes through the formation of intra-group social networks that emerge from levels of affinity between members. Additionally, through inter-organization networks, attitudes and resources may be shared between organizations. Through these internal and external interactions, organizations cause significant changes in perception and attitude and become core protagonists of activism in the model.

Within our model *media* also plays a significant role in providing information to members in the form of reports on well-being and attitudes. Media organizations consist of television, radio, newspapers, and magazines. They make choices about what information to cover, who to cover, what statements to report, what story elements to emphasize, and how to report it. Media is able to set the agenda for domestic policies as well as foreign policy issues. Incidents are framed on well-being components and formalized in a media report.

We model *institutions* as 'governmental entities' such as the army, police, legislature, courts, executive, bureaucracy, and political parties—entities that are able to formulate policies that have legal binding and have more discretionary resources. We also consider institutions as structures that are products of individual choices or preferences, the later in turn being constrained by the institutional structures (i.e., an interactive process). The Government Institution agents represent the leadership and various branches of the government. Institutions are like formal organizations with an additional power to influence the behaviors of members and nonmembers. Figure 1 shows the interactions among the agents.

Fig. 1 Interactions among agents



2.2.2 Sickness model

Refugees can be in one of four states Healthy, Sick Outside the Medical Center, Sick Inside the Medical Center, and Dead. Refugees will remain in a state for a minimum of one time step, representing one hour, after entering. Each time step, every agent checks to see if they remain in their current state or transition to another state.

State: Healthy This is the default state for agents. Agents remain in this state until they become sick and transition to Sick Outside. The probability that an agent will become sick is a nonlinear function, *f(Basic Needs, Food_Water, Sanitation)*, of the refugees current perceived Basic Needs level, the community sanitations level, and the community Food/Water level.

State: Sick Outside the Medical Center When an agent becomes sick, they enter this state and are assigned a number, Δ_d , from a triangular distribution that represents the number of time steps in which they will die if they are unable to enter the medical center. Each time step, the agent checks to see if they have died as a result of their inability to obtain medical attention. If they are still alive, they will attempt to enter the medical center and transition to the Sick Inside state. If the medical center has exceeded its capacity, the agent is forced to remain in the Sick Outside state.

State: Sick Inside the Medical Center When an agent enters the medical center, they are assigned a number that represents the number of time steps in which they will become well again and transition to the Healthy state. The number of time steps until they become healthy is *f(*Δ_h*, Medical Resources, Medical Personnel, security)*, a nonlinear function of a number from a triangular distribution, the community Medical Resources level, the community Medical Personnel level, and the community Security level. Each time step, an agent checks to see whether they have died in the medical center. The probability of dying in the Medical Center is p=0.0001 per time step and is an important model parameter for calibration. If they have not died, they check to see if sufficient time has elapsed that they have become healthy and can transition to the Healthy state.

State: Dead Once an agent dies, they are removed from the camp and undergo no further processing.

2.2.3 Inputs

Policy decisions and actions by governments and NGOs provide the inputs to the model. Levels of Security, Food and Water, Medical Personnel, Medical Resources, and Sanitation can take on values ranging from 1 to 10. The capacity of the medical clinic/hospital is established prior to a simulation run.

2.2.4 Outputs

The outputs of the model include the numbers of healthy, ill, and dead refugees. Also the number of ill refugees being treated by the clinic/hospital is calculated. Figure 2 shows the virtual model of the refugee camp and its health care system.

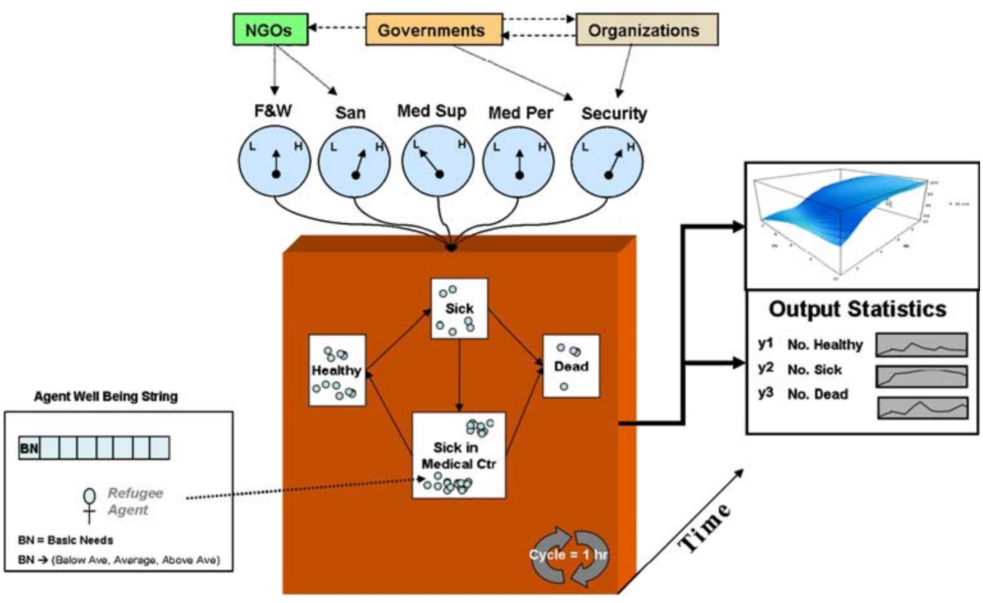


Fig. 2 Virtual health care system for a refugee camp

2.3 Model evaluation

The internal validity, sensitivity, and outcome validity of the model have been evaluated [32, 33]. First, the internal validity of the model was assessed by verifying that its data, variables, and parameters are based on experimentally developed theories such as well-being [29, 30] and data from the UN Refugee Agency.

Second, a sensitivity analysis was performed on the model. For each of the independent input variables (i.e., Food and Water, Sanitation Level, Medical Resources, Medical personnel, and Security level), the model was used to predict outcome variables such as the number of refugees who are sick or who are alive over time. Twenty-eight runs were performed with different combinations of the five input variables. A neural network analysis was performed to estimate parameters of a model that can be used to predict outcomes.

In order to test the sensitivity and stability of the model, levels of food and water were varied while the other four parameters were held constant at their midpoints. As predicted, at low levels of food and water, fewer refugees were alive after 50 h. Moreover outcomes for each level of food and water stabilize after 50 h. Additional runs were performed for each of the other four input variables. As predicted, sickness rates declined as levels of sanitation, medical resources, medical personnel, and security increased. Also, treatment times or length of stay in the medical center decreased as levels of medical resources and medical personnel increased.

Outcome validity was also assessed. While limited historical data are available to verify the model, predictions from the agent-based model were compared with the predictions from a system dynamics model [20, 21]. Over time, predictions of the number of sick refuges, refugees in the medical center, and deaths compare closely to the predictions from the agent-based model presented here.

3 Results

A design of experiment was conducted to capture the underlying relationships in the simulation. A Central Composite Design (CCD) with five factors and three levels was created and analyzed by DOE PRO XL software. The factors were (1) Basic Needs, (2) Food & Water, (3) Sanitation, (4) Medical Resources, and (5) Security. For this experiment the levels of these factors were set by the experimenters, but when the synthetic environment is used for supporting policy analysis events, the levels are modified by autonomous policy-making agents like governments and NGOs.

DOE PRO XL produced two regression equations, one for predicting the percentage sick and one for predicting the percentage of the initial camp population alive at any point in time. The error rates in prediction were larger than expected so the alternative method of using neural networks for function approximation was applied. Using an add-on package for Mathematica®, better performing predicting equations were derived and used for creating response surfaces.

The effects of the level of food and water available to refugees and medical resources available to refugees are shown in Fig. 3. The sickness rate declines with increased food and water and the availability of greater medical resources in the refugee camp. The largest decline in illness occurs when both factors are at higher levels. Errors in prediction appear to be distributed uniformly over the input space.

Figure 4 shows the effects of low levels of food and water and sanitation on the number of sick refugees. For this run the capacity of the medical center was fixed at 45. The simulation run indicates that the number of sick refugees rapidly exceeds the capacity of the medical center to treat them. The rapidity with which the number of ill refugees overwhelms the health care system in this case suggests the importance of surveillance systems for early detection of epidemics in refugee camps [34].

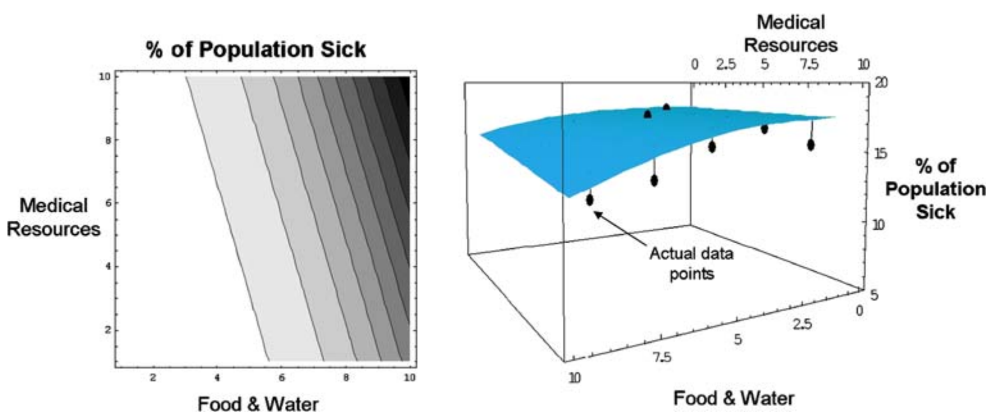


Fig. 3 Effects of levels of food and water and medical resources on the percent of refugees who were sick after 15 days

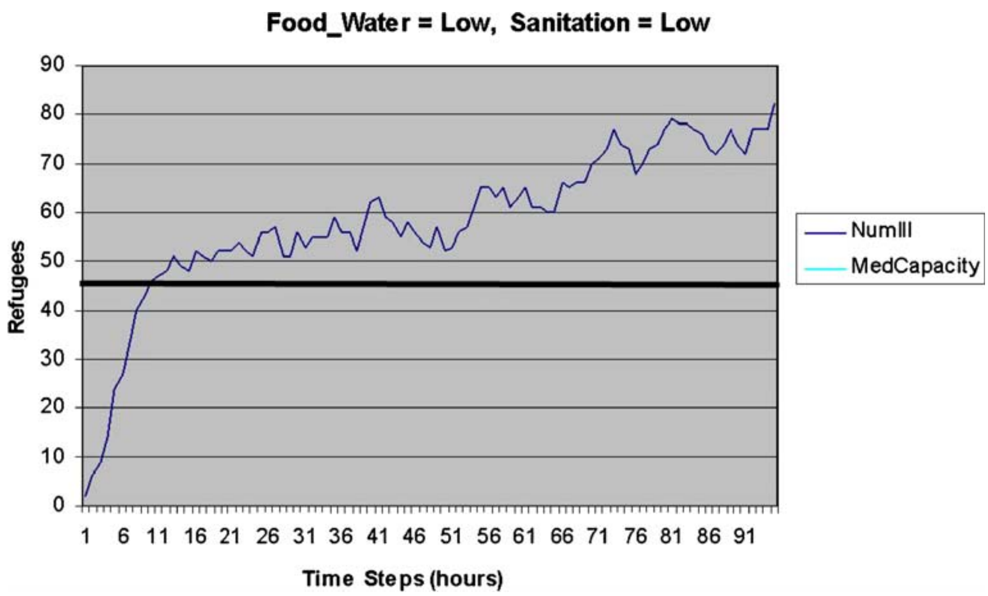


Fig. 4 The effect of low levels of food and water and sanitation on the number of sick refugees over 4 days. Capacity of the medical center equals 45

The interactions between Food and Water, Sanitation, Security, and Medical Resources and their effects upon mortality among the refugee population can be seen in Figs. 5 and 6. For Fig. 5, Basic Needs, Medical Resources, and Food and Water were fixed at medium levels. The results show that decreased Security results in increased morbidity regardless of the level of Sanitation. The worst conditions occur when both Sanitation and Security levels are at minimum levels. The results show that low levels of food and water result in a high number of sick refugees. The levels of food and water appears to interact with the level of security when both food and water supplies and security are low, there is a sharp increase in the proportion of sick refugees living in the camp.

For Fig. 6, Basic Needs, Sanitation, and Security were fixed at medium levels Increases in both Food and Water and Medical Resources have their greatest impact when initial levels are at minimum values. In other words, the lifesaving effects of these two variables diminish as their values increase. These results represent a situation where the supply of food, water, medical resources, sanitation, and security by either a government or NGO are limited.

Figure 7 shows the effects of levels of sanitation and medical resources on the percentage of refugees who are sick after 15 days assuming that no new refugees enter the camp during this two week period. When sanitation and medical resources are very low, the number of surviving sick persons in the camp falls. This is due to the increased number of deaths that result from poor sanitation and limited medical resources. As the number of sick refugees increases, the medical center reaches capacity and an increasing number of refugees do not receive needed care and eventually die.

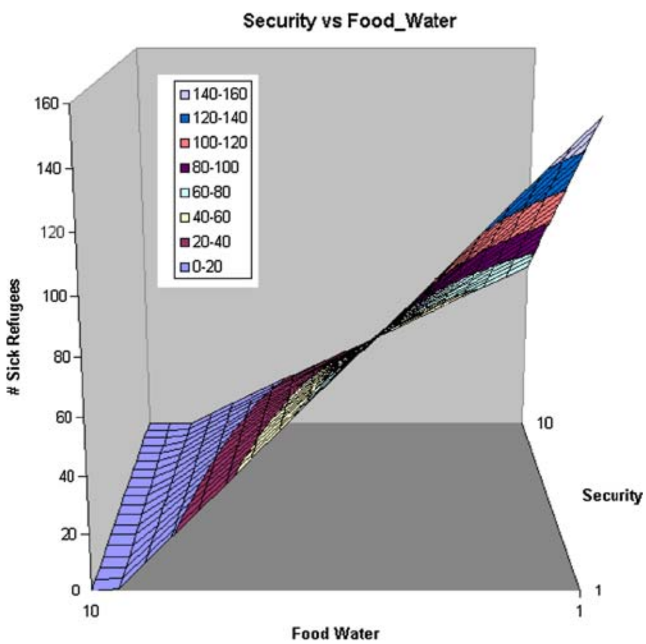


Fig. 5 Effects of levels of sanitation and security on the number of sick refugees after 10 days

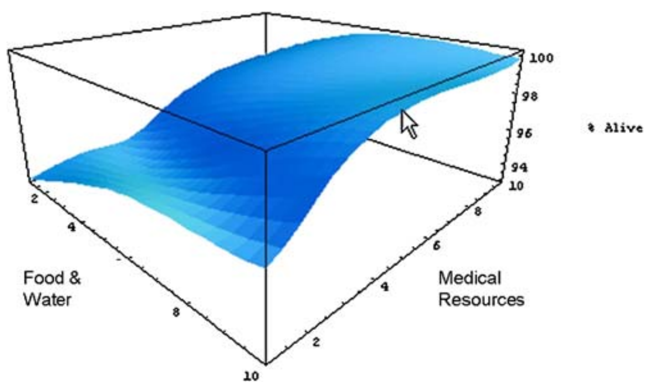


Fig. 6 Effects of levels of food and water and medical resources on the percent of refugees remaining alive after 15 days

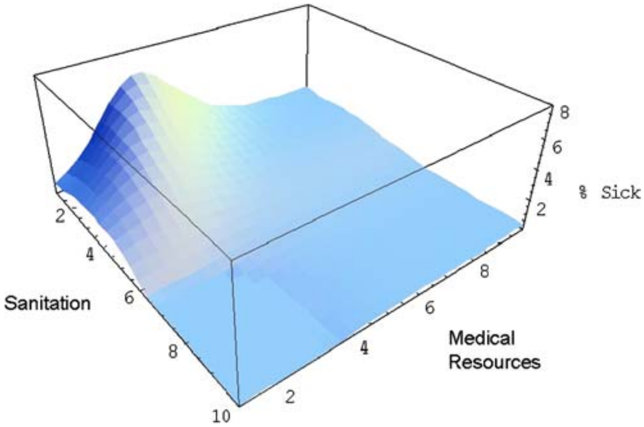


Fig. 7 Effects of levels of sanitation and medical resources on the percent of refugees who are sick after 15 days

4 Discussion

This paper reports the construction of an agent based model that has been used to study humanitarian assistance policies executed by governments and NGOs in a synthetic environment. We have created intelligent agents representing individuals, institutions, organizations, infrastructure, and governments and analyzed the resulting interactions and emergent behavior. A major strength of the model is that it allows policy makers to incorporate specific characteristics of refugees and the governmental and nongovernmental organizations that are providing humanitarian aid to the camp.

For example the simulation demonstrates the critical role of security in providing for the health and well-being of refugees. The importance of security was highlighted in the recommendations that Amnesty International made regarding the African Union Mission in Sudan (AMIS) [8]. The report states that AMIS lacked the manpower and resources to adequately protect the refugee population. As a result refugees were attacked and killed when they sought food, water, and firewood.

Since the factors studied here are likely to be targeted by policy makers in governments, NGOs, and relief organizations, this agent based model can be used to explore alternative policies that may affect the health and well being of refugees and displaced persons resulting from civil unrest, wars, and natural disasters like hurricane Katrina. These factors are likely to be targeted by policy makers in governments and NGOs.

The limitations to the simulation described here are both the unavailability of theories from which to create models and data from which to calibrate model parameters. These same limitations make it even more difficult to utilize other modeling techniques that impose restrictive assumptions. Agent based modeling enables investigators and policy makers to model complex, adaptive social systems and their associated policy problems even when data are limited. These social systems present nonlinear sources of uncertainty that can be modeled by interacting adaptive agents [35].

The present model is largely based on literature regarding well-being. Currently research is ongoing into social science theories that shed light on information diffusion through social networks of actors, public opinion formation, institutional behavior and decision making [36, 37]. A great deal more research and modeling is needed to better understand the dynamics of these processes, especially in refugee communities. The work presented here is an initial attempt to model these processes and their effects on health and well-being of refugees.

Much more extensive work is needed to validate the model. One possibility would be to determine if the present model captures the qualitative histories of existing refugee camps in Darfur; Palestinian camps such as Ain al-Hilweh; and other camps in Ethiopia, Sudan, the Ivory Coast and Afghanistan.

5 Conclusions

Policy simulations are valuable because of their ability to facilitate training and feedback concerning potential impact of decisions. In the real world, policy decisions may have serious consequences. Policy simulation models are useful because they accelerate creation of scenarios, allow rapid changes in parameters, and provide a test bed for concepts and strategies. In the present application, policies can be examined to see how refugee communities might respond to alternative courses of action and how these actions are likely to affect the health and well-being of the community. For example, the model could be used to address some of the following questions:

1. How do different mixes of income level, basic needs, religion education and ethnicity affect the health and well-being of refugees?
2. What are the dynamics among international and national organizations that provide optimal health care and relief for refugees? For example, should refugees be allowed to work and contribute to the local economy? Should relief programs be designed to strengthen existing local welfare efforts rather than remaining independent of these efforts [5].
3. What are the optimal policies for refugee camps in terms of provision of food and water, sanitation, security, medical personnel and medical resources in order to make maximum use of international aid funds?
4. What is the impact of shocks on the refugee camp model: for example, forcing refugees prematurely to

return home, interruptions to the supply of food and water, limited medical resources, etc., and attacks by militia on refugees?

In the future, the agent types included in this model will be expanded and the Refugee Camp Agent will operate inside an even more agent-rich environment. Also, because simulation data can be generated so quickly, larger experimental designs will be conducted across a longer time span. Our model can easily be adapted to represent the conditions that exist immediately after natural disasters such as hurricane Katrina, the Indonesian tsunami, and recent earthquakes. In these situations, large populations become immediately displaced and require basic housing, sustenance, and medical care. In some areas, security may be an important issue as well. The model presented here can be used to represent these types of situations and explore potential policy decisions.

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