An Agent-Based Model for the Spread of the Dengue Fever: A Swarm Platform Simulation Approach

Luís F. O. Jacintho, André F. M. Batista, Terry L. Ruas, Maria G. B. Marietto, Fábio A. Silva
Federal University of ABC - Centre of Mathematics, Computation and Cognition
Rua Santa Adélia 166, CEP 09210-170, Santo André, São Paulo – Brazil
{luis.jacintho, andre.batista, terry.ruas, graca.marietto}@ufabc.edu.br, aragao.silva@gmail.com

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Abstract

The dengue fever is today the most spread arbovirosis in Brazil. Transmitted only by the female *Aedes aegypti* mosquito, it reaches its peek during the hot and humid Brazilian summer season. While there are many approaches to analyze the spread of the dengue fever, most of them focus on developing a mathematical model to represent that process. One disadvantage of such approach is to neglect the importance of micro-level behavior, focusing instead on the macro-level aspects of the system. This work proposes an agent-based model of the spread of the dengue fever arbovirosis, where agents interact between themselves and the environment representing the process of dissemination of the disease. This model will be implemented and simulated through the Swarm platform and the simulation results will then be analyzed.

1. INTRODUCTION

Used as a tool to build a representation of a given system, simulation models mainly differ from traditional models, such as mathematical ones, in the sense that they allow: (i) the study of how the modeled system behaves under certain conditions, and (ii) the examination, in varying degrees of detail, of the consequences of changing internal behaviors of the system, and vice versa.

The results obtained in a simulation can be of great help in the decision-making process, in the evaluation of systems and in reducing implementation time and costs.

In [12, 13] some simulation goals are presented, namely:

- Discover and formalize new theories and models;
- Develop a better understanding of some features of the real system;
- Test hypotheses of the modeled system;
- Predict future actions and behaviors.

More specifically, Ferber [12] defines that an agent-based simulation model relates to the idea that a system is comprised of all relationships of its inner parts, and in that sense, it is possible to simulate an artificial world based on the relationships of its entities.

The simulation occurs when there is a transposition of the population of a target system[1] to a *conceptual model* equivalent, followed by the encoding of this model to a *computational model*. In this case, an agent (or actor) equates to a real world entity or a group of them. Such actors can be of different natures and with various granularities, such as humans, robots, computer programs, inanimate objects and organizations.

The agent-based simulation provides an adequate infrastructure to model and understand processes related to social interactions such as coordination, cooperation, formation of coalitions and groups, development of conventions and standards, intentionality, free will, conflict resolution, among others. This is possible because of the relationship established between local and global behavior, leading to explicit chains of cause and effect of how internal agent components affect the agents behavior, how this behavior affects the agency and, dialectically, how the agency affect its agents components [7, 13, 17].

This work aims to develop an agent-based model for the spread of the Dengue fever through the simulation of the spread process using the Swarm platform. For that goal, this study is organized according to the following: Section 2 presents some studies on modeling the spread of general diseases, including the Dengue fever. Section 3 offers a brief overview of the agent-based simulation area. Section 4 presents a Swarm platform overview, its functioning and architecture to be used in this work. Section 5 shows the current outlook of Dengue in Brazil. Section 6 describes a proposed agent-based model for the spread of the Dengue fever, and Section 7 presents the results obtained in the performed computational simulation, together with an analysis of such results. Finally, Section 8 presents the final considerations for this work, including some proposals for future works.

2. BACKGROUND

Several researches on the simulation of the spread of epidemics have been done in the past. Tran and Raffy in [22]

[1] The target system is equivalent to the simulation domain and can be real or theoretical.

proposed a spatial and temporal model for the dynamics of the dengue fever, where the transmission processes are described by a set of differential equations. Sakdanupah and Morre [20] also proposed a mathematical model for Dengue fever based on nonlinear differential equations.

One common disadvantage of such models is that the micro mechanisms of the spread process are ignored. Agent-based simulation is considered a new method to investigate the micro mechanisms of complex systems. Cellular Automata (CA) simulation can also be regarded as a type of agent simulation. Chaussalet et al [3] developed a CA model of the spread of the barley yellow dwarf virus and performed sensitivity analysis. Deng et al [9] developed a multi-agent simulation model to study the disease spread processes under different amounts of initial patients, infection ratios and rules, cure ratios and population density environments.

Demetrios et al [11] also developed an agent community named "GeneCity" to test some hypothesis about the spread of thalassaemia. Although the mechanisms at the individual level are described in these models, the network structures for the spread processes are ignored.

3. AGENT BASED SIMULATION FIELD: A BRIEF PORTRAY

After the consolidation of the agent paradigm in computer science, the role of agent-based simulation has been acquiring importance in a variety of scientific disciplines. In particular, the sources of analogy between agent-based technologies and models of actual social systems have created an intense interdisciplinary effort, opening new interfaces of research across various disciplines under the umbrella of a new scientific field, which may be called Agent Based Simulation (ABS) [15].

The general objective of ABS researchers is to develop and study simulation models, taking into account the theoretical-technical infrastructure from the Distributed Artificial Intelligence area. These models mainly differ from traditional ones, such as mathematical models, as they allow researchers: (i) to study the global behaviour of the modelled system under certain conditions, and (ii) to examine the consequences of changes in the internal components of the system [8].

More specifically, to [6] an agent simulation model is based on the idea that it is possible to simulate an artificial world populated with interactive computational entities. Simulation can be achieved by transposing the population of a target system to its artificial counterpart. In this sense, an agent is equivalent to an entity of the target system, or a group of them.

In simulation systems, an important issue to be considered is the warranty that both conceptual and computational models represent, in a trustworthy way, the target system. This is obtained by using two processes: validation and verification. The validation process aims to assure that conceptual model represents, within an acceptable degree of adherence, the target system. The verification process aims to assure that the conceptual model is correctly translated to the computational environment. Figure 1 shows the steps of the modeling process.

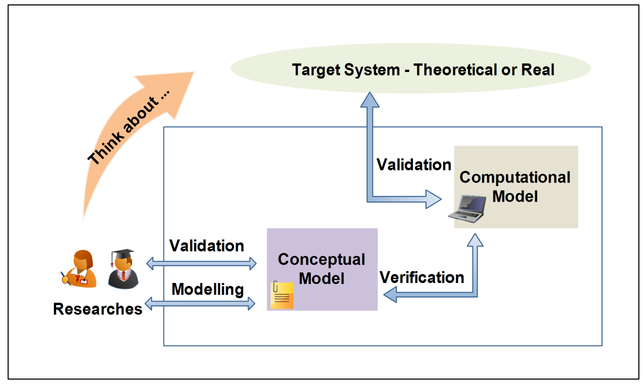

Figure 1. An Overview of the Modeling Process.

4. SWARM PLATFORM'S CONCEPTUAL MODEL AND ARCHITECTURE

The Swarm Platform is a multi-agent software simulation toolkit that supports a hierarchical modeling approach, designed to help modelers simulating complex adaptive systems through the use of object oriented libraries of reusable components [14].

The Swarm's conceptual model deals with a set of agents that interact with each other by discrete events. In the Swarm model, the main component that manages the agents is called SWARM, which can be described as a set of agents with an activity time scheduling for them [1].

The Swarm model architecture keeps the observation actions and the simulation actions apart. In the first level of the architecture, called OBSERVER SWARM, the simulation can be watched. Therefore, what the user sees or perceives is controlled by this level [1, 14]. Among the actions performed in the OBSERVER SWARM are: (i) a user interface management by creating observation screens, (ii) a second hierarchical level instantiation, called MODEL SWARM and (iii) file and/or chart generation based on MODEL SWARM resulting data.

The main goal of the time scheduling at the OBSERVER SWARM is to direct the data gathering process (getting the information and showing it in an interactive manner to the user, or storing it in files when running in *batch* mode). In the second hierarchical level, the MODEL SWARM, the simulation is executed. Some of the actions performed at this level are [1]: (i) instantiation of the simulation agent's along with other possible hierarchical levels, (ii) time-scheduling for the agents, (iii) control of the actions performed by the agents during the simulation, etc.

4.1. The Architecture of the Swarm Platform

What makes Swarm scientifically relevant and often mathematically intractable, is the coupling between the individual and the group behaviors. Although individuals are usually relatively simple, their collective behavior can be quite complex. Swarms allow researchers to focus directly on the fundamental roots of complexity: they capture the point at which simplicity becomes complexity [14].

The behavior of a swarm as a whole emerges in a highly nonlinear manner from the behaviors of the individuals. This emergence involves a critical feedback loop between the behavior of the individuals and the behavior of the whole collection. In a swarm, the combination of individual behaviors determines the collective behavior of the whole group. In turn, the behavior of the whole group determines the conditions (spatial and temporal patterns of information) within which each individual makes its behavioral choices. These individual choices, again, collectively determine the overall group behavior, and so on, in a never–ending loop [1, 14].

Agents that receive messages are free to perform whatever computation they wish in response to the message. Typically, the response to a message will be the execution of some algorithm that captures the modeled agent's behavior. Agents can also insert other actions into the schedule. In this way, Swarm supports a discrete event type of simulation. Swarm programmers are also free to use simple, fixed schedules that continually repeat the same actions [14].

5. DENGUE: EPIDEMIOLOGY AND THE BRAZILIAN SCENARIO

The Dengue Fever is an acute viral disease, transmitted by a specific type of mosquito, the *Aedes aegypti* (female). Considered the most important arbovirus in the world, it annually affects about 50 million people, with great potential for expansion and an endemic-epidemic pattern in almost all continents of the globe. The disease usually manifests itself in a benign fashion but can progress to a severe form known as hemorrhagic dengue fever.

This makes the Dengue Fever one of the most important objects in public health projects in Brazil nowadays, as they focus on controlling the *Aedes aegypti*. Due to the *Aedes aegypti*'s ability to reproduce itself on clean water, the Dengue Fever is present in all of the 27 states of the Brazilian Federation, distributed across 3.794 cities, being responsible for almost 60% of all the notifications in the Americas [4, 5].

There are four soro-types of this disease (DEN-1, DEN-2, DEN-3, DEN-4) spread all over the world. In 1981, DEN-1 and DEN-4 had been the first isolated soro-types, due to an epidemic of Dengue Fever in Boa Vista (Roraima). After a long hiatus, the disease (DEN-1) re-appeared in Rio de Janeiro, Alagoas, Ceará, Pernambuco, Bahia and Minas Gerais in 1986-1987, spreading itself all over the country. In 2001-2002, the soro-types DEN-2 and DEN-3 re-appeared as well. Currently, only three of them are outstanding in Brazil: DEN-1, DEN-2 and DEN-3 [5].

The spread of the Dengue Fever is highly dependent on ecological and social-environmental conditions. Places with high temperatures and constant raining are more likely to present higher infectious rates and larger risk groups. The *Aedes aegypti*'s life cycle is comprised of four stages: egg, larva, pupa and the land form, which corresponds to the adult mosquito. Following, we present a brief overview of this cycle based on [4, 23]:

1. Egg - The egg stage is the most resistant stage of the of *Aedes aegypti*'s life cycle, when eggs are laid by females on the water surface, adhering to the inner wall of containers, and then progressing to the incubation period. Under favorable conditions, it should take no longer than two (2) or three (3) days for them to be ready to hatch. The desiccation resistance increases as the eggs get older, i.e., the resistance increases the closer to the end of the embryonic development, and they can remain viable for six (6) to eight (8) months.

2. Larva - The larva is equipped with great mobility and have the primary function of growth. They spend most of their time feeding on organic substances, bacteria, fungi and protozoa in the water. The duration of the larva stage, with favorable temperature ranging from 25 to 29 ^{o}C and good food supply is about five (5) to ten (10) days, but it could take up to a few weeks.

3. Pupa - In this stage, the insect does not eat, just breathe, being not endowed with good mobility. It is rarely affected by the action of larvicide. The duration of the pupal stage in favorable temperature is about two (2) days on average.

4. Mosquito - Both male and female feed on nectar and plant juices, but the female mosquito requires blood after mating to guarantee the maturation of eggs. There is a direct relationship in tropical countries between rain and the increased number of vectors. Also, the temperature greatly influences the transmission of dengue and the disease is rarely transmitted at temperatures below 16 ^{o}C. Transmission occurs preferentially at temperatures above 20 ^{o}C. The ideal temperature for the proliferation of *Aedes aegypti* is estimated to be around 30 to 32 ^{o}C.

The virus is transmitted to mosquitoes when they feed on the blood of a person already infected with the dengue virus. After an incubation period of eight (8) to twelve (12) days, the mosquito is then ready to propagate the disease. In humans, the incubation period might last from three (3) to fifteen (15) days, and symptoms are noticeable only after this period. Most importantly, there is no transmission through direct patient contact (including secretions) with a healthy person. The virus is not transmitted through water or food as well.

As the disease is of worldwide concern, there is some mobilization by the scientific community to study it. Efforts have been made to better understand, prevent and control the spread of the epidemic. This paper proposes an agent-based simulation model for the epidemic disease in the hopes of contributing to such effort.

6. AN AGENT-BASED MODEL FOR THE DENGUE FEVER SPREAD

To better understand and simulate the features observed in the real world, a transposition was made in order to build a model to be executed in a controlled environment. Rules were established for building a model as close to reality as possible, according to the scope of the project. One challenge was to adequate the model to the time-stepping characteristic of Swarm simulations. As the simulation works in cycles, it was necessary to adopt a time measure, as shown in Equation 1.

$$C(d) = 3d \tag{1}$$

Where $C(d)$ represents the number of cycles and d the number of days in the real world.

In the sequel, we present a description of the simulation model, based on [8, 18, 21], as well as the behavioral rules transposed to the computational model implemented in the Swarm platform.

(A) Mosquito Agent Behavior

As in the real world, this agent is modeled to display four (04) distinct stages: egg, larva, pupa and the land form, which corresponds to the adult mosquito. Each one of them is discussed separately in this section. During simulation, each stage is represented internally in the mosquito agent with no graphical/visual representation being used to differentiate distinct stages. The mosquito agent evolves according to the simulation progress and its behavior is internally adjusted according to its current life cycle stage.

(A.1) Egg Agent Behavior

Egg agents cannot move or feed and have an ideal temperature higher than 20 ^{o}C, with an ideal humidity higher than 70%. Their outbreak will normally take place in about three (03) days.

(A.2) Larva Agent Behavior

These agents move only within their birthplace water spot, feeding on microorganisms and on their own egg remains. Their ideal temperature is between 25 ^{o}C and 29 ^{o}C, and their ideal humidity is higher than 70%. Under such conditions, this stage will take between three (03) to five (05) days to complete.

(A.3) Pupa Agent Behavior

Just like eggs, pupa agents cannot move nor feed. Their ideal temperature and humidity is around 20 ^{o}C e 70% respectively, and they will have an 83% chance to become adult mosquitoes within three (03) days approximately.

(A.4) Adult Mosquito Agent Behavior

In this stage, agents are able to move freely through the environment up to 100m from their birthplace. Only females are capable of transmitting the disease, and that rarely happens at temperatures below 16 ^{o}C, normally taking place under temperatures above 20 ^{o}C. The mosquitoes proliferate at an estimated temperature between 16 ^{o}C and 29 ^{o}C, and they have an average egg positivity of four (04) during their lifetime. Females will lay about 300 eggs on clean water with a 40% survival rate and 60% chance of being capable of transmitting the disease, i.e., other females. So, about 72 eggs will be considered in the simulation.

The mosquitoes can be killed by either exterminator agents or traps in the environment. They have an incubation period of about 8 to 11 days, by the time at which they become infectious and remain so for the rest of their life. Each infected female mosquito can propagate the disease to heathy humans by only a simple bite.

To help understanding the simulation process, Table 1 summarizes the rules for the adult mosquito agent.

Table 1. *Rules for the Adult Mosquito Agent.*

Rule 1:	This rule establishes how the adult mosquito agent operates through the simulation. **IF** age is greater than 33 days **THEN** die **IF** any human is within visual field (10x10 cells) **THEN** chase him to feed **IF** targeted human is close enough (10m) **THEN** bite him **IF** clean water is nearby **THEN** deposit eggs
Rule 2:	When depositing eggs: **IF** eggs are successfully laid **AND** there are proper conditions as show in Section 6. THEN about 72 adult mosquitoes might emerge from the eggs **IF** the water is poisoned (a trap) **THEN** die
Rule 3:	**IF** the adult mosquito is infected **AND** bites a non-infected human **THEN** the human becomes infected within 3 to 6 days **IF** the adult mosquito is not infected **AND** bites an infected human, the mosquito becomes infected within 8 to 11 days

(B) Human Agent Behavior

As in the real world, this agent represents a human being, which might or might not become infected by the disease.

Humans can move freely through the environment. After being bitten, it takes three (03) to six (06) days to start showing symptoms. The Dengue Fever might last from three (03) to fifteen (15) days, with an average of five (05) to six (06) days. After being infected, the human agent can transmit the virus to others non-infected mosquitoes by blood contact during a mosquito's bite. This can occur one day before the first signs of symptoms and continues up to the last day of the disease. The death rates on multiple infections (also called the hemorrhagic dengue) are: 0.5% when infected twice; 10% when infected three times; 15% when infected four times and 25% when infected more than 4 times.

To help understanding the simulation process, Table 2 summarizes the rules of the human agent.

Table 2. *Rules for the Human Agent.*

Rule 1:	This rule establishes how the human agent operates through the simulation. **IF** is bitten twice by an infected mosquito, there is a probability of 0.5% to become infected by hemorrhagic dengue fever and die **ELSE IF** is bitten three times by an infected mosquito, there is a probability of 10% to become infected by hemorrhagic dengue fever and die **ELSE IF** is bitten four times by an infected mosquito, there is a probability of 15% to become infected by hemorrhagic dengue fever and die **ELSE IF** is bitten more than four times by an infected mosquito, there is a probability of 25% to become infected by hemorrhagic dengue fever and die **ELSE** move freely through the environment

(C) Exterminator Agent Behavior

The exterminator agent moves freely through the environment based on the mosquitoes gradient, attracted by areas of high mosquitoes density in the map. This represents the public health organizations that map and notify all risk areas when planning control actions. Their role in the simulation is to perform the killing of adult mosquito agents.

To help understanding the simulation process, Table 3 summarizes the rules of the exterminator agent.

(D) The Environment

The environment is not modeled as an agent on his own, but influences the agents behaviors. Environmental factors such as temperature, food rate (probability to find food) and humidity are globally defined as average values for the entire simulation, simplifying the simulation model and allowing the study of scenarios with different average values. There will be two states presented in the scenario: clean water and trap. Clean water servers as the place where mosquitos will lay their eggs. Traps, on the other hand, are placed by exterminators to eliminate mosquitoes.

Table 3. *Rules for the Exterminator.*

Rule 1:	This rule establishes how the exterminator agent operates through the simulation. **IF** an exterminator locates an adult mosquito **THEN** releases poison that kills mosquitoes in an area of 10x10 cells, with an effectiveness rate directly proportional to the distance from the exterminator **ELSE IF** follows the indications given by the sensors (these indicates, through a gradation of color, where the highest concentration of mosquitoes is located on the map - dark indicates a high concentration of mosquitoes and lighter indicates a low concentration of them)

7. COMPUTATIONAL SIMULATION

In this section, we present the computational simulation implemented for this study. In section 7.1 we describe the simulation environment. In section 7.2 we perform the verification and validation of the computational model through two proposed scenarios. Finally, in section 7.3 we offer a conclusion for the simulation model analyzed.

7.1. Simulation Environment

The conceptual model is transposed to a computational model that was later implemented in the Swarm simulation platform. Figure 2 shows all modeled agents as well as their relationships.

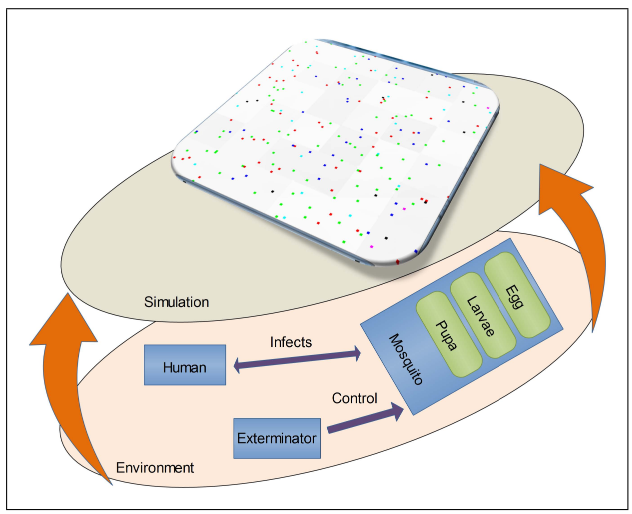

Figure 2. An Overview of the Simulation Environment.

As described in the previous section, the environment interacts with all agents offering food for the mosquitoes, water for their reproduction and traps with substances to inhibit their proliferation. The results of such interactions between agents and the environment can be visualized by a 2D raster provided by the Swarm platform. Figure 3 shows the simulation screen during a given cycle.

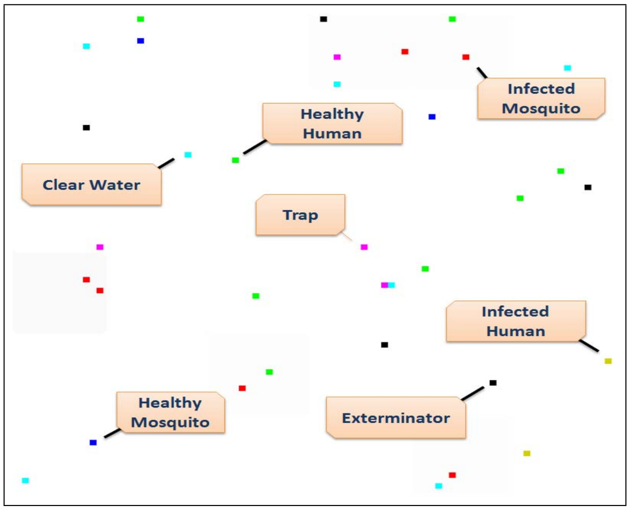

Figure 3. Simulation Screen.

7.2. Verification e Validation

This section focus on verifying and validating the proposed model through analyzing the results obtained in two different scenarios.

According to Dantas et al. [6] and Dibo et al. [10], meteorological aspects such as temperature, humidity and precipitation can be used as Dengue incidence predictors. In that sense, evaluating different climatic seasons allows a better understanding of the spread of the disease.

In this work, we consider a tropical wet and dry climate region (Aw) according to the Köppen-Geiger climate classification [16, 19], as this is the predominant climate for most of Brazil. The weather in Brazil is characterized by high average annual temperatures and by a pluviometric regime that separates two distinct seasons: a rainy summer and a dry winter season.

Following, there is a description of each of the simulation scenarios and their respective results:

7.2.1. Scenario I: Winter Season

To simulate the Brazilian winter season, we considered Rio de Janeiro's climate information [2], with an average temperature of 18 ^{o}C e average humidity of 45%. As the winter in Brazil is characterized by high dryness, we considered 20 water spots, with 5% set as traps. As winter is historically a season with low dengue fever occurrence, only 10 exterminators were made available in this simulation scenario. The simulation started with 100 human agents, with 8% already infected with the disease, and 50 mosquitoes, with 60% already infected by the disease.

After 180 simulation cycles (60 days), we observed no occurrence of hemorrhagic dengue (a human agent being infected more than once) and the infection rate actually dropped to 7%. The number of mosquitoes in the environment also dropped from 50 to 30, with a 100% infection rate and with 111 mosquitoes in non-adult stages of their life cycles.

Figure 4 (a) shows the simulation screen after 60 days. The color gradation shows the density of infected mosquitoes, and clearly shows few concentration spots. Figure 4 (b) shows the chart of mosquitoes in non-adult stages against adult mosquitoes. We observed that even though there were many non-adult mosquitoes, several adults were unable to survive due to the harsh winter conditions (temperature, humidity and lack of water spots). Figure 4 (c) shows the infections chart for the simulation world, and indicates that only a few humans were infected during that season.

7.2.2. Scenario II: Summer Season

To simulate the Brazilian summer season, we again considered Rio de Janeiro's climate data [2], with an average temperature of 29 ^{o}C and humidity of 85%. As the summer in Brazil is predominantly rainy, we considered 38 water spots, with 40% set as traps. Also, as the summer season shows a historical high infection rate, we made 30 exterminators available. The simulation started with 100 human agents, being 8% infected by dengue and 50 mosquitoes, with 60% infected as well.

After 180 simulation cycles (60 days), we observed that 3 humans died due to hemorrhagic dengue and the infection rate raised considerably to 33%. We also noticed that the number of mosquitoes jumped to 394, with 83% infected and with 5086 mosquitoes in non-adult stages.

Figure 5 (a) shows the simulation screen after 60 days. Figure 5 (b) show the chart for the number of mosquitoes in non-adult stages against adult mosquitoes. We can clearly see an almost exponential growth of mosquitoes in non-adult stages, which corroborates to the rapid increase seen in the population of adult mosquitoes. Figure 5 (c) shows the infections chart for the simulation world, with a clear increasing curve in the number infections for both humans and mosquitoes.

7.3. Conclusions

The two simulated scenarios allowed us to validate the proposed model, showing very similar results to the ones found by [5, 6, 10, 18, 21]. Simulating scenarios that considered climatic seasons allowed us to validate the model against infection rates and mosquitoes proliferation data during the same seasons in real life. In both scenarios, it was also possible to notice the emergency of a spreading behavior for the dengue fever caused by the interaction of the simulation agents (mosquitoes, humans, exterminators) and the environment (food, clean water and traps).

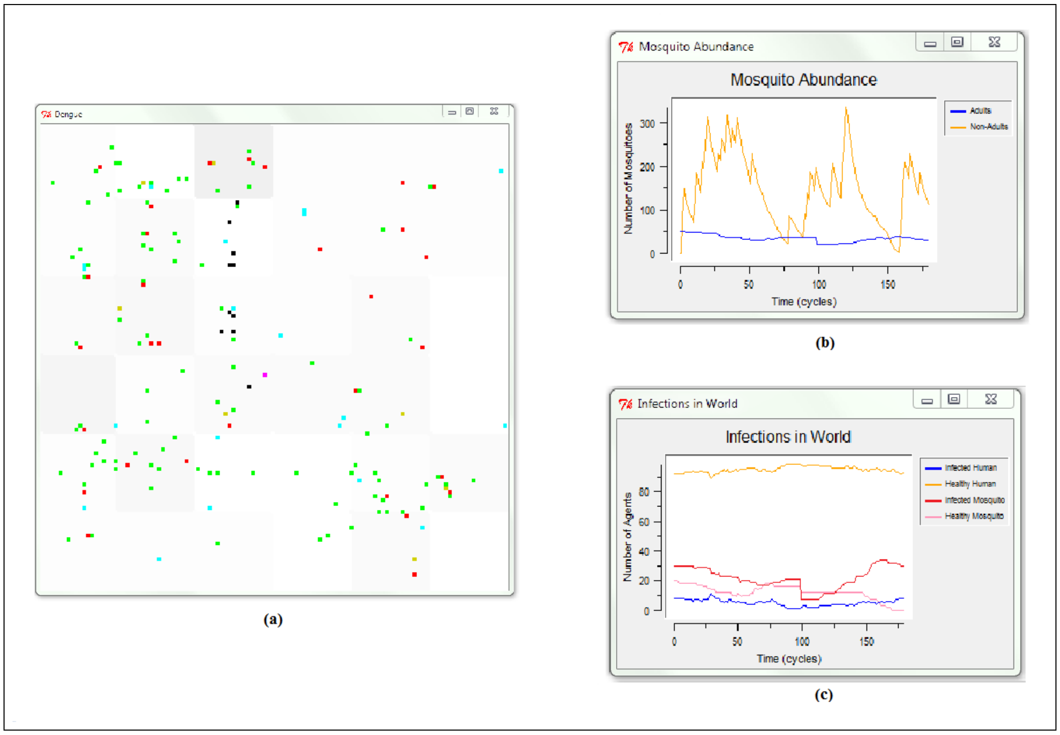

Figure 4. Simulation environment during a winter season and after 60 simulated days.

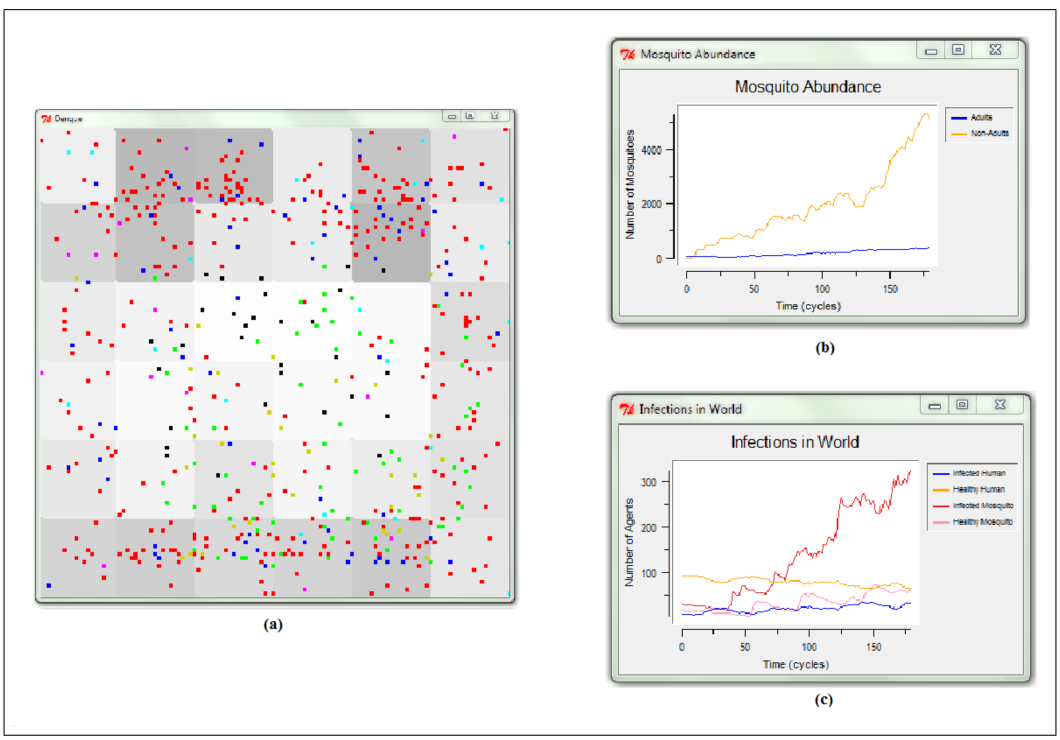

Figure 5. Simulation environment during a summer season and after 60 simulated days.

8. FINAL CONSIDERATIONS

In this paper we propose a model for the spread of the dengue based on the concepts of agent-based systems. Using agents allows the application of intelligence in the decision-making process, narrowing the model and the simulation to real-life situations, with the advantage of relying on a controlled environment.

The multi-agent based simulation model presented in this work was developed aiming to help us analyzing and validating our approach. We simulated the spread of the disease considering two scenarios, both summer and winter seasons, and the obtained results were very close to the ones seem in similar studies.

We implemented the simulation in the Swarm platform, focusing on identifying and modeling behavioral aspects of the micro parts involved in the spread of the Dengue fever. That way, we can provide a framework for better understanding the roles of each entity in the global context of the spread of the disease.

We intend to extend this work in the future to model even more realistic scenarios, including situations of control and extermination of the disease. That way, public health organisms could use the simulation framework as a tool to plan their actions against the mosquito's proliferation more efficiently. Some improvements could also be made on the agent's behavioral model, such as the exterminator agent, for instance, allowing them to react more realistically to the spread of the disease during the simulation.

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