- ORIGINAL ARTICLE -

Green High Performance Simulation for AMB models of Aedes aegypti

Simulación Green de Alto Rendimiento de un Modelo Basado en Agentes del Mosquito Aedes aegypti

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Abstract

The increase in temperature caused by the climate change has resulted in the rapid dissemination of infectious diseases. Given the alert for the current situation, the World Health Organization (WHO) has declared a state of health emergency, highlighting the severity of the situation in some countries. For this reason, coming up with knowledge and tools that can help control and eradicate the vectors propagating these diseases is of the utmost importance. High-performance modeling and simulation can be used to produce knowledge and strategies that allow predicting infections, guiding actions and/or training health/civil protection agents. The model developed as part of this research work is aimed at assisting the decision-making process for disease prevention and control, as well as evaluating the reproduction and predicting the evolution of the Aedes aegypti mosquito, which is the transmitting vector of the dengue, Zika and chikungunya diseases. Decision-making based on these models requires a large number of simulations to achieve results with statistical variability.

The objective of this paper is to demonstrate that the GPU is a suitable platform from the point of view of the reduction of energy consumed for HPC simulations. It is also shown that it is possible to define energy prediction models that allow scientists to plan their experiments based on energy consumption and select those that are representative for decision making by reducing energy consumption in HPC simulations.

Keywords: Aedes aegypti, GPU, Green Computing, ABM models, High Performance Simulation.

Resumen

El aumento de la temperatura a raíz del cambio climático, ha dado lugar a la rápida expansión de enfermedades infecciosas. Dada la alerta por la situación actual, la Organización Mundial de la Salud (OMS) ha declarado la emergencia sanitaria poniendo de manifiesto la grave situación que se vive en algunos países. Es por ello que es necesario aportar conocimiento y herramientas que ayuden al control y erradicación del vector que propaga estas enfermedades. El modelado y la simulación de altas prestaciones pueden ayudar a aportar conocimiento y estrategias que permitan predecir infecciones, orientar actuaciones y/o formar a los agentes de protección civil/salud. El modelo desarrollado en este trabajo, tiene por objetivo ayudar a la toma de decisiones de prevención y control, a evaluar la reproducción y a predecir la evolución del mosquito Aedes aegypti, transmisor de las enfermedades dengue, Zika y chikungunya. Dado que son necesarias un elevado número de simulaciones para tener resultados con variabilidad estadística, se ha utilizado GPU. Con esta plataforma se busca: su potencia de cómputo para reducir el tiempo de ejecución y, además, reducir el consumo de energía. Para ello se proponen diferentes escenarios y experimentos para comprobar los beneficios de la arquitectura propuesta.

Palabras claves: Aedes aegypti, GPU, Green Computing, ABM models, High Performance Simulation.

1. Environmental issues and epidemiology

The global warming caused by greenhouse effect emanations released to the atmosphere has resulted in the appearance and propagation of new or emerging diseases. Currently, the scientific community has taken a position on the matter by issuing a warning about how climate change will affect the future and the evolution of diseases and outbreaks caused by it [1, 2], which is in agreement with signs that describe climate change as the greatest threat for human health [3].

The mutation of vector-transmitted viruses has allowed these viruses to adapt to urban centers. The dissemination of diseases such as dengue/ Zika/chikungunya fever is evidence of the clear relation between climate change and the effects on human health [4, 5, 6]. The WHO estimates that, each year, there will be between 50 and 100 million infections and that more than 40% of the global population is at risk of developing dengue fever. In tropical and sub-tropical countries, 500,000 people are infected each year with serious dengue, with approximately 2.5% of them ending up in death [7].

All three diseases are transmitted by vector Aedes aegypti, a species that originates from Africa and that, due to the increase in temperature and rainfall, can now reproduce at latitudes where its existence was not possible originally. Because of its adaptability to populated areas, and due to the effect of globalization (commercial activities, tourism, people traveling, etc), the species has disseminated throughout the planet [2]. The same other mosquitoes, only adult females bite humans; they do so because they need their blood to lay eggs [8].

Mosquitoes breed in water stored in containers [9]. The number of containers used for breeding varies, as well as container productivity. Removing those containers that are most favorable for ensuring a high survival rate for the species is a non-contaminating, non-invasive, non-toxic and environment- and species-balance friendly method [10].

The infectious cycle of the disease starts with the bite of a female mosquito to a viremic person. After an incubation period of 8-12 days, if the mosquito bites another person who is in a susceptible state, it will infect that person. Once the vector has acquired the virus, it will have it for the rest of its life.

Control strategies are related to ecology and vector behavior in each region, as well as population habits and attitudes in relation to potential egg containers. Even though there are several proposals, such as genetic modification and irradiation, the WHO recommends implementing prevention and mosquito population control campaigns [11] by controlling reproduction, since this method does not affect the environment or break the genetic balance of the species. Surveillance of each phase of the vector's life cycle (egg, larva, pupa and adult) by means of adequate control methods is essential to reduce the risk of infectious disease transmission. For this reason, any applications that can assist during the decision-making process for mosquito population control are highly beneficial both from a health standpoint as well as an economic one.

The lack of antiviral treatment for these three diseases forces health agents to focus on their transmission pathways [11]. However, badly oriented or global, non-specific prevention tasks not only result in useless monetary expenses but also cause social unrest, since the disease is transmitted despite the investments done. For a successful control of vector reproduction, prevention tasks that can be analyzed and simulated in a safe environment, recreating situations that are hard to study in the real world, are required. The use of ICTs (Information and Communication Technologies) and the development of tools such as the one presented in this article can be of great help when making decisions.

In summary, the objective of this work is to demonstrate that the simulation oriented to individuals of these models presents a considerable reduction of energy using GPU and that predictive models of energy consumption can be constructed in order to know in advance the amount of energy that will be consumed during experimentation. These consumption prediction models will allow scientists to plan these massive simulations considering the energy aspects.

2. Green Computing

There are several factors that negatively affect the environment:

Human activities, such as electricity generation, people and merchandise global transportation or global economic activities [12].

The fast progress of technology, resulting in electronic device obsolescence and tons of trash to process (with only a small portion being recycled) [13].

The exponential increase, due to the high demand for electronic devices, of activities related to mineral exploitation, which in most cases degrade their surrounding ecosystems [14].

Additionally, this global environmental impact causes changes and problems in drinking water availability, food production, glacier melting, land and sea ecosystems, etc. [15].

In 1987, the World Commission on Environment and Development (WCED), included in its report 'Our Common Future' the brand new concept of Sustainable Development, which is defined as

follows "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs..." [16].

As described in [13], the ICT industry is one of the main contributors to pollution in the world, with an estimated 60-70% of the energy produced being consumed by computers [17]. For this reason, it is essential that good practices are promoted for using technology, aimed at reducing energy consumption, recycling waste and create awareness about how reusing is better than recycling to reduce the negative impact on the environment.

Based on these premises, Green Computing emerges as a proposal to reduce the impact on the environment, from manufacturing technology-related products to their subsequent recycling. However, it should be noted that information technology resources include, in addition to the manufacturing and recycling process, the efficient use of energy, as well as designs that are more respectful of the environment and aimed at the sustainability for society in the future [13].

Toward this end, significant progress has been made in hardware manufacture, mainly related to the need to increase computing capacity, the main example that can be mentioned is going from mono-processors to multi-cores, which has allowed reducing energy consumption, or the evolution from CPUs to APUs (Accelerated Processing Units), which bundle a CPU and a GPU (Graphics Processing Units) together. All this, in combination with the use of non-contaminating materials in the resource manufacture process, has helped improve hardware elements manufacture efficiency [18, 19, 20].

On the other hand, GPU manufacturers have increased the processing speed and energy efficiency in their units [18, 21, 22]), reducing greenhouse effect emanations and water consumption, and improving the safe elimination of wastes. Proof of this is that, on the Green500 list (November 2018), the DGX SaturnV Volta system is ranked as the second most energy-efficient supercomputer in the world [23].

However, the efforts to achieve energy efficiency must come from both hardware and software. Running applications that misuse computational resources takes us back again to the problem of excessive energy consumption. Additionally, the large volumes of data produced by current applications, and the added problem of processing them, should also be considered. For this reasons, energy consumption has gained greater significance in the development of computational applications, both from the point of view of where and when they are run, as well as considering aspects such as reliability, scalability, portability and efficiency [21]. It should be noted that application scalability, from the perspective of the problem or the architecture,

affects total consumption and, if not adequate, the electrical energy required could exceed available supply or budget.

Thus, it can be concluded that, whether the goal is minimizing environmental impact or reducing energy consumption expense, studying and reviewing computer application energy consumption is critical nowadays, at a point where the scientific community is the driving force for change and future sustainability.

3. Modeling and Simulation

Modeling and simulation techniques have been widely used in computational science as a decision-making tool. The model developed for the Aedes aegypti mosquito by our work group allows carrying out reproduction analyses by assessing pupal productivity of vector breeding containers. Studying the mosquito population in different scenarios and under various conditions allows health agents to plan prevention and control tasks in connection with the vector, in an effort to reduce the number of infection sources and, therefore, reducing the transmission and dissemination of the corresponding diseases.

The first version of the model was implemented on NetLogo (developed on Java) [24], which is an agent-based model simulation environment. The implemented model allows simulating a reduced number of individuals and containers, which translates to reduced areas within a city. NetLogo is a very powerful tool for modeling, but not for simulating large models (large number of agents) due to the limitations imposed by its execution model (sequential) and Java Virtual Machine (JVM) memory. To overcome these limitations, and to meet requirements for simulating large areas with a high number of individuals and containers in a short time, a change in strategy had to be implemented, which was accomplished by migrating the hardware infrastructure, and a model and simulator that allow parallel execution had to be developed.

To migrate the model, the Flame GPU framework was used, since it allows modeling agent virtual environments on GPU. This environment uses the model (XML file) and agent behavior rules (functions.c file) as input, and it generates the base code that will be run on the GPUs.

There are three basic actors in this model (see Fig. 1) to simulate individuals interacting with the environment – people, mosquitoes and containers. The model is fully parameterized, and virtual world dimensions are defined by the observer, as well as the number of people, mosquitoes and containers and the percentage of infected people and mosquitoes. With the model in its initial state, mosquitoes are at their egg stage in all containers. After the days corresponding to the larvae and pupae stages, they will reach adulthood. Female mosquitoes will look for people to bite, and after having fed, they will look

for a container to lay their eggs, starting over the life cycle for the vector. Containers have a type and productivity percentage that is connected to the pupal index, which is a variable that allows estimating the number of mosquitoes that will reach adulthood. The types of containers are defined by the user, as well as their productivity percentage.
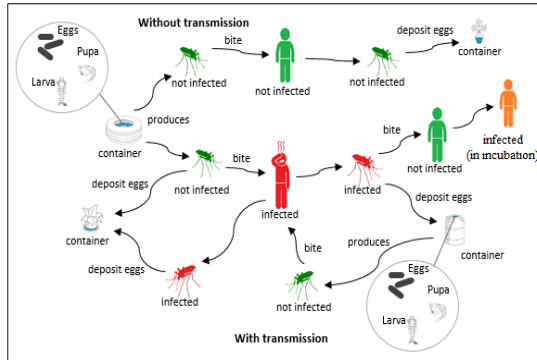

Fig. 1 Agents of the proposed simulation model

The model can be configured to either consider or disregard container productivity – if considered, mosquito population will be reduced. Disregarding container productivity means that, in each container, the number of mosquitoes will reach adulthood will be 100% of the eggs laid in it.

The results obtained with our current version of the model have been validated with the previous model and with the data obtained from a field work carried out in an area of 400 Km2 in São Sebastião, Brazil [25], 220 km away from the state capital. For the information gathering stage, containers were inspected during the months corresponding to the non-mature stages of the vector for the proliferation seasons in 2002-2004. The results obtained with the model migrated on Flame GPU validate the results obtained with the model on NetLogo, as well as the data obtained from the real system. The details of this validation and a comparison of the results obtained on Flame GPU, Netlogo and the real system can be checked in [26].

4. Experiments and Results

The development environment is used as a tool to support the decision-making process for health/civil protection agents to plan actions and direct awareness campaigns to reduce the number of containers that serve as dissemination vector.

This model and environment can be used to acquire knowledge by analyzing various scenarios, evaluating the likelihood that they could actually happen or obtaining information about cases that are hard to reproduce in the real world. The model can also be used to analyze real situations where the decision-making process has failed or where the decisions made were correct/incorrect. The information thus obtained can be used to improve health agent actions in future campaigns or as a

training tool for such agents to guide and define relevant actions. To achieve this, a large number of simulations is required to achieve the necessary statistical stability (more than 68,000 simulations per environment/scenario), and this is where the efforts to reduce execution time and energy consumption become relevant.

The GPU architecture allows achieving these two goals, and we have carried out a number of experiments that will be detailed in this section with the purpose of analyzing the energy consumption under different scenarios, varying the number of individuals and containers to check that the objectives proposed are met.

For our experimental environment, we used a GPU GeForce GTX 960 with an acceptable consumption/number of threads ratio; our support environment was a server based on Intel Core I7-3770K. For current measurements, we used a clamp ammeter (with a sensitivity pf 1A/100mv, 1A/10mv, 1A/1mv), and a transformer to measure voltage directly from the power line. Both devices were connected to a digital oscilloscope Rigol DS1074Z with a sampling rate of 1GSa/s and memory of 24 Mpts used by the input channels.

The information gathered during the simulations is processed offline, since the oscilloscope stores physical current (I) and voltage (V) measurements from both channels and, to find out the amount of power required to run the model at a given point in time (t), instant power is calculated using the equation $P(t) = I(t) * V(t)$ [watts] o [joules/sec]

The total sum of the instantaneous powers divided by the range of oscilloscope samples during the run time of the simulation gives as result the energy consumed (measured in joules). Figure 2 shows the energy consumed by the simulation models (NetLogo and FLAME GPU versions). For this experiment, the number of initial mosquitoes was increased from 300 to 30,000. As it can be seen, for the model developed on NetLogo, when container productivity is not considered, the simulation cannot be run at all due to the limited memory resources of the JVM. On GPU, we simulated a total of 80 days with a maximum value of 30,000 mosquitoes (container productivity was not considered). The results displayed here are the average of all power measurements for fifty runs of the simulation for the same scenario and parameters.

As shown in Figure 2, the use of a GPU platform for a reduced number of individuals (for instance, 300 mosquitoes) is not recommended, since the data show the overhead imposed by the environment negatively affects execution and performance and, consequently, consumption. In figure 2 the results of the energy consumption for 30 mosquitoes have not been plotted since their value is not significant.

As shown in [27] and [28], the average energy consumption per point in time is much lower on CPU architectures than on GPU ones. However, the significant decrease in runtime achieved by a GPU

architecture results in a lower overall energy consumption when using these platforms as opposed to conventional CPU ones. It can be clearly seen that, when the number of individuals increases, the energy consumed by the NetLogo version of the model (container productivity not considered and using the largest input size that the model could run) increases abruptly. This shows that the difference in energy consumption is evident and that the GPU architecture yields better results.
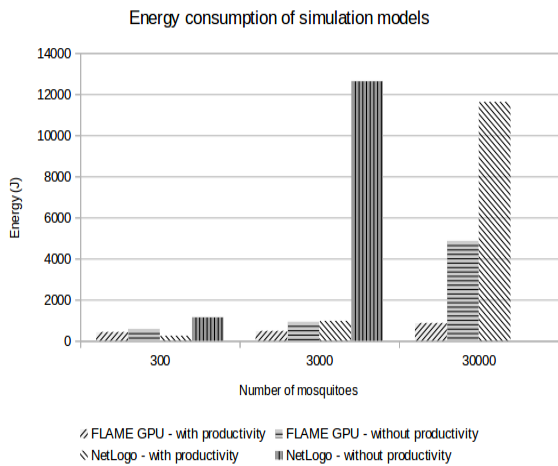

Fig. 2 Energy consumption of simulation models, considering containers with productivity and without productivity of the models

Considering the previous analysis, which verifies that the use of a GPU platform contributes to the reduction of energy consumption for each simulation experiment. As a consequence, it is possible to define a model that allows estimating the amount of total energy consumed by the simulation when the GPU is used as a computing platform. The average power represents the average energy required by the GPU to run the simulation experiments Table 1 lists the average power consumed by the GPU to run the simulation and the execution time required for simulating 80 days, with different entry settings for number of mosquitoes and container productivity, for the Flame GPU version of the model.

Table 1 Average power and execution time (seconds) for different initial numbers of mosquitoes.

Number of mosquitoes	With Productivity	Without productivity
30	114.45/3.61	114.90/4
300	115.69/3.7	120.45/4.56
3000	115.55/4.1	117.61/7,97
30000	115.46/7.53	113.51/40.27

We will consider the mean power for the GPU used to be 115.95, which is the average of all mean power

values measured. Using equation (1), the energy consumed by the simulation on the GPU used is calculated, where PMGPU is the mean power consumed by the GPU at a point in time, Time(N) is simulation time, in seconds, for an input size N, and v is a constant that includes factors such as temperature, cooling and environment conditions.

$$Energy = PMGPU * Time(N) + v \quad (1)$$

To estimate the time required for the different input sizes, a linear regression model is used, which allows estimating execution time for different sizes without having to run the simulation beforehand.

Using the regression functions obtained (Fig. 3), execution times can be estimated when increasing the initial size of the mosquito population considering container productivity or disregarding it.

Based on the power estimation model presented in (1), and the time estimation models (to simulate 80 days) obtained through linear regression (Fig. 3), the total power consumed by the simulation when using a GPU GeForce GTX 960 architecture can be calculated. Power measured results are an average for fifty iterations of the simulation.
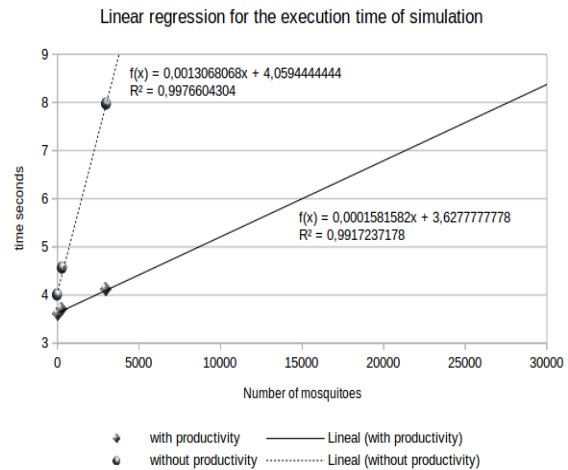

Fig. 3 Linear regression for simulation execution time.

Figure 4 shows the calculated power with PM_{GPU} = 115.95 and the execution times (in seconds) listed on Table 2. The estimation error when considering container productivity or disregarding is also shown. The largest error corresponds to a starting population size of 30,000 individuals and container productivity not considered, with a difference of around 3% between measured and calculated power. Figure 5 shows the percentage error when estimating the power required by the simulation for different initial mosquito population sizes.
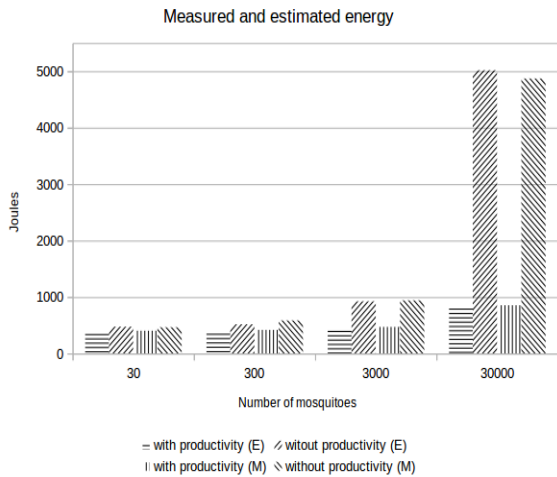
Fig. 4 Measured energy (M) and estimated energy (E), varying the number of initial individuals considering or not the productivity of the containers.

Table 2. Estimated time (seconds) for 80 days for various input sizes for mosquito population.

Number of mosquitoes	With Productivity	Without productivity
30	3.63	4.09
300	3.67	4.45
3000	4.1	7.97
30000	8.37	43.26

5. Conclusions

There are different aspects that affect our global ecosystem, such as power generation, global economic activities, people traveling, and so forth, that translate into an unprecedented change on global warming. This increase in temperature favors the reproduction of species that are the ideal vectors for the dissemination of new diseases or even those that were considered to be eradicated. It has been proven that in Argentina there is an uncontrolled expansion of the Aedes aegypti mosquito, which is the agent that carries the dengue fever, Zika and chikungunya, and that, as health authorities state, there has been a significant increase of corroborated cases of these diseases at latitudes that were once considered to be not suitable for the proliferation of this species.

From the point of view of computer science, tools are required that can assist the decision-making process and act as starting point for awareness and warning campaigns in relation to the problems caused by global warming in general and the propagation of diseases in particular. Towards this end, the tools proposed should not only provide accurate information to decide on strategies and policies, but should do so while not using more power than

absolutely necessary, so as to avoid contributing to the problem they are helping solve.

Thus, agent-based models have been developed to use simulations to obtain information about the system and support the decision-making process, while aiming at running these simulations in the shortest time possible and consuming the least amount of power.

In this article, the evolution of a model developed by our research group is presented and discussed, showing that the model and simulation environment proposed meet the requirements and that running on GPU + Flame GPU allows reducing simulation time and energy consumption for real population sizes. Additionally, it was shown that the simulation environment developed can predict the power consumed in each simulation run based on the number of individuals to be simulated and the desired life cycle, which allows researchers plan the experiments to carry out so as to not contribute to the causes of the initial problem that the model was designed to help solve.

In the future, this research line will focus on providing appropriate graphic interface tools to allow non-ICT-experts scientists analyze the data obtained with the simulations, as well as on exploring different GPU architectures that could potentially contribute even more to the objectives proposed and migrating the environment to cloud systems with this type of hardware to allow running simulations as SaaS (Software as a Service).

Competing Interests

The authors have declared that no competing interests exist.

Authors' contribution

RS conceived the idea. EM wrote the program, and with RS, conducted the experiments, analyzed the results and wrote the manuscript. RS, MN and LD analyzed the results and revised the manuscript. All authors read and approved the final manuscript.

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