Distributed Simulation of Greenhouse Climate: Canopy Models

R. Guirado, L. F. Iribarne, J. R. García, J. F. Bienvenido
Dept. of Computer Science. University of Almería, E-04120, Almería (Spain)
Phone: +34 (9) 50 21 56 91, Fax: +34 (9) 50 21 51 29
rguirado@ualm.es, liribarn@ualm.es, jrgarcia@ualm.es, jbienven@ualm.es

Abstract

Simulating greenhouses is a powerful method of testing possible structure designs. DAMOCIA-Sim is a general greenhouse simulation tool, which uses formal definitions of structures (generated by DAMOCIA-Design) in order to analyze them as radiation captors. This tool is composed by a set of independent and sometimes alternative submodels, which are related to specific physical models of given parts of the global simulation process, as the sun radiation model, cover optical behavior, solid elements shadows, etc. In this work, we present mainly a set of alternative submodels for the simulation of the effect of the greenhouse inside, as the vegetal canopy.

Keywords: computer simulation, multimodel simulation, canopy effect, radiation simulation, distributed systems

1. Introduction

Almeria province, in southeast Spain, is the biggest concentration of plastic greenhouses in the world. Actually, there is a process of renewal of the productive structure. This renovation includes ordering productive space and uses of natural resources as water, and improving the greenhouse structures themselves. Between the efforts that have been done by public and private organizations, it was the DAMOCIA project, *Computer-aided design for the Construction of Automated Greenhouses* (Bienvenido et al., 1996). It was developed by a consortium of private companies, the FIAPA research center and the University of Almería, and financed by the European Union into the framework of the ESPRIT projects (Special Action P7510 PACE) and the Spanish Ministry of Industry (PATI PC-191).

One objective of this project was simplifying the testing process of new structures, incorporating previous computer simulation to their design process. Our proposal was to develop a specific simulation tool, which simulates the behavior of the structures as radiation captors. The final objective was to test virtually multiple structures and build, only, those offering good behaviors. The complex simulation process is broken into several submodels that correspond to different steps of the global process. These submodels are computed with independent software elements, agents, which are integrated by a general manager module. It is possible to incorporate different alternatives for the execution of a given step of the simulation process. These alternatives use different physical models, with different approaches to a same problem and require different resources.

This work presents specifically a set of alternative submodels for the simulation of the effect of the greenhouse inside, as the canopy. We discuss six different models, applicable to different

situations and with different computing resources requirements and final precision.

2. General model of simulation

One of the main objectives of the DAMOCIA project was evaluating the behavior of the radiation, which goes into the greenhouse, for different structures. This evaluation is made obtaining a map of the incident radiation on inner faces of the greenhouse. The proposed model takes account of possible absorption levels in different zones of the greenhouse and a set of internal reflections. The DAMOCIA-Sim (Bienvenido et al., 1997) tool is complemented with another tool, DAMOCIA-Design, which generates formal definitions of greenhouse structures. By means of our design and simulation software tools any greenhouse structure can be pre-evaluated, simply defining its design parameters and simulating its behavior (Critten, 1988) (Bot, 1983). Between the simulation characteristics are the period of time and location of the simulation, greenhouse cover and soil characteristics, and the parameters of the selected absorption model (this depends of the growing and its evolution).

2.1. Methodology

One of the techniques used in the implementation of DAMOCIA-Sim is discretization. This is applied at three levels: time, surface and volume. Simulation time is divided in fixed intervals, associated to precise moments, evaluating the greenhouse behavior in each one of them (we use intervals between one and ten minutes). Surfaces are divided in finite elements too. A finite element is the minimal computing unit, whose behavior, concerning radiation direction and intensity, is considered uniform. There are situations, where there are surface extensions with uniform behavior that have sizes superior to that of the finite elements. So, it is introduced the concept of macroelement, a group of finite elements with same behavior. Volume discretization divides the inner space of the greenhouse in regular cubes, assigning them specific absorption coefficients.

DAMOCIA-Sim was implemented using the DACAS architecture (Bienvenido et al., 1998), that implements the different modules (and relative submodels) as independent agents (Kirchner, 1997). So, the execution of the application can be distributed between several machines when the computing requirements demands it (Kurihara, 1997). Communication between modules is accomplished through message passing; using pre-established formats. These are transferred through a software bus that connects the modules. The modeler executes the modules using three basic schemes, showed in Figure 1 (Iribarne et al., 1997):

a) Sequential execution, where the output of each module is used as the next module input.

b) Alternative execution, where the modeler selects one of several modules that use the same input format and generate outputs with the same format.

c) Parallel execution, where, from a given state, several independent modules can be executed. The whole set of outputs allows reaching the next state of the execution.

These modules implement, usually, simulation submodels, specific parts of the simulation general model with domain meaning. The alternative schema allows using alternative models,

which evaluates the same domain object with different computing methods.

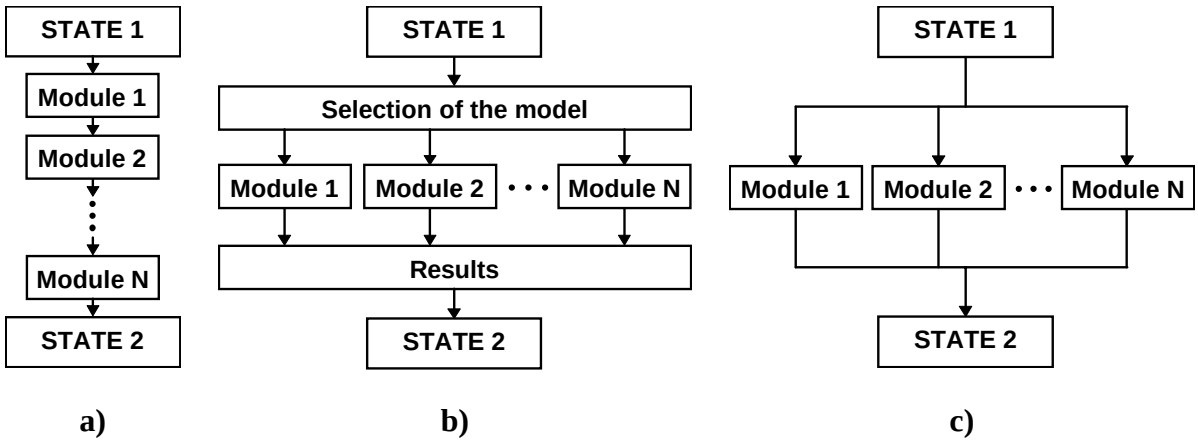

Figure 1. Module execution schemes: a) Sequential, b) Alternative, and c) Parallel.

2.2. General architecture

The general architecture of the tool shows three main submodels (Figure 2). First, it is calculated the sun position (A), as well as the intensity and direction of the radiation that reaches the earth surface in a given instant (B). Second, the tool obtains the radiation that crosses the greenhouse cover (C), taking in account its structure, cover optical characteristics and external reflections. Finally, once it is obtained the radiation that crosses each surface, it is computed its evolution taking account of the canopy and the cover and soil characteristics. It computes reflections and energy absorption for successive iterations (D), generating radiation maps for each surface.

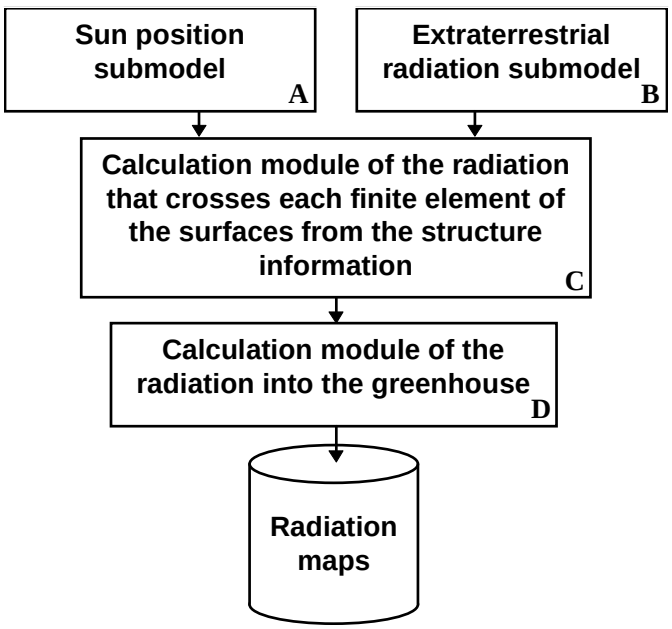

Figure 2. Tool General Architecture

This work is centered mainly in the last submodule (D), that is, the behavioral study of the

radiation into the greenhouse. Their inputs are the intensity and direction of the radiation that has crossed the different greenhouse surfaces, the structure characteristics and the crop density. This submodule architecture is showed in the Figure 3.

Since this is an iterative process, it should be established an end condition that defines limit for the execution. This limit can be established from two points of view. First, it could be restricted the number of iterations to do during the submodule execution. Second, it could be established a minimal radiation threshold, below of which is not considered the reflected radiation. Actually, the loop end condition has been implemented as an OR operation between the two previous simple conditions.

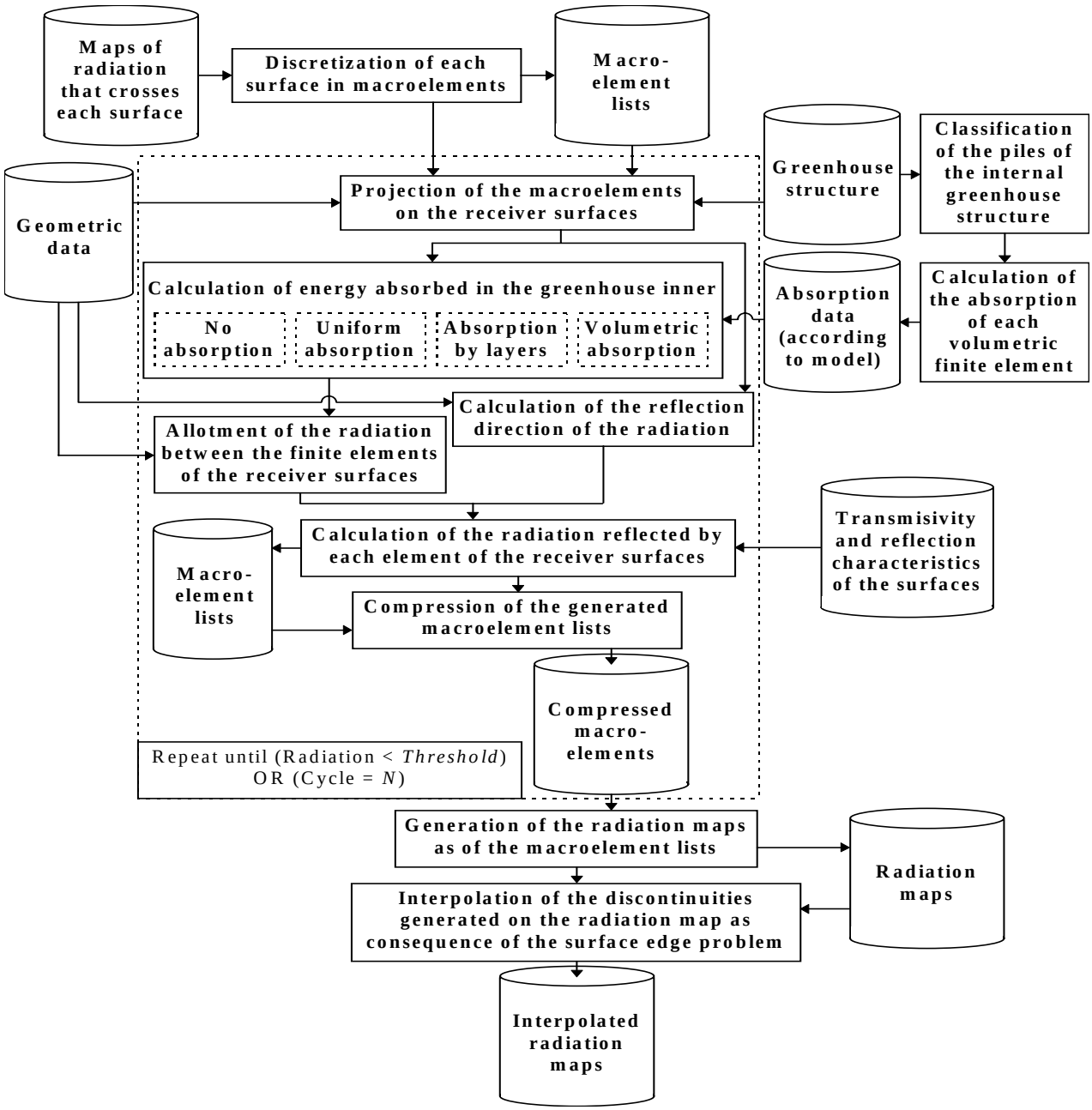

Figure 3. Module architecture of behavioral study of the radiation into the greenhouse.

3. Absorption models

The greenhouse canopy can present several situations. So, we have developed several alternative models representing main situations. This set of alternative canopy models is not closed. Thereby, if it is considered a new situation of the canopy, we can design and implement a new and independent executable module. In a first level, we have developed four absorption models:.
a) No absorption. This model is applicable to greenhouses without vegetal canopy and low humidity. In the Figure 4, the radiation intensity that, coming from one surface (E.S.) macroelement, reaches other surface (R.S.), it is exactly just the same for their point. Since the radiation that crosses the macroelement MACRO of E.S. is uniform, in this cycle, the incident radiation over P1 is equal to the incident radiation over P2.

b) Uniform absorption. This model is applicable to greenhouses without canopy and high humidity and/or great quantity of scattered dust. This model is based on applying an absorption coefficient (constant), and taking account of the distance traveled by the light front into the greenhouse. The more distance, the more quantity of energy will be absorbed. In this case, the absorbed energy into the greenhouse is

$$E_{ab} = E_e \cdot C_{ab} \cdot d \qquad \text{Eq. (1)}$$

where E_e is the energy emitted by the radiant finite element, C_{ab} is the absorption coefficient per traveled meter and d is the traveled distance by the light ray from the emitted surface to receptor surface. In the Figure 5, the incident radiation over the point P1 of the receptor surface (R.S.) is different than that over the point P2. As D1 is minor than D2, more energy will be lost by absorption in P2 than in P1, receiving less radiation in this cycle.

c) Uniform absorption by layers. This model has application in greenhouses with canopy compactly distributed with different heights. In this case, the implementation has been done over a similar schema of that of the previous model, but with the greenhouse divided in horizontal layers, each one of them with its own absorption values. This way, the absorbed energy is calculated using the distance covered by the ray in each level and its absorption coefficient. So, energy absorbed by each layer is computed with this equation:

$$E_{ab} = E_r \cdot C_{ab} \cdot d \qquad \text{Eq. (2)}$$

where E_r is the energy received from the previous layer, C_{ab} is the coefficient of absorption of the layer, and d is the distance traveled by the ray within this layer.

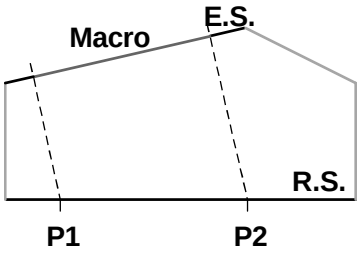

Figure 4. No absorption scheme

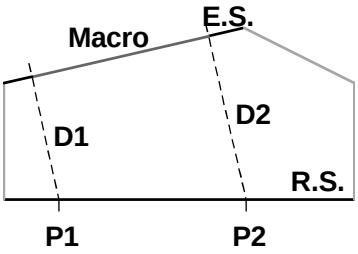

Figure 5. Uniform absorption scheme

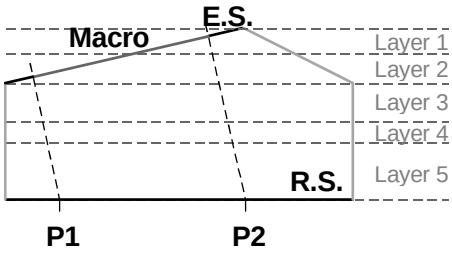

Figure 6. Scheme for uniform absorption by layers

Radiation loses intensity as it crosses each layer, evaluating this reduction using the distance covered into each layer. In the Figure 6, the ray that reaches P1 crosses layers 3 to 5, while the one that reaches P2 crosses in addition layers 1 and 2. Therefore, radiation falling over P1 will be minor than that falling over P2. The different layers, in which the greenhouse is divided, are established in the definition of the experiment. They can have different heights.

d) Absorption by volumetric finite elements. It is applicable to greenhouses with high vegetal canopy and wide corridors. Inner space of the greenhouse is divide in volumetric finite elements (parallelepipeds). Associating, to each one of them, an absorption coefficient based on the density of the growing mass and fixed elements of the structure.

In this case, beams lose intensity by absorption as they crosses the volumetric finite element in their routes until the receiver surface (R.S.). The absorption on each volumetric finite element can be different. The fraction of a volumetric finite element crossed by the projection of an „emitter“ macroelement can be computed using different submodels, which requires different computing efforts. We have implemented, by the moment, three alternative models:

d1) One surface projection submodel. It computes the fraction of the superior surface of the volumetric finite element crossed by the light front. The absorbed radiation for each finite element is computed with the following expression:

$$E_{ab} = E_r \cdot C_{ab} \cdot \frac{A_{EFR-EFV}}{A_{EFR-S}} \qquad \text{Eq. (3)}$$

where E_r is the received energy from the previous level, C_{ab} is the absorption coefficient of the volumetric finite element, $A_{EFR\text{-}EFV}$ is the intersection area of the projection of the radiating finite element on the superior surface (of that level of elements, L_n) with the volumetric finite element superior face, and $A_{EFR\text{-}S}$ is the total area of the projection of the radiating finite element on the superior surface of that level. In Figure 7, these intersections can be appreciated with different tones of gray scale. This model is similar to that of uniform absorption by layers, but using same height layers and spliting the layers on blocks with different absorption levels.

d2) Two surfaces projection model. It takes account of the fractions of the light front that cross

the volumetric finite element superior and inferior surfaces. Using the average value, it computes the absortion of each specific finite element using the following expression:

$$E_{ab} = E_r \cdot C_{ab} \cdot \frac{\frac{A_{EFR-SEFV}}{A_{EFR-S}} + \frac{A_{EFR-IEFV}}{A_{EFR-I}}}{2} \qquad \text{Eq. (4)}$$

where E_r is the received energy from the previous layer, C_{ab} is the absorption coefficient of the finite element, $A_{EFR\text{-}SEFV}$ is the intersection area of the projection of the radiating finite element (or macroelement) on the superior surface of that level with the superior face of the volumetric finite element, $A_{EFR\text{-}S}$ is the total area of the projection of the radiating finite element on the superior surface of that level, $A_{EFR\text{-}IEFV}$ is the intersection area of the projection of the radiating finite element on the inferior surface of that level with the volumetric finite element inferior face, and $A_{EFR\text{-}I}$ is the total area of the projection of the radiating finite element on the inferior surface of that level.

In order to obtain the radiation absorbed by each finite element, it computes the intersection areas of the superior and inferior surfaces of each finite element with the projection of macroelement M on the their planes. In the Figure 8, these intersections can be appreciated with different tones of gray. This model improves the exactitude of the previous one.

d3) Cross volume model. It computes the volume of the volumetric finite element crossed by the light front. Using this volume it calculates the radiation absorbed by each specific finite element using the following expression:

$$E_{ab} = E_r \cdot C_{ab} \cdot \frac{V_{EFR-EFV}}{V_{EFV}} \qquad \text{Eq. (5)}$$

where E_r is the energy received from the previous layer, C_{ab} is the absorption coefficient of the volumetric finite element, $A_{EFR\text{-}EFV}$ is the volume of the volumetric finite element crossed by the projection of the radiating finite element, and V_{EFV} is the total volume of the volumetric finite element. In order to obtain the radiation absorbed by each finite element, the module computes the volume of the finite element crossed by the projection of macroelement M (in a dark gray in Figure 9) and the volume of the L_n layer crossed by it (volume included by the clear tone of gray surfaces, including previous volume). This model obtains the best results of the proposed methods, but with a high cost due to the complexity of its calculations.

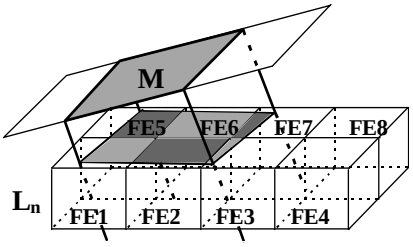

Figure 7. Model 1 for volumetric absorption

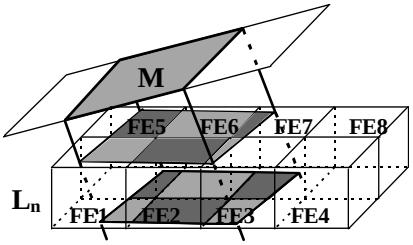

Figure 8. Model 2 for volumetric absorption

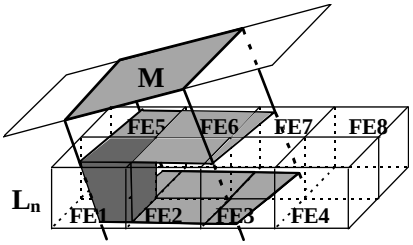

Figure 9. Model 3 for volumetric absorption

4. Conclusions and future works

In this paper, we present how it has been possible to apply modern simulation techniques to the simulation of greenhouses in a general way. Main conclusions related to the work are:

- It is possible modeling the radiation behavior in greenhouses with alternative submodels, *each one of them representing different greenhouse conditions and/or use of simulation resources*. One of the most interesting sets of submodels includes canopy models.
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- Using of distributed simulation architectures improves adding new models of the greenhouse inside, and modifying previous models.
- A general simulation tool lets us to estimate the behavior and compare multiple different greenhouse structures. This way it is possible a virtual evaluation of the structures.
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- Between actual and future works, it is possible to sign these:
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- Including evaluation of the diffuse light behavior into the model. Actually, the tool evaluates greenhouse differences evaluating the fractions of direct light that reach greenhouses. Diffuse light is computed as a uniform and constant value.
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- Developing temporal models of the canopy, changing automatically the absorption values associated to the volumetric finite elements.
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- Interconnecting temporal canopy models with the radiation models, in order to evaluate the appropriateness of different structures for specific cultures and canopy organizations.

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5. References

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