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Microclimate simulations by Freefem++ for efficient Architecture design

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Abstract— The interaction between the buildings and the atmospheric phenomena produce microclimates in its nearby environment, characterized by air characteristics that differ from the outside average. These characteristics depend, among other factors, on its architecture. A certain building design can modify greatly the temperature in these spaces in a natural way. This is the case of courtyards, where there have been monitored air temperatures one quite lower the exterior ones during the summer in hot and temperate climates like the Mediterranean one [1]. To understand and to quantify this effect allows a building design to take advantage of it in an effective way improving the building's energy efficiency. But the physical complexity of the phenomenon and its strong interaction with formal design, has prevented its controlled use in architecture till now. The present study confronts the problem by means of a proper collaboration among mathematicians, engineers and architects. In this sense this makes more accessible the big potentiality of the free code FreeFem++ mathematical tool to develop the numerical simulations of these microclimates proposing its simple integration with the proper architecture and engineering software. Therefore, to confront the problem, the use and the integration of these programs: AutoCAD® , SketchUp®, FreeFem++ and ParaView will be proposed.

Keywords: Applied mathematics, Architecture, finite element method.

1 Introduction

To achieve to understand, quantify and apply in the building design the described microclimatic phenomenon, it is necessary:

1. The possibility of a rapid three-dimensional geometries elaboration by means of proper architecture CAD software.
2. A precise but simple meshing of this geometry.
3. A direct introduction of this meshed geometry in numerical simulations software based on Freefem++.
4. Its later analysis by means of proper engineering software.

Thus the efforts will be optimized so that every knowledge area provides the best of its specialty. The goal is to be able to use this tool for real construction of more efficient buildings in an operative and professional way.

Following this strategy, the activity of the project PATIO TEP-7985 [2], project of research excellence of the government of Andalusia, it integrates knowledge of these three fields (engineering, mathematics and architecture) belonging to two universities (University of Seville, University of Cadiz). The research studies the quantification of the phenomenon in order to take advantage from its performance. The energy save is obtained if the courtyard's air is introduced mechanically in the air conditioning system, improving the installation performance and therefore the energy efficiency of the buildings [3].

Understanding and quantification of the phenomenon requires a powerful simulation tool that provides accurate calculation, flexibility and transparency: powerful enough to calculate the Navier-Stokes equations to define the behaviours of the fluid mechanics coupled with those equations that define thermodynamic behaviours; with sufficient flexibility so that the model can be modified according to the adjustments needed when comparing them to the physical reality; and transparency to enable understanding of the mathematical model of the physical processes.

These characteristics are typical of the open source code methods used in science. Although applying them to real situations requires such tools to have a level of usability that allows the complex geometric data in real architectural situations to be entered and meshed quickly and easily. If the architectural form is the key factor in this microclimate then the architect must study

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this environment carefully and apply the knowledge acquired. However, usability is more a feature of commercial programs than those developed in the scientific field. Open source code and usability are usually incompatible, and the lack of the latter means that the knowledge generated in the course of an investigation cannot be put to best use by professional architects when designing and studying strategies to improve energy efficiency in real buildings.

2 The proposed method

Based on what we have described so far, we propose specific tools for each part of the simulation (pre-process, process and post-process) for the execution of this method. For constructing the geometry, we propose the programs for drawing, design and 3D construction most widely used among technicians. For the meshing, we recommend GMESH. The pre-process is the building of the geometry and the meshing. For the process, the nucleus of the calculation of the numerical simulation via the finite elements method, we propose Freefem++. And for the post-process, in other words the visualization and analysis of the results, we suggest the ParaView program.

2.1 Assisted drawing programs

There are many assisted drawing tools on the market for 3D constructions, and the two most widely used are AutoCAD® and SketchUp®. AutoCAD® is the main commercial CAD program for computer-assisted design but SketchUp® is becoming the preferred program of use for quick and intuitive geometric 3D constructions as its basic version is free. Both are standard tools in architecture and engineering faculties.

As we emphasise in this article, the aim is to involve in the method those who best understand each part of the investigation: the pre-process (constructing and understanding 3D forms). To understand the science of the processes of interaction between the forms and the physical medium, as in the case of microclimates, we consult experts who understand physical media and forms. And to understand the forms means acquiring a better understanding of the characteristics of 3D objects and, consequently, of the three-dimensional physical phenomena they cause. This is true of the flow patterns that are so vital to the study of microclimates [6].

So, to achieve this we need to study the bridges that link the CAD programs already discussed to Freefem++.

2.2 File exchage

After studying the import and export compatibilities of the various programs, we propose using the IGES format (whose file have extension *.igs) between drawing programs and the GMESH meshing, and the MESH format (whose file have extension *.mesh) between GMESH and Freefem++.

IGES (Initial Graphics Exchange Specification) is a neutral data format that enables the digital exchange of information between computer-assisted design (CAD) systems. Despite the emergence of STEP, IGES continues to be the most widely used standard format for exchanging 3D graphics files.

2.3 AutoCAD®

The Autodesk program is widely used in universities and architectural and engineering companies in many countries. Its official website offers ample information on the program's features and a downloadable test version [5].

Thanks to the utility of the IGES format, the AutoCAD® 2012 version exports directly to IGES although this option does not appear by default in the export dialogue box. You have to deploy the submenu "other formats" in the "export" option to locate it.

2.4 SketchUp

Although the AutoCAD® program is the most popular, it has two major drawbacks that led us to search for possible alternatives.

Although the program is made specifically for CAD drawing, constructing three-dimensional volumes with this tool is not fast or intuitive. It is difficult to outline a volume and modify the finished geometry quickly. By contrast, AutoCAD® offers considerable accuracy, and final projects are normally drawn up using this program.

However, the nature of the study in this investigation does not require mathematical precision. What is important is that the architectural spaces and their microclimate features are not affected by alterations in millimetres to their dimensions since the details of the architecture and the spaces are normally defined in centimetres. A meshing that generates a mesh of 10 to 30 cm is usually sufficient for the dimensional accuracy needed.

What is more important is the speed at which 3Ds can be constructed, something which AutoCAD® lacks. To boost the potential of the study at the heart of this research requires constant experimentation with various geometries that can be quickly put together, thus enabling comparisons and decision-making on its formal design.

A good alternative is the much-used program for constructing 3D objects, SketchUp. It is simple and fast, the models can be easily modified and the SketchUp Make version is free (this is the basic version but sufficiently sophisticated for this study). Information about the program and downloading can be found on the official website [6].

So, the proposal is to use SketchUp to build geometries quickly and simply and then export them in the IGES format, which GMESH can read, and continue the method described above.

The SketchUp Make export options do not include exporting in IGES format, but the SketchUp community on internet has developed a plugin that enables this [7]. The "iges-export.rb"export file is copied in the Tools folder of SketchUp 15 which is in the program files. The option to export the solid is found in the program tools' submenu under the name "IGES export".

2.5 ParaView

For the presentation and analysis of the results (post-process) we also consider using another program designed specifically for this task, ParaView. This is an open source multiplatform tool for data analysis developed by the Los Alamos National Laboratory of the U. S. Department of Energy in collaboration with Kitware Inc. [8].

After performing the simulation calculation process in Freefem++, the results can be exported from Freefem++ to a VTK library ((whose file have extension *.vtk) and read by ParaView, which provides the user with ample scope to analyse the data [9].

2.6 An example of process application

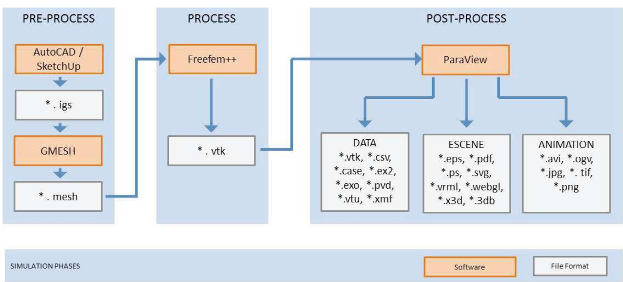


Figure 1: Diagram of the method proposed

In synthesis, the method proposed is the following: the geometry is drawn using AutoCAD® or SketchUp® and exported in the IGES format and read in GMESH. This program is used for meshing the volume generated as it is made specifically to carry out this task. The mesh is then exported as MESH. All this constitutes the pre-process. Freefem++ reads the mesh format (*.mesh) and this program is then used to make the calculation (process). The results are presented and analysed (post-process) by exporting the results from Freefem++ to a *.vtk library. These results files are read by the ParaView program where they can be easily studied and analysed, and then exported to other data presentation formats (fig. 1).

A simple example can illustrate this by entering in Freefem++ a mesh of a room measuring 3x3x3m with a 1x1m window in the middle of the two walls facing each other. The first step is to construct the geometry in SketchUp® (fig. 2).

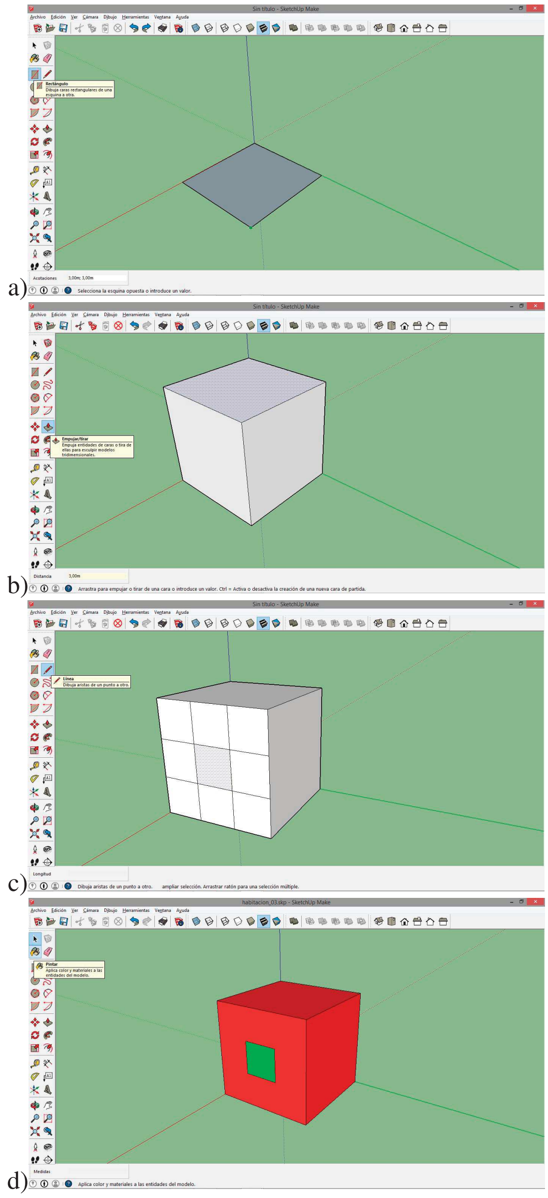


Figure 2: Construction of a geometry in SketchUp®

This type of sketch is one of the simplest systems available for constructing volumes, allowing us to try out various forms with different thermodynamic behaviours. The volume can be modified at any time by stretching one of the sides with the push-pull tool; this is an example of the program's flexibility enabling the volume to be modified quickly when searching for a form that generates a different microclimate.

The line tool lets us trace reference lines on the sides. The lines on a plane that delimit one area of a side of a solid in SketchUp® defines a region that is different from that plane (fig. 2c). We can identify this feature by clicking on the zone and observing the shadowed area, and this can be stretch, cut or coloured separately from the rest of the plane. This quality is very interesting because the program automatically identifies the region, labelling it so that it can then be recognized as a numerical model. The IGES format uses numbers to automatically identify each of the regions generated.

So now we export the geometry to IGES using the plugin we have placed in the tools menu (fig. 3a). When dealing with more complex geometries, we check that only one group has been created in order to ensure the exportation is done correctly. It is also important to remember that GMESH does not import files stored on lower levels (subfiles inside subfolders). It is advisable to temporarily shift the *.igs export files to the desktop to import them from GMESH without problem.

Next step is to open the GMESH program and the *.igs file is imported. This is done by opening the File menu, selecting Open and locating the *.igs file on a level close to the desktop (fig. 3b). When we import the file nothing appears in the window, which means it is not very intuitive. This happens because the geometry elements of the "Geometry"dialogue box remain closed by default. You have to open the "Tool"menu, select "Option", then "Geometry"and mark the elements that you wish to visualize (fig. 3c).

It is important to check that, as in our example (fig. 3c), there are labels for the points, vertices, and differentiated sides and regions within the sides. These labels are fundamental so that the regions can be identified and assigned different contours in Freefem++.

Now the 3D meshing can be done. This is done by opening the "Mesh" menu and clicking on 3D (in red in the figure). After a few seconds for processing due to the complexity and volume, the first meshing then takes place. As in the previous case, the data which appear are confusing as you only see the labels that correspond to the mesh nodes. You have to return to "Option" and select "Mesh" and mark the elements of the mesh you wish to see (fig. 3d). In "Mesh", it is important to be able to visualize the lines, the sides and the vertices of the sides (2D mesh in sides) in order to check that the elements have different colours. We then select "Lines", "Surface Edges" and "Surface Faces", by which we ensure that the program has separated and correctly labelled the different sides and the different regions of the same sides.

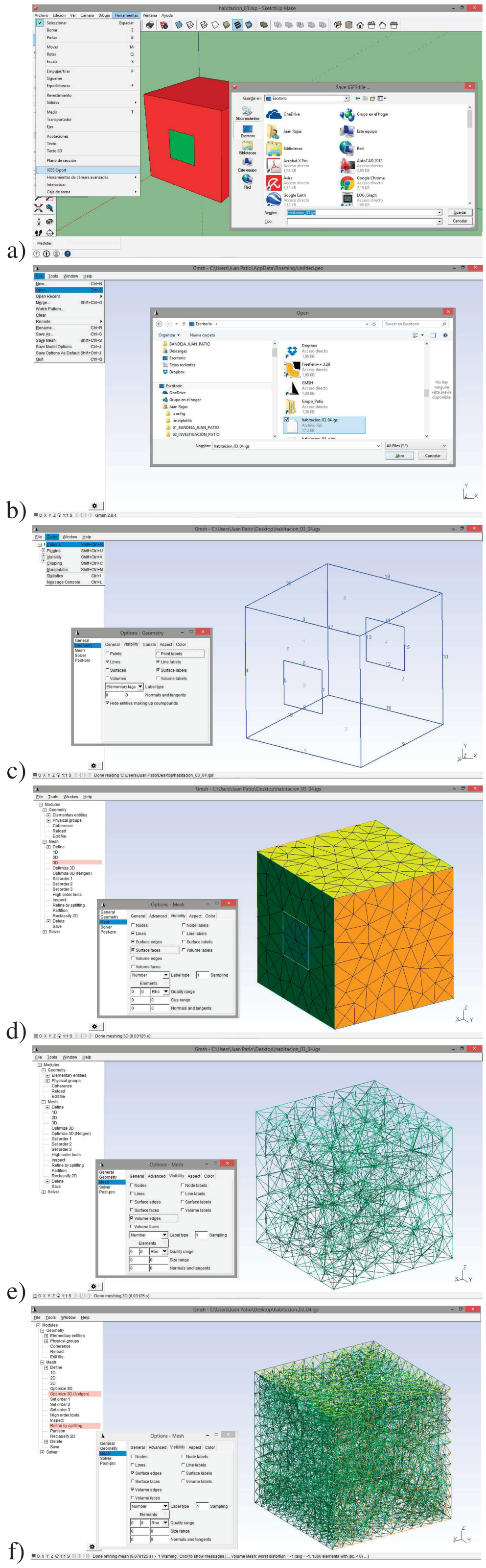


Figure 3: Exporting the geometry in the *.igs format from SketchUp®

We check that a 3D mesh has been done in the volume by selecting “Tool”, “Option”, “Mesh”and marking “Volume Edges”(fig. 3e).

Now we can proceed to optimize and refine the mesh, first by clicking on “Optimize 3D (Netgen)”, which is marked in red (fig. 3f). By clicking on it once, a slight repositioning of the mesh’s tetrahedrons occurs. Another click produces the same effect but this time it is less perceptible. If we continue clicking, we notice that the alterations become smaller and smaller until the mesh no longer changes. At this point maximum optimization has been reached, thanks to the program’s Netgen module.

If we need the mesh to be even finer, we can use the “Refine by Splitting” option. Unlike the previous example only a single click is normally necessary, as the mesh grows considerably in density (fig. 3f). A second click for this geometry could make the mesh very dense, with too many polygons to enable calculation in Freefem++ in reasonable time. A third click would produce a mesh impossible to calculate. At this point we notice that GMESH has no option to “undo”. If we make a wrong calculation in refining the mesh and we make it too dense, we have to go back and start again by importing the *.igs geometry. However, this process is quite quick so miscalculating is not such an important error.

To export the mesh for Freefem++ we select “File” and “Save As”, and in the menu that appears with different import formats we choose *.mesh (fig. 4a). It is important not to confuse it with the *.msh native format that GMESH uses to save the meshes by default. Freefem++ cannot read the *.msh format, only *.mesh. And although we have selected the *.mesh format in the option menu the file still has the *.igs extension, so we need to attach the new extension manually.

A *.mesh file has been created and now which we can save on any subdirectory level in the computer. If we have Freefem++ installed, it can be read without problem.

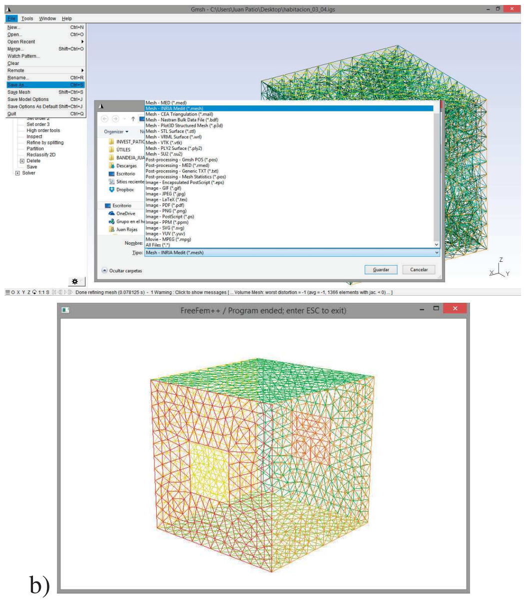
And with Freefem++ installed on the computer, we can import the mesh from Freefem++ by writing the following lines of code:

```
mesh3 malla=readmesh3("room1.mesh ");
plot(malla);
```

This is saved as *.edp, placing the mesh file “room1.mesh” in the same directory as *.edp. When executing the edp we observe that the mesh has been read by Freefem++, as appears in fig. 4b. The meshing and labelling are correct, so we can proceed to the nucleus of the process.

In the process or calculation phase, an application of the method to the study of fluid dynamics in the room is showed. We apply the Navier-Stokes equation for a three-dimensional space.

a)



b)

Figure 4: Mesh made in GMESH and imported in Freefem++ with geometry constructed in SketchUp®

In the Freefem++ code, we write the commands to read the mesh, the commands to solve these equations and the commands to resolve save each iteration in a *.vtk library.

We then use the ParaView tool to open the *.vtk library. This program allows us to analyse pressure values, speed vectors and current lines, among other results of the simulation. It also helps us to visualize and understand its distribution and evolution within the three-dimensional space. This is vital for understanding the specific structures that emerge and which are the results of the interaction between the physical properties of the fluid in motion and the form of the space in which it moves. In other words, the design of the space modifies these structures. So, being able to see them more clearly enables us to produce an architectural design that best fits these characteristics.

Fig. 5a shows the meshing of our example in ParaView, and fig. 5b a display of the simulation results representing the streams lines.

Thus we have got what we intended to achieve at the start of this work. The use of specific programs optimized for each of the processes. In particular the coherent use of programs that are powerful and comfortable to use when constructing 3D geometries which are compatible with the other programs used in the various processes, as well as programs that can offer better 3D interpretation of the results.

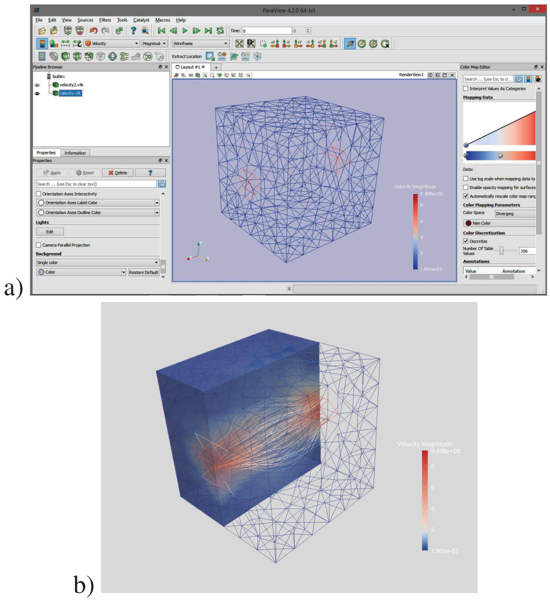


Figure 5: Displays results in Paraview. Study of fluid dynamics in a room with windows. Streams lines

3 Conclusions

The immense potential of microclimates generated by architects to increase energy efficiency in buildings requires the development of simulation tools that enable us to understand these environments better and calculate them more accurately. The nature of the challenge means that different fields of knowledge, such as architectural design, mathematic models and energy engineering, need to interact.

The physical aspects of the problem demand that the nucleus of the calculation tool is based on a numerical simulation of considerable power. The Freefem++ based tool possesses these characteristics. However, It is necessary to support the usual drawing programs to make it suitable for its application in architectural desing.

A method that builds bridges between these drawing tools to create the geometry (AutoCAD® and SketchUp®) is proposed, which allow the meshing (Gmesh) and a tool based in Freefem++. Finally we consider the use of a specific program for analyzing data (ParaView).

This path both leads itself to interdisciplinary collaboration between architects, mathematicians and engineers while maintaining the use of the tools that are most appropriate for each of these fields of knowledge. Beside this enhances the overall quality of the work as each phase is controlled by the specialist in each area. This is a good procedure to improve the knowledge of the phenomenon, producing a design process more responsive to the requirements of eco-efficient building.

Acknowledgements

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