SIMULA_3D : A MULTI-ZONE UNSTEADY THERMAL SIMULATION TOOL BASED ON A 3D MODELLING OF THE BUILDING

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ABSTRACT

Generally, geometrical data of the building do not constitute an usual detailed input for the thermal simulations, but nevertheless they become necessary as soon as accuracy is needed to take into account incoming solar energy, to measure the radiant exchange or to assess comfort. Our objective, in the elaboration of a new version of the thermal simulation SIMULA_3D code is to give the right place to the 3D geometric data to achieve such performances. Thus, our presentation underlines principles and methods elaborated to generate these 3D data and exploit them in the different simulation and of visualisation modules.

INTRODUCTION

Simula_3D, actually in progress, is a new version of the multi-zone unsteady thermal simulation tool called Simula, elaborated by our laboratory, that re-uses existent procedures of the actual version and includes new procedures developed in a solar and luminous simulation program, called Solene, also developed in our laboratory. During the development phase that was concerned, at the same time, by the design of a user interface in the Windows environment and the integration of new simulation functions, the 3D modelling of the building was an essential feature of the new product.

First, this way to consider the building in 3D enables a very easy and visual mean to input the necessary data about thermal links in the building. So, modelling the volumes of the building defines, automatically, at the same time, the thermal model to simulate. It constitutes the base of the user interface.

Secondly, in many procedures where precision is desired, information about geometry is absolutely required. It is the case, for example, for assessing the luminous or solar spots inside the rooms taking into account, geometrically, the mask effects. It is particularly useful for determining the solar transmission inside the building taking into account the successive crossing of various windows and, for obtaining the realistic distribution of solar absorption during time on internal or external walls of the building .

Moreover, 3D geometrical data enable to use, dynamically, a spatial discretization of surfaces to resolve specific problems such as the ones that deal with the solar or luminous multi-reflection using the view factors, the thermal radiant effect or the assessment of radiant comfort in rooms.

At last, the geometry of the building can be an ideal and attractive support to display results of simulation, showing the different zones or surfaces of the building with temperature, comfort level or others thermal characteristics.

More than a presentation of thermal principles involved in Simula_3D, this paper aims to expose and to explain the ways by which the 3D geometrical input of the building are used in the various simulation phases of Simula_3D and how they can improve, in a large amount, the realism of simulation conditions, especially for solar and comfort analysis.

THE 3D MODELING OF THE BUILDING AND THE INPUT DATA FOR THE THERMAL SIMULATION

Several ways and means are able to represent and model the building as a thermal system in such a way that it can be numerically resolve. Basically, to build the system enabling to do thermal simulations, it is necessary to produce a decomposition of the building in elements in terms of thermal exchanges with usual associated transfer characteristics of conductivity, capacity or air exchanges. A wall becomes a surface node with eventually several internal nodes, each one related to the other, and the external ones linked to the node corresponding to the air volume of the room or the outside. The system representing the whole building is then a network of nodes; links between nodes representing specific heat transfer following thermal rules.

The node represents thus either a surface element (wall, floor…), either a volume (building, room…) and the thermal model can be reduced to a structured set of thermal links between nodes. If the node is a surface, it can support properties such as solar coefficients or radiant characteristics, but, whereas topological links between air nodes can be exploited, its geometrical definition is unknown. At the most, one can associated to a wall node an exposition and an inclination to define its situation relatively to solar or wind exposure. This way to not consider geometrical properties of the walls and rooms constitutes however a serious obstacle for dealing precisely with specific thermal exchanges or for taking into account, for example, with sufficient accuracy the internal solar gains. But the simplicity of this kind of model makes it commonly used.

However, the list of nodes and thermal links has to be defined by the user and input for the simulations, constituting a time-consuming and sometimes fastidious task. We can easily substitute a new way to input that type of data (identifying nodes, evaluating surfaces, giving thermal and solar properties…) by modelling in 3D the main thermal zones and volumes of the building.

However, some conditions must be respected:

- First, that the task for modelling the building be no longer and no harder comparatively to the usual way to proceed;

- Secondly, that the 3D definition frees the user to input others data, like surface or thermal links;

- Thirdly, that the user can dispose of a simple 3D modeller, with convenient facilities and friendly user interface for dealing with thermal problems in building;

- at last, that it enables to improve significantly the building simulations.

For modelling the building in 3D, two ways seems to be convenient. The first one is to import an existing model and to structure it in a way that it can be used by the simulation programs. But, generally two important obstacles are put in the way of this plan. The model is generally design for others purposes, corresponding to an architect layout or a plan for structural calculations, that do not match necessarily the model to build for carrying out thermal simulations. Moreover, the data that can be extracted are sometimes not sufficient for building the model (extraction from a 2D layout, for example); and some are totally missing; or inversely they are too numerous and precise to be quickly and efficiently used. The thermal model of the building is generally very different from the simple room distribution as designed in a layout of the building. Thus, this import task, even it is desirable, constitutes a job in itself and can be considered only when exchanges format and standards will be sufficiently developed and commonly accepted to translate a 3Dmodel in another 3Dmodel.

The second one is simply to build a specific thermal model of the building, retaining only pertinent information, in direct relation with the used procedures to resolve the thermal problem. So, one can imagine volumetric entities and operations between them. To help to build these entities for a specific building, existing layouts of that building can be use as an informative layer to locate or give right sizes to the different elements under constructions. The final 3D model is thus generally considerably simpler that a detailed plan made by an architect.

THE 3D MODEL OF THE BUILDING IN SIMULA_3D

In Simula_3D, this second solution was chosen but with the possibility to import, under some conditions, a 3D model from usual CAD software. It is based on a system that mixes thermal and volumetric entities in a combination that enables their easy manipulation and their management by the ACIS geometrical library. Three types of entities are proposed:

- The thermal zones (called thermal "ambiances") where one can consider that the air temperature inside is quite homogeneous. This entity can represent one or more rooms (volumes) of the building submitted to the same climatic and use conditions.

- The "mask" entities are volumes of the surrounding that can interfere on the thermal behavior of the thermal zones (opposite building, adjacent building…). They constitutes mainly obstructions to the sun for the thermal zones.

- If these two first entities have a thermal meaning, the "volume" entity has a geometrical definition and properties. The volume can be derived from volumetric primitives (cubes, pyramids, parallelepiped volumes..) or build due to Boolean operations (union, intersection, difference).

The thermal zones and masks are only built from one or several volumes. During construction of the 3D model, volumes and thermal zones keep their geometric and thermal coherence as well as the one of derived elements, like the thermal links constituted by adjacent surfaces between volumes. For example, when a volume is modelled; its dimension, size and location are known and its topological links with others volumes are established.

MODELLING VOLUMES AND ADJACENCY BETWEEN THEM

The user builds the 3D geometry of the building using volumes, through a set of usual volumetric primitives (cube, prism, cylinder, extrusion on a polygon…). A volume is defined by its faces and its vertices, having volume and surface properties. The faces have no thickness but they will refer to a wall defined by its material layers and their thermal properties, giving them a thermal meaning.

When creating a volume from a primitive, the geometrical properties of the facets that forms the building envelope, especially the angle of the normal vector of facets with the horizontal plane, and its orientation, enable:

- first to identify vertical or inclined ones or horizontal facets and according to the angle to decide whether the facet is a wall, a roof or a floor and to attribute them physical properties by default (wall or roof by default defined by the user and chosen among a list of walls stored in a data base);

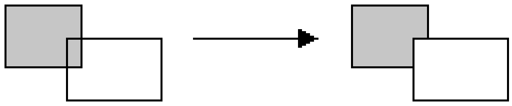
- secondly, to distinguish an interior and an outdoor accordingly to the direction of the normal vector of the correspondent facets.

So, for example, by building the first primitive volume of the model, we know about inside and outside, walls and floors, facet surfaces and air volume. In our structure, the topology is maintain due to the adjacency properties. In this simple case with a unique volume, a facet is an adjacent surface between the interior of the building and the outside.

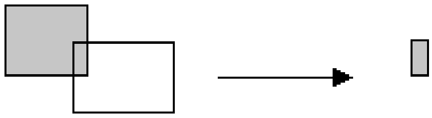
By keeping at any time these properties of volume and surfaces adjacency, the 3D modelling becomes an operation that, at the same time, participates greatly, to the construction of the thermal model of the building. For succeeding to identify volumes and common surfaces, the constraint of non intersection between volumes has to be respected at any moment. Thus, when adding a new volume, the modeller has to pay attention to potential volumetric intersections with the already existing volumes and has to resolve conflicts when they occur.

Thus, when an intersection occurs, Boolean operation have to be applied between the existing volume (grey) and the new one (blank), as expressed in the following figures:

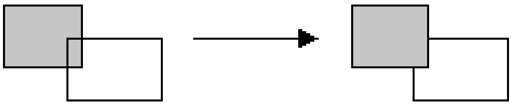
- Subtraction, to keep the only part of the existing volume that does not belong to the new volume (but modifying and creating common walls accordingly);



- Intersection, that leads to keep as resulting volume the common part of the two volumes, with its adjacent surfaces;



- Subtraction, to keep the only part of the new volume that does not belong to the existing one (modifying and creating common walls accordingly).



Union, that gives as resultant volume the outer envelope of the two initial volumes, removing the internal common surfaces, can be applied afterwards on adjacent volumes.

For each operation, the identification of common walls between volumes and with outside is continually performed.

These Boolean operations can help to build a complex shape but also to build the thermal zones. Thus, a union may be use to combine two volumes in order to form a single thermal volume; setting two adjacent volumes in a single thermal zone enables to create internal surfaces (corresponding to walls with inertia, for example); at last, and maybe it is the more common situation, two volumes can be seen as two distinct thermal volumes. But, at the volume modelling level, the only geometrical and topological data handled concern the volumes and the common surfaces between volumes and outside.

Using in our procedures the standard and powerful graphical and geometrical library (called ACIS) of Autocad, should enable us, in a near future and under specific conditions, to directly import the volumes of the thermal system from the corresponding modeller. Doing this way should minimise our investment in the development of the 3D interface.

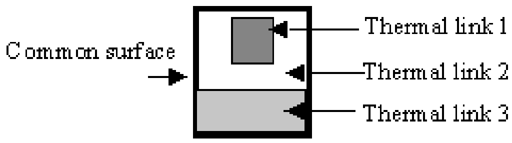
FROM VOLUMES TO THERMAL ZONES

The two steps, volume modelling and thermal zones definition are not strictly separated in the user interface we propose in Simula_3D. Logically, the thermal zones are only constituted by one or several volumes. And, inversely a volume belongs to a unique zone. Thus, links, known at the topological level as common surfaces between volumes, finally became thermal links (walls, roofs, floors…) between thermal zones. Each zone has its own properties: a type of regulation for the air temperature, a use scenario, equipment and light internal loads and so on.

REFINING THE THERMAL MODEL : FROM COMMON SURFACES TO THERMAL LINKS

Common surfaces between volumes (or thermal zones) result from volumetric constraints. They can be associated with a homogeneous wall as we do by default in the modelling stage but, in reality, the surface can support different wall parts (opaque and glazed) with different thermal properties, thus with different thermal behaviour. In fact, to take into account this inhomogeneous properties in a same surface, we made a distinction between common surfaces and what we call thermal links.

The common surface is the concern of the geometry (separating to thermal zones) whereas the thermal link is simultaneously the concern of the geometry and the one of the thermal problem. Thermal links are associated with the surface (are bearing by the surface) and occupied a part of this surface, having therefore a geometrical definition. It is associated also with a type of wall or roof defined in a library. Some geometrical operation are thus permitted to decompose, by partition or inclusion, the common surface.



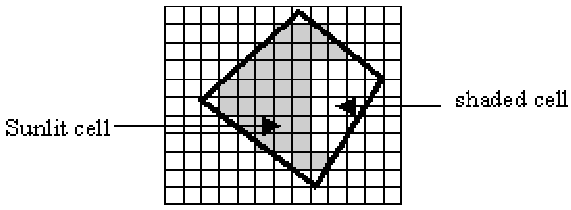
The structure can be represented schematically as follows: A thermal zone is composed of volumes. A volume is composed of common surfaces. A common surface is composed of thermal links.

In a sense, building the 3D geometrical model is also building automatically the thermal model, needing not to do a supplementary work. But doing this way give many advantages, even at the thermal modelling level, reinforcing coherence, and offering interesting perspectives for carrying out better simulations.

THE SOLAR SIMULATION AND THE 3D MODELING OF THE BUILDING

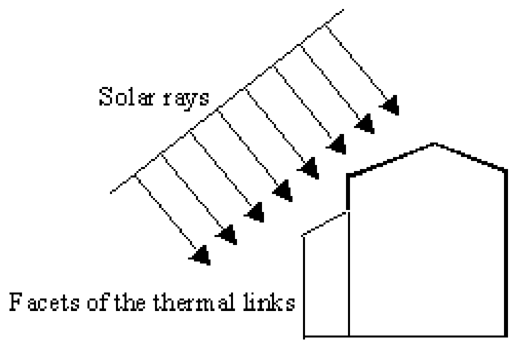
The geometrical and thermal model we have just described previously can very simply improve the solar simulation. In fact, a thermal link is a surface on which we can compute the incident solar energy (giving a value in Watt), but it is also a 3D polygonal facet on which we can determine, with the desired precision, the sunlit parts during daytime. At each time, a specific portion of the facet is sunlit, corresponding thus for the wall to a direct irradiation in Watt in relation with the only sunlit surfaces of the wall. This time dependant value is next transformed in a flux density (Watt/m2) to take into account the entire surface of the wall.

At a given time, the process we use for one facet is equivalent to project the only visible part of the facet, perpendicularly to the direction of the solar ray, and to discretize the facet accordingly to a rectangular grid. Each cell corresponds to a normal flux. The sunlit cells are the visible cells from the sun. The summation of the flux received by these cells gives the solar flux for the total facet.



The accuracy of the result is then directly related to the size of the grid element; and the process imposed to determine geometrically the hidden parts (or inversely the visible and therefore sunlit ones) of the view representing the building in the axonometric projection.

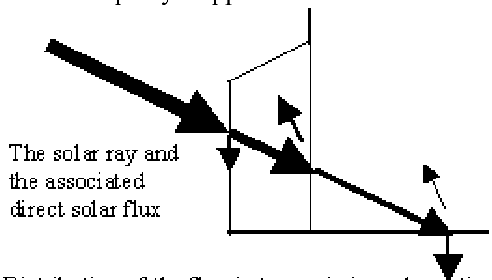
It is therefore a geometrical problem; and to determine the sunlit part of facets of all the thermal links of the building, several methods can be used in our situation. The one implemented in Simula_3D consists in moving a solar ray (whose direction corresponds to the time of the day on consideration), along the nodes of a square grid (perpendicular to that direction) in order to hit, successively, each part of the whole building, including mask volumes. The size dx of the grid element gives the normal direct solar flux associated with each solar ray (and therefore the precision of the direct solar evaluation).



Each considered solar ray intersects different facets (thermal links) of the geometrical model. By ordering the intersections, we have just to follow the path of the solar ray to manage the normal flux each time it hits a facet, accordingly with the properties of the facet and the associated thermal link : masks of the surroundings volume, opaque surface, transparent surfaces.

SOLAR TRANSMISSION THROUGH GLAZED SURFACES

At each time and for each considered solar ray, the solar path is analysed in order to distribute the associated solar flux on the facets (walls) hit by the sun. When the solar ray hits a glazed surface, then the flux is split in three components, the first one that crosses the window (transmitted component in relation with properties of the window), the second is absorbed by the window and the third one is reflected towards the thermal zone where the solar ray comes from. It is the transmitted flux that is then considered next when examining the following wall hit by the sun. When the solar ray hits an opaque wall, then the remaining flux is absorbed and reflected inside the corresponding thermal zone; and the process is stopped. When the solar ray hits a mask facet, the process is equally stopped.



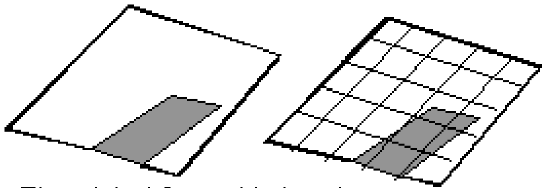
Distribution of the flux in transmission, absorption and reflection, each time the ray hits a wall facet

The multiple transmissions through glazed surfaces are thus carried out without difficulty with the help of this specific procedure. Others procedures enable us to take into account the diffuse flux and the flux reflected towards thermal zones in order to compute, at the end of the solar simulation, the global solar flux absorbed on both sides of the wall thermal links.

DISCRETIZATION OF THERMAL LINKS FOR MORE ACCURATE RESULTS

The previous procedure introduces a great accuracy in the solar simulation and mainly in the direct solar component calculation. However, due to the fact that the result is related to the whole facet, heterogeneity of the facet can be not very well taken into account. It is the case of floors or of large size walls submitted to different sunlight conditions. A simple way to improve accuracy, at the surface of the wall facet, is to cut into pieces the facet and to apply the same previous process to each piece of the facet. This spatial but planar discretization enables to distinguish, for example, a continuously shaded part from differently sunlit ones, depending of the time,

The geometry of the facet is then cut into pieces, applying it a triangular or quadrangular mesh, whose number of facet elements is relative to a chosen size or a given surface. Each mesh element of the facet will have therefore its own solar energy value, will intervene in the thermal simulation with its own impact and finally will have its own surface temperature profile over time.



The original facet with the solar spot energy related to the whole surface and the meshed facet with solar data related to each mesh cell.

This discretization would normally increase very strongly the number of thermal nodes to calculate. In reality, the thermal resolution by the "harmonic method" we use in Simula_3D enables us to keep the same number of equations, whatever the number of wall surface nodes is; the matrix system to resolve depends only of the number of thermal zones and of the precision of the Fourier decomposition. However, the time needed for the solar simulation is of course increased.

THE SOLAR MULTI-REFLEXIONS

Knowing the solar energy input upon each wall facet or part of facet, and the solar characteristics of the corresponding surface, it may be possible to evaluate the solar reflexions. The method we use in Simula_3D is based on the well known radiosity method that computes the energy leaving each facet, as a function of its solar reflectivity and of the energy reflected, towards itself, by all the others facets. This reflected energy depends also from the form factors, between each facet or facet element.

The calculation of form factors is also based, like for direct solar evaluation, on an analysis of visual rays between a given surface element and the others. We do not give, in this paper, precise details of that procedure that evaluates visibility between elements (taking into account potential occultation). It is however important to underline that, once more time, a geometrical method is used and can be implemented only because, at first, a 3D model of the walls of the building is available, and secondly, the surfacic discretization applied to the wall facets makes this kind of calculation realistic.

Finally, the absorbed solar flux is introduced as a limit condition on both sides of each wall facet element and the thermal simulation can then be carried out. When the whole thermal system is resolved, air temperatures are known in every building zone and surface temperatures can be computed on wall surfaces.

ASSESSMENT OF THE RADIANT TEMPERATURE IN A ZONE

At this step, user comfort evaluation is possible in two ways.

Either simulating a black ball located in a whatever place in the room and computing the radiant temperature from the surface temperatures of the surrounding wall elements weighted by their form factor with the ball.

Either simulating the radiant temperature on a point located on an oriented vertical plan surface, therefore, according to an hemispherical point of view. By calculating two temperatures, the first looking in a direction, the second looking in the opposite one, the difference between the two can be a very good indicator to outline the cold wall effect in rooms having walls with different surface temperatures (as in the case of very glazed one-side rooms).

AN EXTENSION TOWARDS THERMAL RADIANT EXCHANGE EVALUATION AND DAYLIGHTING SIMULATION

Up to now, we have seen that the 3D model and the surfacic discretization of the walls have enabled to take into account with accuracy the solar problem and the determination of the surface temperatures. Furthermore, they have lead to develop special procedures for evaluating multiple transmissions through a solar ray, for calculating form factors between facets elements and for carrying out multi-reflexion through a radiosity method. Thanks to the spatial discretization, the reuse of principles and methods elaborated in the frame of the solar simulation, can be reinvested:

- to refine our thermal simulation, by taking into account radiant exchanges;
- to improve the capacity of the software by integrating a daylight evaluation module.

The radiant exchanges are dependant of the surface temperatures of the walls and of the form factors between elements of surfaces. The importance of that kind of exchange is generally limited when surface temperature differences are weak inside a room. And, due to the geometric factor, the effect is generally concentrated in the very closed zone of the emitter surface. So, two conditions seem necessary in order to the radiant exchange calculation makes sense: the first is that the effects or parameters that contribute to create temperature gradient are well taken into account (from this point of view, the solar energy coming into the room and received differently by the wall surfaces is greatly responsible of that heterogeneity of temperature); the second is that the wall can not be considered as a surface entity (with an only mean value of surface temperature) but it must be discretized in relatively small size elements (each one having its own solar and thermal behaviour).

In Simula_3D, the radiant exchange between walls constitutes a calculation module that can be launched, optionally. The thermal simulation is thus carried out in an iterative way: the conduction phase enables to determine surface temperatures, but the radiant phase modifies these temperatures creating a supplementary flux that is applied to the wall elements and the conduction phase is launched again; the process is stopped when stability is obtained.

Procedures for calculating daylight illumination in buildings are quite similar to those used in the solar simulation and are well defined in the software Solene. So, it is not the convenient place to develop here such instrumentation, mostly focused on thermal model and simulation issues. However, the main interest to mention this specific development is to underline the coexistence, in the same simulation tool, of two very frequently correlated factors: solar and luminous, whose effects, in term of energy and comfort, are sometimes opposite but always present as soon as windows or glazed surfaces are present in buildings.

THE 3D MODEL OF THE BUILDING : A SUPPORT TO DISPLAY THE RESULTS OF THE SIMULATION

At last, the 3D model of the building can be a very convenient and attractive support to display the results issued from the simulation that can be various, as much at the thermal zone level as at the thermal link level.

Generally, results are displayed as curbs, profiles drawn on diagrams or graphics. Simula_3D uses these necessary and interesting display means, but imaging procedures enable to use the 3D model itself to communicate information. As an example, the volume of the thermal zones can be coloured by air temperature or by energy power to supply to maintain the desired comfort level or by solar gains. Animation may render the dynamic effect of these results. Opportunities are important to design new display modes using axonometric, perspective or cross-sections view that can be applied to the model.

At the level of the walls, solar spots over time can be displayed, but also gain due to reflexions, properties of walls, surface temperature, as many values as necessary to understand better the behaviour of a wall and its impact on the thermal zone.

But, other display potentialities are offered by this 3D model to analyse thermal data output of the building. One simple is to display the ”Heliodon” pictures enabling the user to understand over day time and season how volumes receive the sun. Another would be to design profiles in a room, along a line or according to a plan to assess the comfort level or the daylight factor. As we see, this list is not limited, and everyone can imagine other interesting means to interrogate and display results, making a large and extensive use of the data contained into the 3D model of the building.

CONCLUSIONS

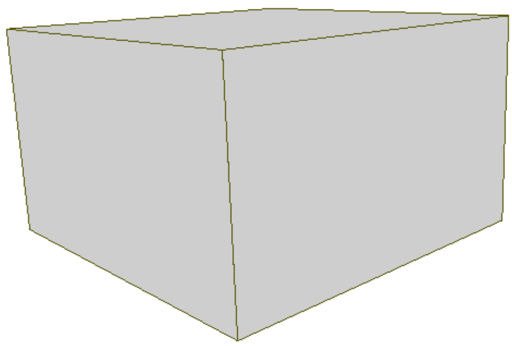
It seems that an accurate thermal simulation can not be carried out without sufficient and precise geometrical data input of the building. It is why our research about the design of a new thermal simulation tool, Simula_3D, set the 3D geometric model of the building as the basis of the thermal model. The main interests to proceed this way, are multiple:

-modelling the 3D geometry of the building participates, at the same time, to the definition of the thermal model; it another way to input data by volumes rather than by a list of thermal links;
-solar simulation gains in accuracy, because it is possible, by appropriate geometric procedures, to evaluate precisely the solar transmissions and the correspondent energy absorbed by each wall surfaces;
- the possible discretization of walls in small surface elements enable great possibilities to take into account all issues relative to multi-reflexion, thermal radiant exchanges and daylight assessment, each of them includes always as part of the whole physical problem, a geometric dimension.
- 3D model can be a very attractive support to display results of simulation.

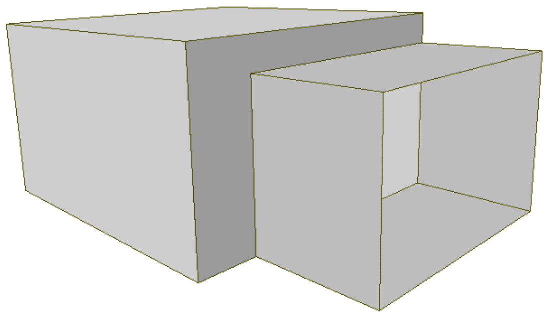
Up to now, the correspondent geometric procedures are elaborated in a prototype product that mainly focuses on the solar simulation, but they are planned to be extended or transposed to other equivalent physical phenomena, as daylight illuminance.

ILLUSTRATIONS OF THE MAIN PRINCIPLES ELABORATED IN SIMULA_3D

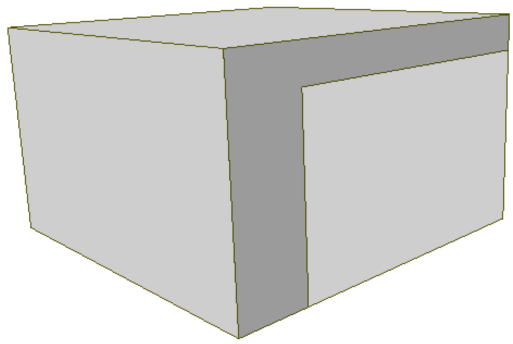
Model one volume; each wall surface is adjacent with the outdoor.



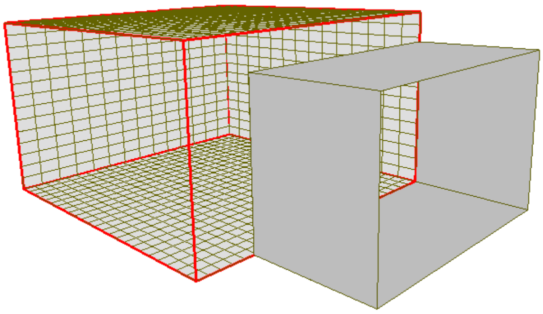
Add a second volume adjacent to the first one (suppose a greenhouse).



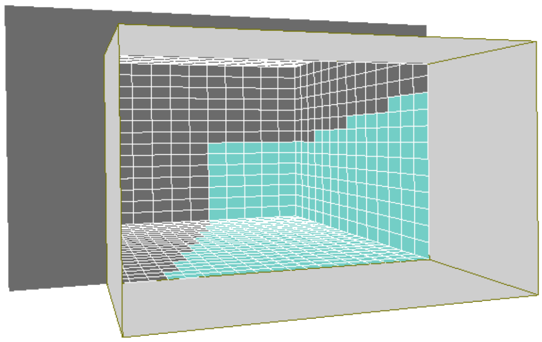
The adjacent face of the first volume is therefore cut into two surfaces, and we suppose that the common surface is a glazed wall transmitting the solar energy.



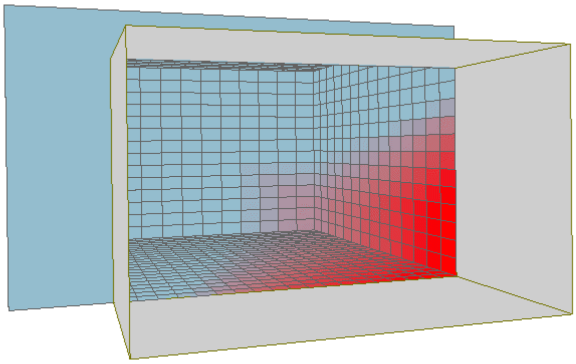
To approximate better the luminous spot, the different wall surfaces are discretized in small surface elements.



Then , the solar direct simulation can be launched. At a given time, the solar spot can be approximated on the small elements, and the correspondent energy is absorbed by the sunlit cells.



Finally, due to multi-reflexion, the inertia of the walls and, eventually due to the radiant exchange, the spatial distribution of wall surface temperatures can be obtained, at every time during the day.



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