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A Level-of-Detail Technique for Urban Physics Calculations in Large Urban Environments

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Abstract

In many applications, such as urban physics simulations or the study of the solar impact effects at different scales, complex 3D city models are required to evaluate physical values. In this paper we present a new technique which, through the use of an electrical analogy and the calculation of sky view factors and form factors, allows to simulate and study the thermal behaviour of an urban environment, taking into account the solar and sky radiation, the air and sky temperatures, and even the thermal interaction between nearby buildings. We also show that it is possible, from a 3D recreation of a large urban environment, to simulate the heat exchanges that take place between the buildings of a city and its immediate surroundings. In the same way, taking into account the terrestrial zone, the altitude and the type of climate with which the simulations are carried out, it is possible to compare the thermal behaviour of a large urban environment according to the chosen conditions.

CCS Concepts

•Applied computing → ***Environmental sciences; •Computing methodologies*** → *Rendering;*

1. Introduction

The study of urban physics to explain physical behaviours of an entire city involves the compilation and treatment of large volumes of data. Nowadays it is possible to have access to a 3D model of a real urban area, or to generate it procedurally by reconstructing it geometrically from its corresponding 2D map. However, the complexity and the amount of geometry of this class of 3D models present a difficulty when performing physical simulations and studying their behaviour under certain phenomena or circumstances.

Muñoz et al. [MBP18], presented a procedural technique to simulate the thermal behaviour on a large urban environment while keeping simplicity and accuracy. Users set the level of precision with which they want to work and the technique allows to simulate different case studies by changing the input parameters, both physical and structural. As can be seen, there is a direct relationship between the computational cost and the amount of geometry to be processed in the 3D model with which one works. As a result of this direct relationship, if we want to perform a complex simulation in a very large urban environment, the cost in memory and simulation time may be unsustainable at some point. Thus, this paper presents a solution to this problem.

The problem of the amount of geometry to be processed was somewhat confronted by Muñoz et al. [MBBP15, MBBP18]. In their work, they implemented a Level-of-Detail (LoD) technique that decoupled an entire 3D city into smaller subsets named *view-cells*, in order to be able to treat them more efficiently. In that case, the decoupling was performed to massively measure the amount of visible sky in an urban environment without processing all the geometry available in each calculation, measuring the so called *Sky View Factor* (SVF). Their technique was based on the fact that, to calculate the sky view factor in an urban environment, it would rarely be necessary to process the enormous amount of geometry that makes up a complex 3D model of a large city.

In this paper we propose that the same practical principle can be applied to the problem of thermal simulation, too. In a large 3D city, simulating the thermal behaviour at an specific point of the model will have a greater contribution of the surrounding geometry than of the furthest one. We propose to approach the problem in the same way as previously done [MBBP15, MBBP18] for the SVF, decoupling the large urban environment into smaller viewcells and using a LoD technique with impostors to replace the geometry that will be omitted in each simulation. As a result, each calculation would use much less geometry and computations, considerably reducing computational times with a user-controllable impact on the calculation accuracy.

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2. Related Work

A large number of methods have been developed to construct energy consumption models that simulate a building system with different goals [HK16, ZHYW13]. Such models vary in magnitude from modelling a single slab (or a wall) to modelling a complete building through rooms subjected to temperature variations. The energy model we present requires simulating the behaviour of entire buildings, composed of multiple floors. To do this, the model uses both a radiative and conductive calculation, using climatic data and procedural rules.

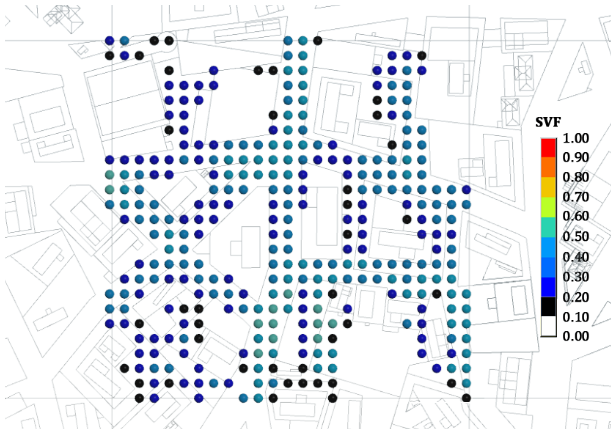
2.1. Radiative Exchange and Sky View Factor Calculations in Large Cities

Radiative exchange transfer was the starting point for global illumination computations in computer graphics [SP94]. Radiosity was introduced early on as a method for computing radiant heat exchanges between surfaces [Spa18]. At the heart of radiosity is the idea of breaking the surfaces in an environment down into a finite number of patches and solving the heat transfer for these patches. Attempts to obtain the best from radiosity and Monte Carlo techniques have been made through a series of steps using progressive refinement radiosity and Monte Carlo path tracing [CRMT91]. First, approximate images are quickly produced, and then more accurate images are systematically created. Here, we also deal with related concepts such as the computation of the Sky View Factor (SVF) and the Form Factor (FF) of the exterior surfaces of the buildings.

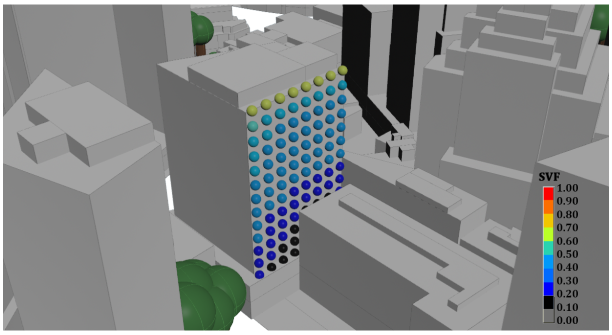
Muñoz et al. [MBBP18] proposed an efficient system for quickly computing the Sky View Factor (SVF) for a massive number of points inside a large city. They embedded the city into a regular grid, and for each cell select a subset of the geometry consisting of a square area centred in the cell and including it. Then, the selected geometry is removed from the city model and the rest is projected onto an environment map. Their system can perform several evaluations inside a cell's area, see Figure 1. When multiple SVF evaluations are required, it is only necessary to determine which cell each evaluation point belongs to, and compute its SVF using the geometry of its cell plus its corresponding environment map. The inaccuracy introduced by this LoD technique is controlled by adjusting the size of the cells and the number of cells that maintain all their geometry during the calculations, according to the maximum relative error that one wants to have.

2.2. Thermal Simulation

Thermal behaviour analysis on buildings is an important goal for all tasks involving energy flow simulation in urban environments. However, the number of variables to be taken into account and the difficulty of implementing some of them make the problem difficult to pose at an urban scale. Methods for computing transient heat transfer in buildings can be classified into two categories: explicit solutions of the heat diffusion equation [Cla01, KHJ17] or model simplification techniques [KR07]. In the first case, finite difference numerical methods can be used. The main drawback to this is that the computational effort is prohibitive for the early stage simulation of project goals [LNS04]. On the other hand, the simplified models offer a good compromise between simplicity, data requirement and computational effort. Electrical analogy simplification is one of the methodologies most commonly used to represent heat transfer [KR07]. The main idea behind electrical analogy is to connect the rooms (or floors) in a building by nodes that represent wall conductivity and capacitance [Nah17]. The walls and roofs may be represented by many layers and could also be linked to the outside temperature. By solving the equivalent circuit network that has been composed, dynamic temperatures over time can be obtained. One of the drawbacks to this approach is that the nodes are mostly set manually [Lev15]. That is, the nodes are established by defining convenient zones. Furthermore, as it is a simplified model, it is difficult to know in advance how many nodes may be required and where to put them before testing the system with the corresponding building parameters.



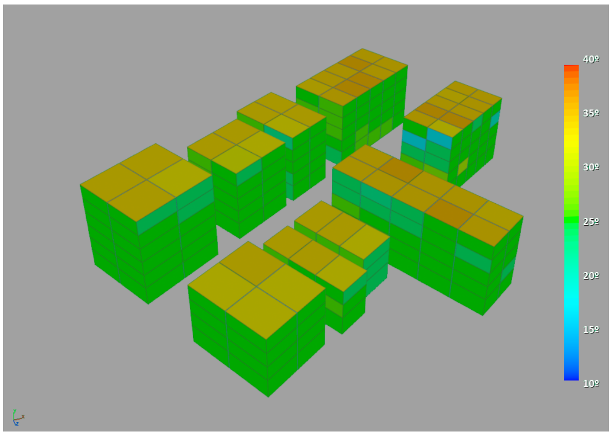
(a) *An horizontal mesh measuring SVF along a street. SVF values below 0.10 are transparent to make the figure clearer, avoiding cluttering the image with black points.*



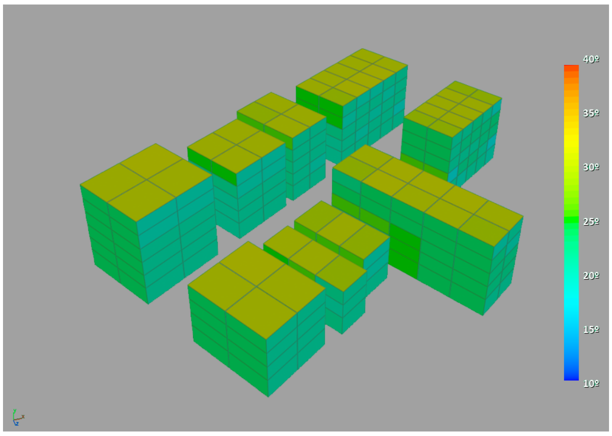
(b) *A vertical mesh measuring SVF through the facade of a building. In this way it is possible to measure the SVF from the facade (and even the windows) of one or several buildings of the studied area.*

Figure 1: *The technique developed by Muñoz et al. [MBBP18] allows multiple calculations of SVF in a specific area within a large urban environment, both horizontally at street level (a) and vertically at the level of the facades (b).*

Muñoz et al. proposed [MBP18] a procedural approach that, from a 3D urban model and a set of parameters, simulates the thermal exchanges that take place inside and outside the buildings of an urban environment. They developed a rule-based methodology that automatically generates the circuit system for a given procedural building. They also provide a technique to efficiently visualize thermal variations over time, both of the interior and exterior of buildings in an urban environment, see Figure 2.



(a) *Temperatures in the outer walls of the Barcelona case study at 14:00.*



(b) *Temperatures in the outer walls of the Barcelona case study at 17:00.*

Figure 2: *Visualization of the thermal behaviour of buildings in an urban environment in a case study located in Barcelona on a day in April [MBP18].*

2.3. Sky Simulation

There are many methods to calculate the emissivity and temperature of the sky [EGA18, AFMAA12]. In this work, we use the sky radiation model developed by Clark and Allen [CA78] as it is frequently used in energy simulation applications; for instance, EnergyPlus [CLW*01]. Our simulator assumes that the sky is always clear and without the presence of clouds, which this model admits.

The potential impact of climate change on buildings was investigated through transient building energy simulations and hourly weather data, which are typically used to calculate the demand for heating and cooling [AC18]. Weather stations allow access to climatic data collected over decades, in order to use that reliable source as input for recreate simulations of the thermal behaviour of buildings and many other kind of studies [RMSR10].

3. Material and Methods

The main objective is to reduce the computational cost when we need to simulate, with a certain degree of accuracy, the thermal behaviour of a specific area within a large urban environment. To achieve this objective, we superimpose a regular grid, and we identify all the buildings inside each grid cell. Then, for each cell, we classify the whole city geometry into three sets: the geometry associated to the cell, the geometry next to that cell and the rest of the other geometry in the city, see Figure 3.

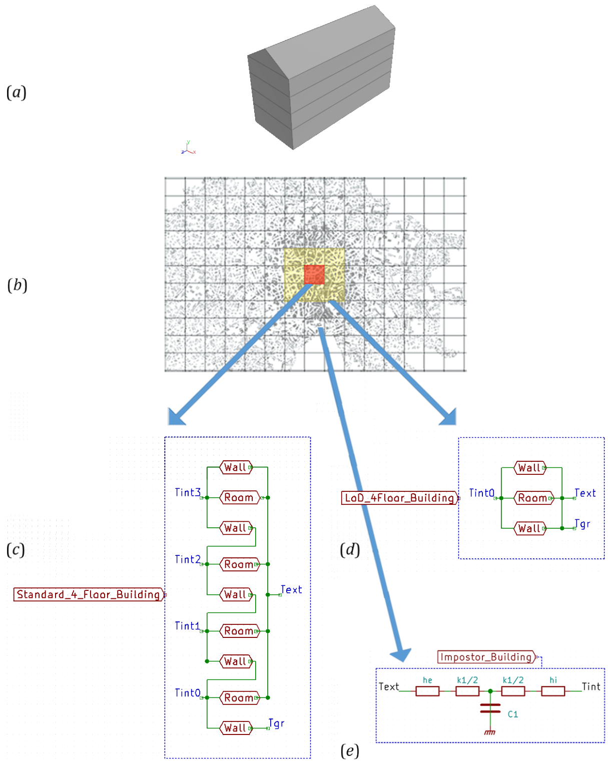


Figure 3: *Overview of our method. If a building (a) is inside the studied viewcell (in red) its circuit will be generated in a standard way (c), while if it is in a neighbouring viewcell (in yellow), its circuit will be generated in a simplified way (d). If the building is beyond the buildings neighbourhood, the viewcell (outside the yellow area) will be replaced by an impostor and represented by a circuit consisting of a single wall of one material layer (e).*

The electrical analogy is used and the circuits are generated in each buildings present in the urban environment. The circuits corresponding to buildings within the current viewcell are generated in a standard way, while the circuits of the most distant buildings are simplified versions to reduce the computational cost of the simulation. This is explained in detail in Section 3.2.

The impostor method developed by Muñoz et al. [MBBP15, MBBP18] is used, so that when ray casting is used to calculate the SVF, the FF or the solar radiation from a specific position in the city, the rays must collide first against the geometry and then against the environment map in order to take into account all the original geometry of the scene. An environment map is generated by taking a panoramic image of the surroundings of a viewcell from its centre, replacing then the distant geometry by the environment map.

3.1. Thermal simulations

The thermal calculation algorithm is described following the procedure presented in Algorithm 1.

Algorithm 1 Procedure to simulate the thermal behaviour

```
procedure SIMULATE(cellGeo, farGeo, cellEnvMap, simTime, timeStep)
    local variables
        circuitsIn          //circuits inside the viewcell
        circuitsOut         //circuits outside the viewcell
        t                   //current simulation time
    end local variables
    IMPORTGEOMETRY(cellGeo)
    CALCULATEVIEWFACTORS(cellGeo, cellEnvMap)
    circuitsIn ← GENERATECIRCUITS(cellGeo,temperatures)
    circuitsOut ← GENERATECIRCUITS(farGeo,temperatures)
    PARAMETERSSETTING( )
    t ← 0
    while t < simTime do
        RADIATIVEPASS(cellGeo)
        CONDUCTIVEPASS(circuitsIn, circuitsOut)
        TEMPUPDATE(circuitsIn, circuitsOut, cellGeo)
        VISUALIZATIONUPDATE(cellGeo)
        t ← t + timeStep
    end while
    EXPORTTOCSV( )
end procedure
```

First, the geometric model of the urban environment is loaded from a file. This file can contain any type of urban element, because the presented technique only deals with its geometry, without discriminating its nature. Then, a grid appears over the top-view of the 3D model, allowing the user to adjust the cell size, and with this, its accuracy.

Next, a grid cell (the viewcell) must be chosen, thus determining in which region of the urban environment the thermal simulation takes place. Only the geometry of the designated viewcell plus the neighbouring $N \times N$ cells is kept, where N is also a parameter adjustable by the user. With all the unselected geometry in the previous step, an environment map composed by a panoramic photograph of the geometry beyond the designated $N \times N$ zone is generated. After these two elements are determined (i.e., the geometry to keep and the environment map), the method is ready to perform the thermal simulation.

The thermal simulation takes as input the geometry selected for a given cell (cellGeo), its corresponding environment map (cellEnvMap), the geometry unselected for the given cell (farGeo), the simulation time (simTime) and the time step of the simulation (timeStep). The simulation starts, calculating a radiative pass and a conductive pass at each time step, updating the external and internal temperatures of the buildings and changing their representative colour to visualise their evolution over the period of time being simulated.

When a ray casting technique is used to determine the visibility between the elements of the geometry of the urban environment, if the ray does not hit the city geometry, we check the intersection against the projected geometry of the environment map. In this way, the impostor technique is applied to the calculations of SVF, FF and solar radiance.

3.2. Model simplification

As Muñoz et al. show [MBBP18], the simplification of the model is implemented through the use of the impostor technique. However, the LoD technique we consider here not only consists of replacing the far geometry to the observation point with an environment map that represents it in its place. Unlike when we used the impostor to massively measure SVF from a single area of a large urban environment, simulating the thermal behaviour involves calculating the interactions between all the buildings of the city at each time step, updating their temperatures. For this, once the partitioning of the urban environment has been done, each building is associated with a data structure that identifies it and that stores a global temperature. In this way, all the buildings of the current viewcell generate their circuits with the standard procedure presented [MBP18], while their neighbouring buildings use simplified circuits, simulating buildings of a single floor, see Figure 3. However, for every building whose geometry is replaced by the impostor technique, it is represented with the lowest LoD, a simple "wall" rule with a single resistance and capacitor between its exterior and interior temperatures, since the circuits are generated from geometry but we are interested in reducing to the minimum the geometry that does not belong to the viewcell or its adjacent cells.

It is important to note that, for the impostor to function correctly, it must be possible to identify each building of the urban environment both at the geometry level and at the environment map level. To do this, each building is assigned a unique identifier number and a corresponding unique RGB colour code. At the moment of partitioning the city and creating the data set and the environment map corresponding to the viewcell, the distant buildings are coloured so that they can also be identified in the environment map when the calculation of radiative heat is made in the simulation. In this way, it is possible to use the impostor instead of the geometry to calculate the radiative pass by identifying the buildings that exchange heat between them by means of the RGB colours of the environment map and using the global average temperature of each one instead of having to count all temperatures of the exterior surfaces of the buildings.

4. Results and Discussion

4.1. Case Study

To test this new hybrid technique, a case study was designed from an urban 3D model that recreates an area of Vienna (Austria), see

Figure 4. A climate data file from Vienna was used and the simulation date was adjusted to August 16, 2018, from 04:00 to 23:59. The temperatures were initialized at 15° C for the interior temperatures and 12° C for the exterior surfaces, and the ground temperature was maintained at the average temperature of that day plus 2° C. The parameters of the materials are presented in Table 1 and the general physical parameters are presented in Table 2. Finally, the coordinates were adjusted to $48.21°N, 16.36°E$ in the simulator interface.

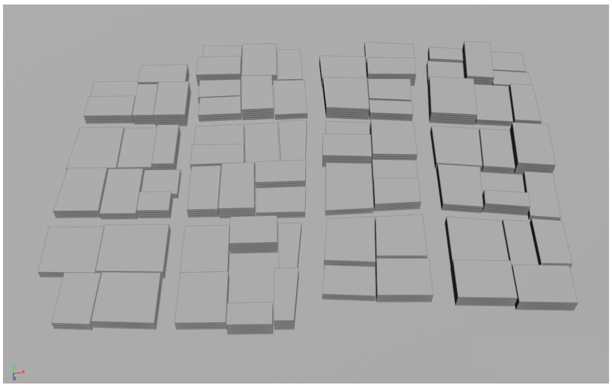


Figure 4: *3D model procedurally recreated from the map of the Vienna case study.*

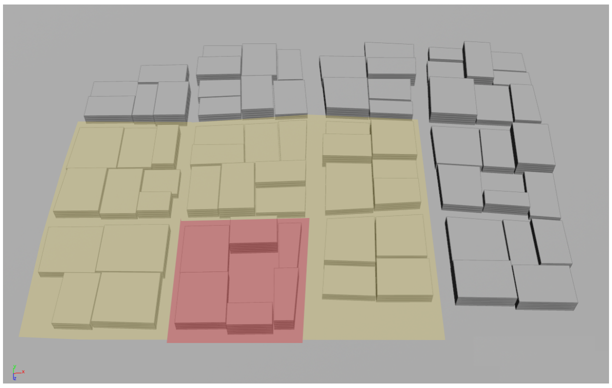
Table 1: *Material parameters for the simulation of the case study.*

Material	Thermal conductivity (W/mK)	Thermal capacity (J/kgK)	Density (kg/m^3)	Thickness (m)
Concrete	1.75	920	2,200	0.2
Polyester	0.04	1,380	30	0.2
Plaster	0.35	800	1000	0.1

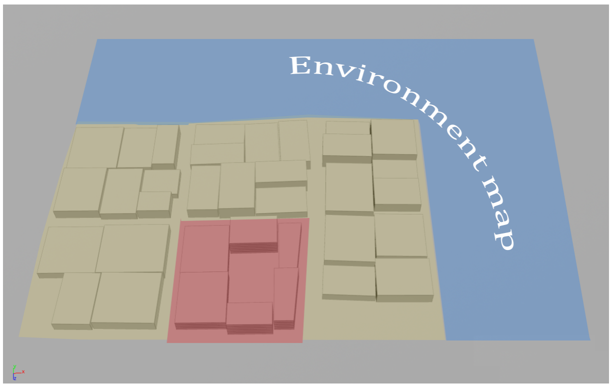
Table 2: *Environmental parameters for the simulation of the case study.*

Air density $(kg \cdot m^{-3})$	Air heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$	Air infiltration $(vol \cdot h^{-1})$	Q_{other} $(W \cdot m^{-2})$
1.413	1,005	0.25	0.0

In this case study a subset of buildings was selected, determining the viewcell to be studied. Another subset of buildings neighbouring the chosen viewcell was also selected. The rest of the buildings were replaced by an environment map and an associated data structure, using the imposter technique, see Figure 5(a). As a result of this selection of buildings, the ones belonging to the viewcell maintain their original LoD, while the buildings belonging to the set of neighbouring buildings reduce their LoD using the procedural rules of single-story buildings. The buildings that do not belong to the viewcell or its neighbouring buildings, replace its geometry with the environment map and an associated data structure, see Figure 5(b). Once the LoD technique is applied, the simulation is carried out following the Algorithm 1.



(a) *In red the viewcell, in yellow the buildings neighbouring the viewcell and without colour the buildings distant to the viewcell.*



(b) *The buildings in the red zone maintain their original LoD, while the buildings in the yellow zone use the procedural rule for single-floor buildings. The buildings beyond the yellow zone replace their geometry with an environment map and their associated data structure.*

Figure 5: *Three subsets of buildings are created on the 3D urban model, according to their distance from the viewcell.*

4.2. Analysis

We can study the time complexity of the algorithm by considering that the cost of solving the thermal circuit of a building of a number R of floors is $O(f(R))$, with f an arbitrary function that depends on the acceleration data structure used. Using this hybrid technique, this cost will be different depending on whether the building is located inside, next to or far from the limits of the selected viewcell. In this way, there will be three sets of buildings: a large one with a computational cost of $O(1)$, since the technique will treat distant buildings as if they were from a single wall, a smaller one with a computational cost $O(f(r))$, where $r < R$, that treat buildings as if they were a single floor and a very small one with a computational cost $O(f(R))$ to treat all the floors of the buildings on which no LoD has been applied. This implies a strong reduction of the computational time with respect to a full geometry solution.

However, it must be noted that the computational load in this case is transferred to memory consumption: As seen in the literature [MBBP15, MBBP18], the evaluation of several SVFs for a given cell requires a constant memory, proportional to the number of buildings associated to the cell, which we can assume roughly proportional to its size $C_{size}^2 \times N^2$, plus the memory needed for the environment map itself. Nevertheless, this new hybrid technique also reduces the consumption of virtual memory with respect to the technique presented by Muñoz et al. [MBP18] by not having to generate the complete circuits of all buildings in the urban environment when only a subset of them is needed to be comported accurately. In the same way, the calculation time of radiative and convective steps in buildings is also reduced. The conductive calculations of buildings far from the viewcell under study are very fast, although less accurate, since far buildings use the electrical analogy over simplified circuits. Radiative calculations, on the other hand, will be very accurate between the viewcell and the buildings immediately surrounding it, and less accurate between the viewcell and much more distant buildings.

4.3. Results

After performing the simulation twice for this case study, the first time using all the geometry and the second time using the LoD technique, it is easy to compare the results qualitatively (visually) and quantitatively (hour by hour), focusing on the previously chosen area of interest, see Figure 6. Visually, it is possible to appreciate how, despite having eliminated part of the geometry and simplifying another part, the results of the area to be studied do not differ much with respect to the results using all the geometry of the urban environment.

Table 3 presents a comparison of the computational time gain when using the imposter technique. By drastically reducing the amount of geometry present in the calculations, the simulation time decreases markedly. However, the impostor introduces an error that decreases the accuracy when simulating the thermal exchange between buildings in an urban environment. To analyze the error introduced by the use of the impostor, three specific surfaces of the scene have been chosen and its heat flow emitted to a building visible from them and belonging to the evaluation viewcell has been measured. Of the three chosen surfaces, the first one belongs to the viewcell, the second one to the buildings neighbouring the viewcell and the third one to the area where the impostor technique has been applied. With these three surfaces it is possible to compare the energy that they contribute to the studied surface, both using all the geometry of the scene and applying the LoD technique to reduce the computational cost, see Figure 7.

Table 3: *Geometry and timings for the model from the Vienna case study. The time required to calculate the SVF and FF from the first run of the model is included in the pre-processing time.*

3D Model	Number of Primitives	Pre-processing time (minutes)	Simulation time (minutes)
Full Geometry	1,549	21.42	24.56
LoD Geometry	326	4.50	5.09

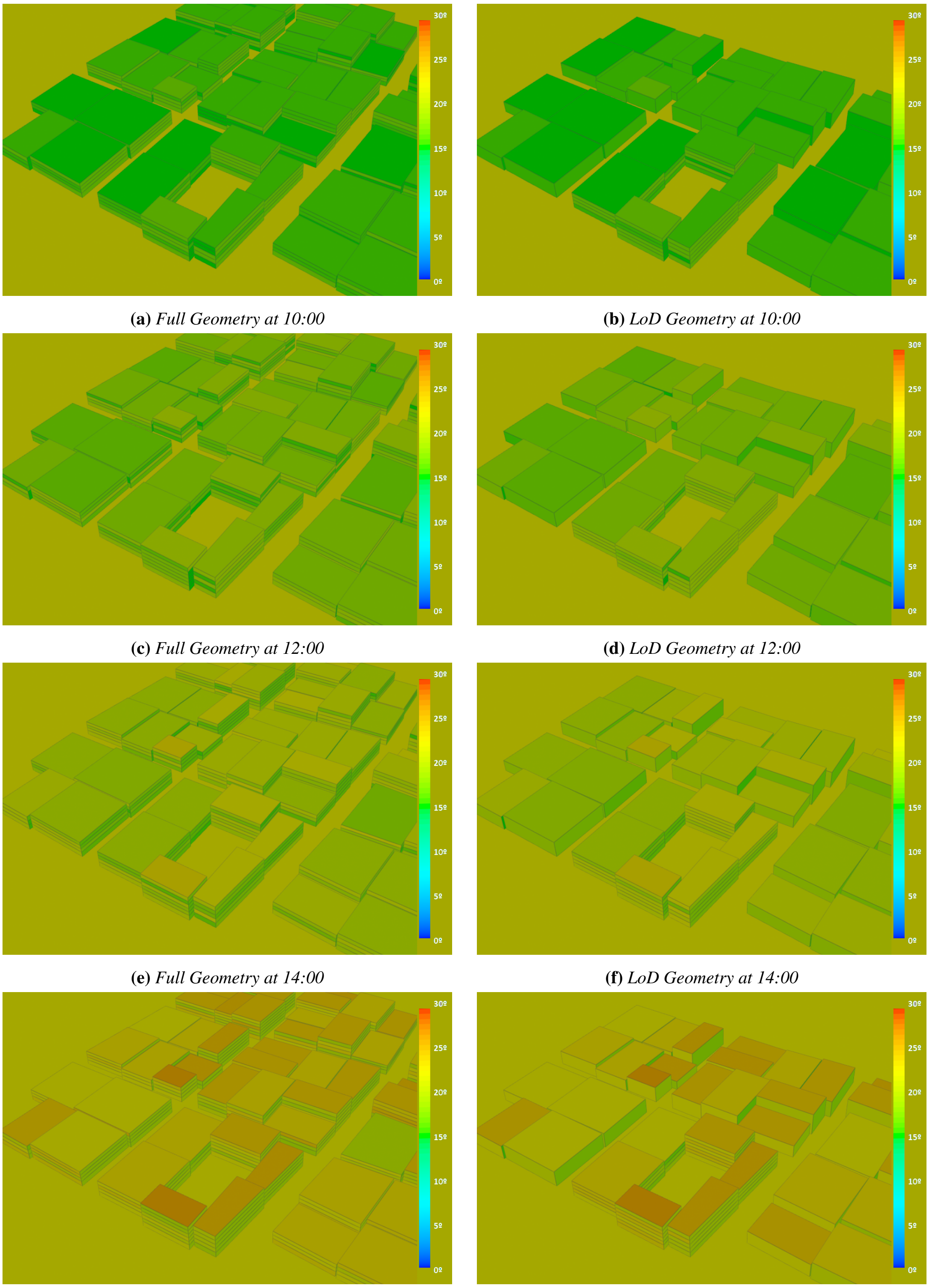
It was observed that in the viewcell area, the difference between using the LoD technique is negligible, since in both cases the buildings maintain all their geometry and the differences in the calculations are the result of slight variations in temperatures, due to the changes between the simplified 3D model and the original. When measuring in the area neighbouring the viewcell, the difference is greater, since the buildings in the neighbouring area are treated as large one-story buildings when using the LoD technique. Finally, when measuring in the impostor area, the difference between using the LoD technique or not using it is much clearer, but its effect is diminished due to the distance and the low view factor with respect to the viewcell. With these results, it is observed that the farther away the surface that emits the heat flow to the building to study is, the less important the error will be, since the view factor between these two surfaces reduces its impact. Therefore, it does not matter if the error is significant in the area of the impostor, although it is recommended to try to keep it controlled in the area neighbouring the viewcell. To keep the error controlled, it is best to enlarge the size of the viewcell and the neighbouring area to the viewcell, in order to ensure that the error in the results is not significant until the building is at an adequate distance from the study area and its impact is minor.

Users must choose which technique use to study the thermal behaviour of an urban environment. If they want to simulate and visualize the evolution of temperatures in a large urban environment, with all its zones at the same level of accuracy, the technique presented by Muñoz et al. [MBP18] is better, although of course its computational cost is higher. On the other hand, if they want to perform a simulation in a large urban environment, but focusing attention and accuracy in a particular area, this new technique is more efficient at the expense of losing some accuracy.

This type of techniques serve as tools designed to examine case studies by changing the parameters in order to observe how the thermal behaviour changes, thus letting the user decide which combination of parameters is the most optimal to get the desired thermal behaviour. It is important to mention that this technique inherits the limitations of the other two techniques it combines. On one hand, the shape and distribution of the buildings of the urban environment in which to perform the simulations will affect the values that the variables C_{size} and N must have in order to maintain the desired level of accuracy in the calculations. By other hand, the simplification of the model must be applied so that the areas in which the geometry will be divided have an adequate subdivision size (l) for the simulation to converge. Thus, the correct setting of variables C_{size}, N and l is the key to achieving the desired balance between precision and calculation time.

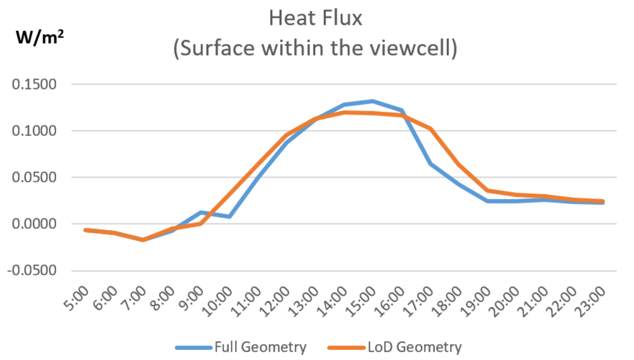
5. Conclusions and Future Work

The main goal of our study was the proposal of combining a LoD technique with a procedural simulation, with the objective of simulating the thermal behaviour in a huge urban area. The computational complexity was greatly reduced by avoiding taking into account geometry not very relevant for calculations, while retaining results accurate enough. The resulting algorithm has been presented, explaining the changes and implications of the combination of the existing techniques. In this way, it is possible to have differ-

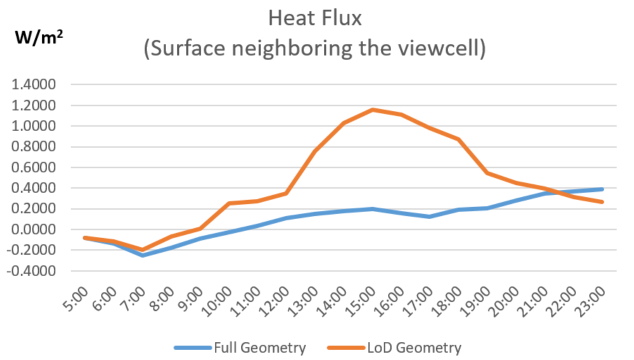


(a) *Full Geometry at 10:00*
(b) *LoD Geometry at 10:00*
(c) *Full Geometry at 12:00*
(d) *LoD Geometry at 12:00*
(e) *Full Geometry at 14:00*
(f) *LoD Geometry at 14:00*
(g) *Full Geometry at 17:00*
(h) *LoD Geometry at 17:00*

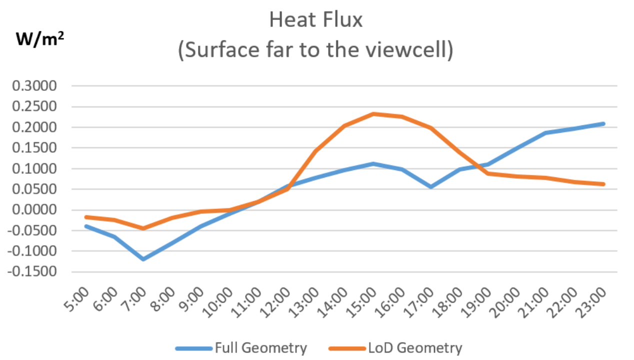
Figure 6: *Visualizations of the Vienna case study. using all the geometry in the images on the left and using the LoD technique in the images on the right.*



(a) *Evolution of the heat flux added to the studied surface from the buildings in the viewcell area.*



(b) *Evolution of the heat flux added to the studied surface from the buildings in the area neighbouring the viewcell.*



(c) *Evolution of the heat flux added to the studied surface from the buildings in the impostor area.*

Figure 7: *Comparison of results when using the LoD vs Full technique to measure the heat flow contributed to a specific surface within the viewcell.*

ent techniques to simulate and visualize the thermal behaviour of buildings, according to the size of the 3D model to be used as a case study. If one wants to work with a large environment, the impostor technique may reduce the computational cost drastically, although losing some precision in the results, as shown in Section 4.3.

One of the most promising avenues for future work is finding ways to take advantage of the observation that only a limited number of geometric elements surrounding a projection point have actually any influence on the computations in a large urban environment. This would require a computation of the involved geometry, which can be a complex task for highly detailed city models.

On the other hand, an accurate error metric should be developed in order to automatically determine N and C_{size} depending on the maximum allowable error. The automation of the partitioning parameters of large urban environments would be a first step so that, by means of the simulation of an enormous quantity of case studies, rules of categorization of 3D cities would be created and stored in a learning database. This would allow the system itself to recommend and even adjust the sizes of the viewcells of an urban 3D model, detecting its patterns when imported and comparing them with those of the learning database.

Another interesting line for work is to upgrade these techniques by improving their accuracy by simulating more 3D models of urban environments with real measurements (and if possible with measurements of indoor temperatures), as they become available. Also, the calculations and the data structures should be optimized to reduce the simulation time even further; although compared with the techniques that use finite elements, the relationship between computational cost and accuracy is quite positive.

Acknowledgements

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