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# Procedural urban modeling for accurate thermal analysis in contemporary cities

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# Procedural urban modeling for accurate thermal analysis in contemporary cities

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**Abstract**. This study introduces a workflow for efficiently generating urban digital twins using procedural geometry, aimed at facilitating thermal analysis in urban planning. The methodology employs Blender's Geometry Nodes to automate the creation of architectural typologies represented as simple cubic forms, such as ground floors, apartment units, and roofs. These cubes are parametrically manipulated to form flexible, scalable building models. The focus is on creating conformal, all-quad hexahedral meshes to ensure accurate thermal simulations using the Finite Element Method. The workflow was validated through simplified thermal simulations, which highlighted the ability of the mesh to handle varying boundary conditions and perform under thermal gradients, thereby successfully demonstrating the potential of procedural modeling for urban thermal simulations as an initial approach. Future work will focus on expanding the methodology to handle more complex urban environments, integrating dynamic environmental factors, and refining simulations for more realistic outcomes.

## 1. Introduction

As cities increasingly face the challenges of climate change and rising urban temperatures, Urban Digital Twins (UDTs) offer valuable solutions for simulating thermal behavior, predicting energy consumption, and assessing the effectiveness of potential interventions ([1], [2]). Given the complexities of urban environments, thermal simulations are more appropriately tackled using advanced numerical methods, such as the Finite Element Method (FEM) [3], rather than the simplified numerical models commonly employed in other UDTs. FEM is a numerical technique that divides a continuous domain into smaller, manageable elements [4] within both small-scale components, such as individual buildings, and larger systems, such as city-wide environments [5].

However, creating detailed UDTs for thermal analysis is both complex and computationally demanding because accurate modeling requires highly detailed geometries [6]. For instance, FEM simulations require specific conformal meshing, where each element shares full edges to minimize numerical errors ([7], [8]). Moreover, highly detailed UDTs are traditionally created manually, which can be prone to errors and inefficiencies, particularly when working with large-scale urban environments [6].

A promising solution to these challenges is the use of procedural modeling techniques. First introduced in [9] for city-scale modeling, procedural modeling involves the automated and dynamic creation of building structures through parametric and algorithmic methods. Instead of manually creating each building or component, procedural modeling enables the rapid generation of complex urban environments by adjusting key parameters, such as size, shape, and layout. This approach significantly reduces the time required to build detailed UDTs, while maintaining flexibility and adaptability [10].

This study aims to develop a systematic workflow for creating a procedural geometry that enables the dynamic and efficient generation of UDTs. The focus is on ensuring that the geometry remains flexible, scalable, and adaptable to various urban designs, while maintaining conformal hexahedral meshing for thermal analysis.

## 2. Methodology

The proposed workflow is designed to enable the rapid creation and modification of UDTs, which can then be used for various simulations, including thermal analysis, without the need for manual intervention in the geometry generation process.

A core aspect of this work is the creation of an orthogonal, all-quad conformal mesh for the FEM, which is directly controlled through geometric modeling by subdividing each volume. Blender 4.1 [11] was chosen for this task due to its suitability as an open-source 3D modeling platform, offering flexibility, ease of use, and the ability to handle procedural modeling through the Geometry Nodes interface [12].

Starting from a primitive cube, architectural elements such as beams, columns, walls, roofs, and floors are modeled as hexahedra, embedding the mesh into the model from the outset. These elements are then assembled into basic structures, where intersections, such as those between beams and columns, form new joints, as highlighted in blue in Figure 1.

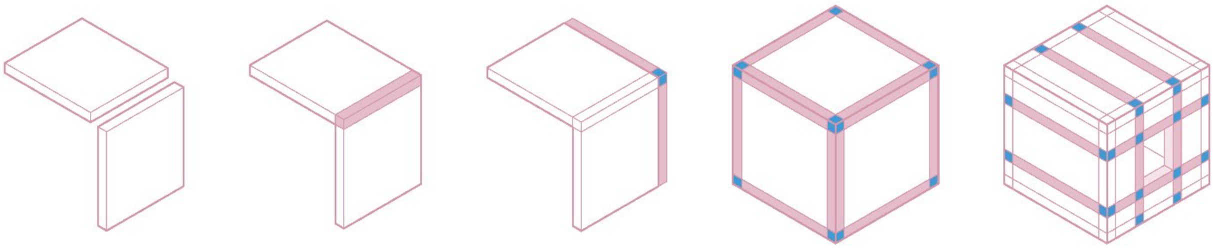

**Figure 1.** Example of embedded conformal meshing within the model.

From this foundation, five typologies are created as assets for use in building construction. These typologies, shown in Figure 2, follow a modular parametric approach, allowing for easy and rapid modifications to the model. This approach is similar to assembling components in a game engine or design platform, where each part can be adjusted or replaced without disrupting the overall structure, thus offering flexibility in building design.

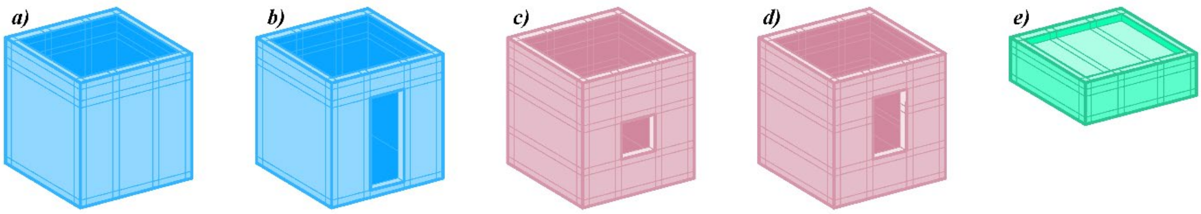


**Figure 2.** Typologies classified as "GroundFloor" (a and b), "Apartments" (c and d), and "Roof" (e).

The typologies all have dimensions of 1.00m x 1.00m x 1.00m, with a thickness of 0.03m, and are described as follows:

a) *"GF":* A basic ground floor unit with fully enclosed walls, forming a solid cube; b) *"GF-door":* Similar to the previous typology but with a door opening; c) *"Apt1":* An apartment unit with a central window measuring 0.30m x 0.30m; d) *"Apt2":* An apartment unit with a central window measuring 0.30m x 0.50m; and e) *"Roof":* A flat-roof structure with a height of 0.30m.

### *2.1. Procedural geometric modeling*

The procedural process begins by configuring the Group Input node to accept user-defined parameters, namely "Width" and "Levels," which control the dimensions of the generated building. The "Width" parameter determines the number of modules along the X-axis, while the "Levels" parameter defines vertical stacking along the Z-axis. For example, if "Width" is set to five and "Levels" is set to three, the grid will have five modules along the X-axis, and three modules are stacked vertically along the Z-axis.

Once the values are set through the Group Input, they are passed to the Grid node, which defines a two-dimensional array of points where the building components are placed. This grid serves as the foundation of the model.

The grid is then populated using the Instance on Points node, which places instances of predefined typologies or collections. This means that it can create a group of elements, namely, "GroundFloor", "Apartments", and "Roof," and instance these groups at each point on the grid. This setup allows the typologies to be dynamically adjusted using the Collection Info node, thereby facilitating easy swapping between different building types.

To ensure the correct division of space between "GroundFloor", "Apartments", and "Roof" along the vertical axis, the Separate XYZ and Compare nodes are used. These nodes extract the Z-component from the grid points, allowing the model to differentiate between the ground floor, apartment units, and the roof. This process ensures that the appropriate typology is assigned to each section based on its correct position along the Z-axis. Finally, all instances are joined into a unified geometry and exported as an OBJ file.

The workflow is designed to handle a degree of flexibility in input geometry. While the procedural components rely on predefined modular typologies, these elements can be adapted to different heights, facade types, and layouts without affecting mesh conformity.

## 3. Model validation

The primary objective of model validation is to ensure that the procedural modeling methodology generates a conformal, all-quad mesh suitable for the FEM. As a representative case, a test building was generated using a 5x5 grid composed of 25 instances of the previously defined typologies, as shown in Figure 3. To assess the modeling efficiency, the same building block was also assembled manually by instancing each typology and positioning it carefully to avoid overlapping elements. This manual process took 12 minutes and 28 seconds, while the procedural workflow generated the same structure in 7 seconds, decreasing the modeling time by over 90%.

### *3.1. Solid geometry conversion*

Following procedural creation in Blender, the model is imported into FreeCAD [13], an open-source 3D computer-aided design software, for solidification. This step is essential because, while the Blender model is suitable for visual representation, it must be converted into a solid structure for compatibility with simulation tools. Once solidification is complete, the building model is exported as a .STEP file, a widely used format that maintains geometric integrity.

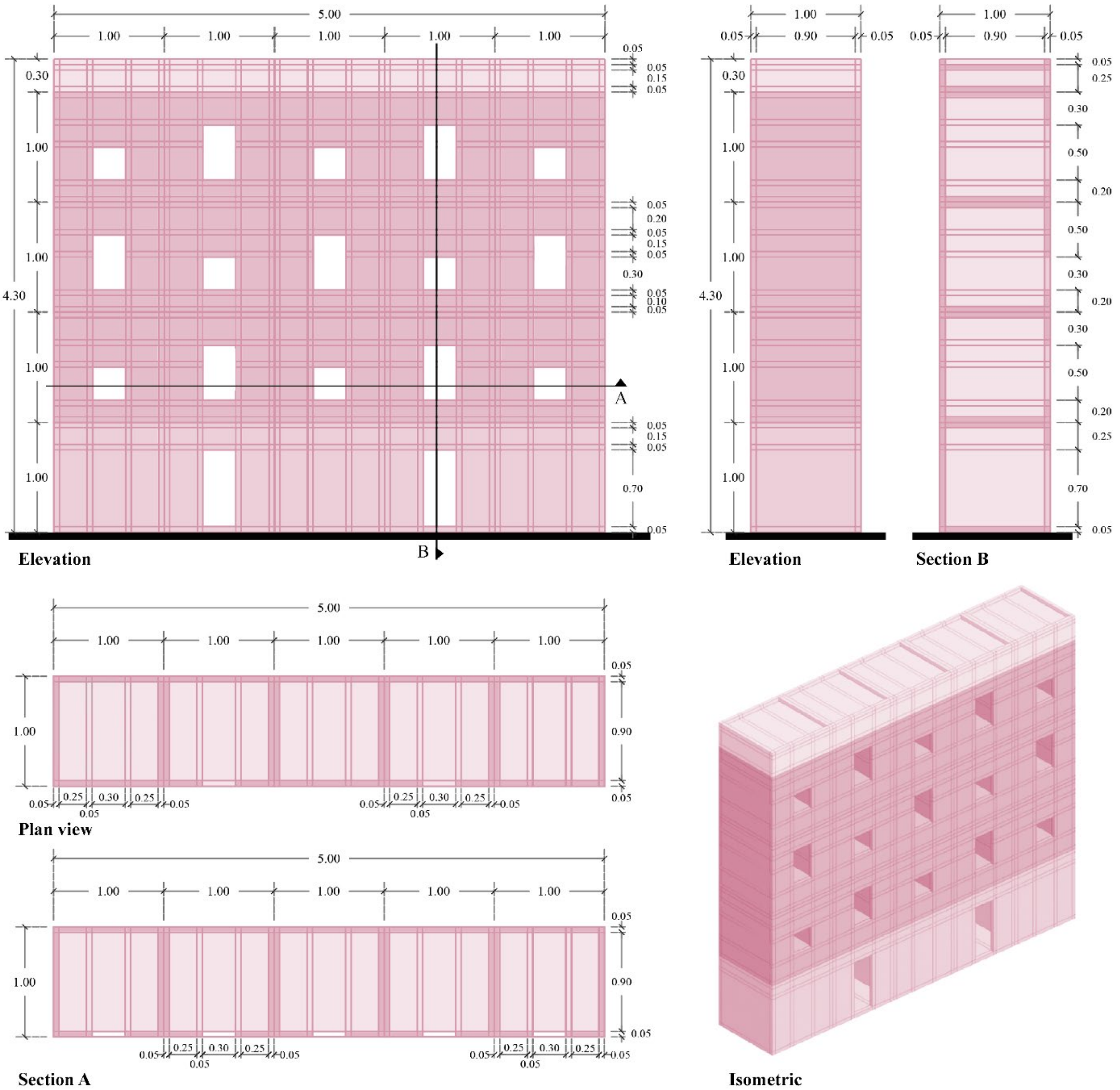


**Figure 3.** Procedural building generated using the developed workflow.

### *3.2. Mesh and thermal simulation*

The solidified model is then imported into the chosen simulation software ANSYS 2022 R1 [14], where thermal simulations are performed. Although the thermal simulation is not representative of a full-scale real-world analysis, it serves as a useful test for evaluating the behavior of the generated mesh under varying temperatures across the facades of the building model.

To test the mesh, simplified boundary conditions were applied by randomly assigning higher temperatures to certain facades of the building to simulate the effect of external thermal sources. The FEM analysis performed in ANSYS calculated the temperature distribution across the model considering the geometry defined in the simulation setup.

The results in Figure 4 illustrate the performance of the mesh under these simplified conditions. The first image shows the geometry generated in Blender before analysis and the thermal boundary conditions applied to three different parts of the facade, with temperatures set at A = 38.0ºC, B = 30.0 °C, and C = 28.0ºC. The material used in the analysis was concrete from the built library of ANSYS, with thermal properties including a density of 2392 kg/m³, specific heat at a constant pressure of 936.3

J/kg°C, and a thermal conductivity of 2.933 W/m°C. The second image depicts the refined mesh created in ANSYS with a sizing of 0.10m, confirming that the mesh is both conformal and composed entirely of hexahedral volumes. The third image displays the temperature distribution across the facades of the building, with red areas indicating higher temperatures and blue areas showing lower temperatures.

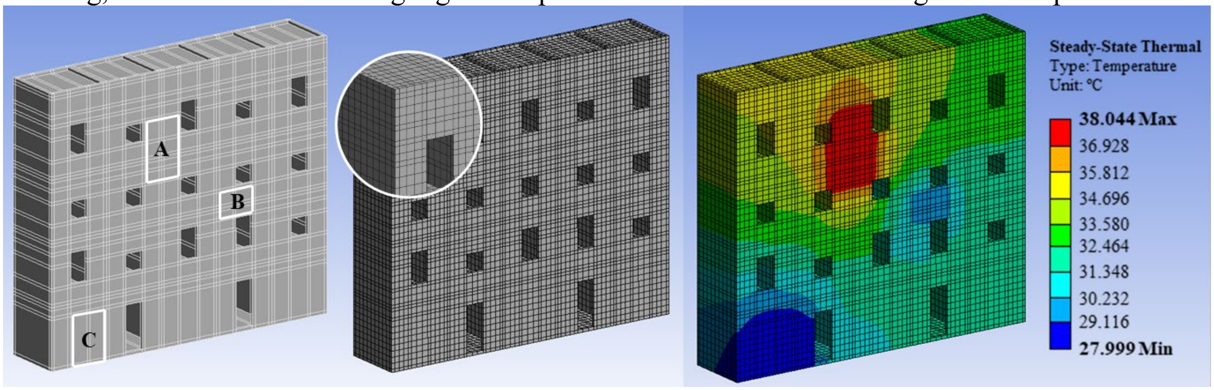


**Figure 4.** Thermal analysis results.

## 4. Conclusions

This study successfully demonstrated the potential of procedural modeling to generate urban buildings to be used in thermal analysis. The workflow, utilizing Blender for geometry creation, effectively produced conformal all-quad hexahedral meshes suitable for FEM-based thermal analysis. Beyond mesh quality, the workflow also demonstrated significant efficiency gains. A building block composed of 25 typologies required approximately 12 minutes to assemble manually by instancing and positioning each element, while the same structure was generated procedurally in under 7 seconds.

The FEM-based simulation results validated that the mesh remained stable and geometrically accurate even under varying thermal conditions. This is an important finding, as the accuracy of the FEM results is heavily dependent on the quality of the mesh [15]. Although this is not a full thermal analysis, the focus of this exercise was to demonstrate that the procedural mesh generation methodology results in a model that can be used effectively in simulations and can withstand varying boundary conditions while maintaining its structural and geometric properties. This validation process confirmed the robustness and adaptability of the generated mesh, which is a key feature for future urban thermal studies.

This approach offers a promising solution to the challenges of creating detailed UDTs, reducing the time and complexity traditionally associated with manual modeling, while ensuring high-quality mesh structures. However, although this is a first step, there is significant potential for further refinement and expansion.

Future work will focus on enhancing the adaptability of the procedural modeling system, integrating additional urban typologies, and refining the thermal analysis process for more realistic and comprehensive results.

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## References

[1] F. Johari, G. Peronato, P. Sadeghian, X. Zhao, and J. Widén, "Urban building energy modeling: State of the art and future prospects," *Renew. Sustain. Energy Rev.*, vol. 128, p. 109902, Aug. 2020, doi: 10.1016/j.rser.2020.109902.

[2] R. Rogers, D. Nall, and D. Greenberg, “Computer graphics input methods for building energy analysis,” *Comput. Aided Des.*, vol. 9, no. 3, pp. 165–171, Jul. 1977, doi: 10.1016/0010-4485(77)90113-0.

[3] J. P. Aguerre, R. Nahon, E. Fernández, and B. Beckers, “Improving FEM Computations For The Simulation Of Thermograms At The Urban Scale,” presented at the Building Simulation 2019, in Building Simulation, vol. 16. IBPSA, 2019, pp. 3274–3281. doi: 10.26868/25222708.2019.210360.

[4] K. Ho-Le, “Finite element mesh generation methods: a review and classification,” *Computer-Aided Design*, vol. 20, no. 1, pp. 27–38, Jan. 1988, doi: 10.1016/0010-4485(88)90138-8.

[5] G. Besuievsky, S. Barroso, B. Beckers, and G. Patow, “A Configurable LoD for Procedural Urban Models intended for Daylight Simulation,” 2014, Accessed: Oct. 07, 2024. [Online]. Available: https://doi.org/10.2312/udmv.20141073

[6] E. Muñumer Herrero, C. Ellul, and S. Cavazzi, “EXPLORING EXISTING 3D RECONSTRUCTION TOOLS FOR THE GENERATION OF 3D CITY MODELS AT VARIOUS LOD FROM A SINGLE DATA SOURCE,” *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. X-4-W2-2022, pp. 209–216, Oct. 2022, doi: 10.5194/isprs-annals-X-4-W2-2022-209-2022.

[7] J. P. Aguerre, E. García-Nevado, J. Acuña Paz y Miño, E. Fernández, and B. Beckers, “Physically Based Simulation and Rendering of Urban Thermography,” *Computer Graphics Forum*, vol. 39, no. 6, pp. 377–391, Sep. 2020, doi: 10.1111/cgf.14044.

[8] B. Beckers, “Multiscale analysis as a central component of urban physics modeling,” in *Computational Methods in Applied Sciences*, vol. 41, Ibrahimbegovic A., Ed., Springer Netherland, 2016, pp. 1–27. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84964252240&doi=10.1007%2f978-3-319-27996-1_1&partnerID=40&md5=9b93d410d5c201fa2dd6a67e2847f77c

[9] Y. I. H. Parish and P. Müller, “Procedural modeling of cities,” in *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, in SIGGRAPH ’01. New York, NY, USA: Association for Computing Machinery, Aug. 2001, pp. 301–308. doi: 10.1145/383259.383292.

[10] I. Demir, D. G. Aliaga, and B. Benes, “Proceduralization of buildings at city scale,” in *Proc. - Int. Conf D Vis., DV*, Institute of Electrical and Electronics Engineers Inc., 2015, pp. 456–463. doi: 10.1109/3DV.2014.31.

[11] B. Foundation, “blender.org - Home of the Blender project - Free and Open 3D Creation Software,” blender.org. Accessed: Mar. 25, 2025. [Online]. Available: https://www.blender.org/

[12] R. Župan, A. Vinković, R. Nikçi, and B. Pinjatela, “Automatic 3D Building Model Generation from Airborne LiDAR Data and OpenStreetMap Using Procedural Modeling,” *Information*, vol. 14, no. 7, Art. no. 7, Jul. 2023, doi: 10.3390/info14070394.

[13] “FreeCAD: Your own 3D parametric modeler.” Accessed: Mar. 25, 2025. [Online]. Available: https://www.freecad.org/

[14] “Ansys | Engineering Simulation Software.” Accessed: Mar. 25, 2025. [Online]. Available: https://www.ansys.com/

[15] C. H. Wolters, A. Anwander, G. Berti, and U. Hartmann, “Geometry-Adapted Hexahedral Meshes Improve Accuracy of Finite-Element-Method-Based EEG Source Analysis,” *IEEE Transactions on Biomedical Engineering*, vol. 54, no. 8, pp. 1446–1453, Aug. 2007, doi: 10.1109/TBME.2007.890736.