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Building geometry data from online maps for accurate thermal simulations of districts

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Abstract

Current approaches for simulating the energy performance of buildings on a large scale are limited by numerous assumptions and simplifications, which can lead to inaccurate estimations. While new tools and procedures are emerging to improve accuracy, there remains a need for more user-friendly methods. This study proposes a new tool based on online maps to create the geometry of districts in a simple way. The tool also enables an automatic evaluation of all buildings through dynamic hourly simulations, using a building simulation software and allowing to consider different weather conditions. To illustrate the procedure, a district at risk of energy poverty in Seville (Spain) is modeled, where hourly temperature data for a whole year are available to demonstrate the need for building improvements. The tool is used to evaluate the energy demands of the district under several retrofitting alternatives, and free-floating simulations are also performed to evaluate the improvement of thermal comfort without air-conditioning systems. The aim is not to discuss the actual values for this particular case, but rather to identify the correct direction for large-scale studies, so as to make them more easily conducted. Overall, it may be concluded that the results provided by comprehensive tools, such as the one proposed in this study, enable easy yet accurate evaluations of buildings on a large scale with significant time savings, as well as the identification of locations where retrofitting interventions would have the greatest impact.

Keywords

buildings;
districts;
energy demand;
efficiency;
GIS;
urban scale

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1 Introduction

1.1 Moving beyond single buildings: thermal analysis at the district scale

The importance of energy efficiency has been highlighted in the past years as a result of the realization that fossil fuel resources are finite and that carbon emissions have detrimental effects on our surrounding environment. That is the reason why many researchers are developing different procedures to produce and consume energy more efficiently, in order to diminish the environmental impacts. In this respect, many studies focus on buildings, which are one of the most important contributors anywhere in the world. In fact, buildings account for about 36% of CO_2 emissions and 40% of energy consumption at EU level (Ascione et al. 2021).

Buildings have been traditionally studied individually, but lately the focus has shifted to groups of buildings. The reason is the realization that, usually, individual actions are performed in an uncoordinated way, with a limited success compared to considering districts instead, where the synergies between the different buildings may be exploited. Due to this, the term Nearly Zero Energy Districts (NZED) is now being used; this term originates from the more popular acronym of Nearly Zero Energy Buildings (NZEB). NZED's aim is to increase the implementation of renewable energies at larger scales as well as to improve energy efficiency, in order to bring cost savings and environmental benefits by sharing resources.

The issue however is that energy plans at a district scale should find an economically optimized solution for the whole neighborhood, not just for a few buildings, otherwise

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a comprehensive implementation would not be possible (IEA 2014). In addition, decision making for large-scale building assessment is a challenging task, due to the presence of various uncertainties (Zheng et al. 2019a). One of the challenges when improving the energy efficiency of many buildings in urban areas is the lack of accurate prediction models that consider the whole urban context, which significantly affects the energy use of buildings due to shading impacts or changes in wind patterns (Nutkiewicz et al. 2018). Those implications of the urban context for evaluating the solar gains are in fact frequently ignored, and are only sporadically considered to study the reduction of the heat emitting envelope area (Ghiassi and Mahdavi 2017). In addition, an integrated urban scale assessment should be carried out in order to study demand side management strategies at large scales (Kazas et al. 2017).

In order to achieve a NZED, several steps are suggested in Romero Rodríguez (2018):

- Preliminary analysis of the district: gather information about the district and all the resources at hand (location, climate, building use, geometry and construction, energy requirements).
- Conceptual design and optimization of the technologies to be implemented at the district scale: develop a procedure for the evaluation of different alternatives based on cost-benefit analyses, including solutions that affect energy demand reduction, the improvement of the HVAC installations or the implementation of new systems. This involves the estimation of the energy demands in the initial situation of the district, ideally on an hourly basis and during a whole year.
- Design development and final sizing of the optimal solution: final dimensioning of the elements that compose the optimal alternative chosen during the previous stage, and selection of the optimal control strategy.
- Optimal management of the district and the grid: guarantee the selection of the optimal operating strategy by using an objective function and taking into account energy production and different storage possibilities.

1.2 Methods for large-scale building energy demand assessments

There are many different building energy simulation software, but they are usually complex, making them inaccessible for early-stage design decisions or large-scale simulations (Forouzandeh et al. 2021). That is why there are other methods that make the process simpler for large-scale assessments, such as reduced-order methods, but they frequently make large simplifications and strong hypotheses such as constant heating or cooling set-points. Therefore, although these models may provide a useful overview of the spatial distributions of energy demands, they cannot realistically represent the temporal dynamics of the energy loads or their dependency on transient phenomena (Ghiassi and Mahdavi 2017). In this section, we will explore alternative solutions.

As mentioned before, to achieve a NZED many buildings need to be evaluated together, so as to calculate their total heating and cooling demands. In this regard, the study in Malhotra et al. (2022) presents a taxonomic analysis of key urban building energy modeling components, including: input data formats, simulation tools, simulation results and validation techniques. A similar study is performed by Wang et al. (2022), which reviews appropriate acquisition approaches for the four data inputs deemed necessary for urban energy-related applications, including geometric data, non-geometric data, weather data, and validation and calibration data. According to Katal et al. (2022), the main issues with current urban simulation tools are generating the 3D model of the buildings, creating an archetype library and capturing the two-way interaction between buildings and microclimate.

In essence, two different strategies are usually utilized in the literature to estimate the energy demands at large scales: top-down and bottom-up. In the case of top-down approaches (among which are the previously mentioned reduced-order methods), the data is processed on a monthly or yearly basis, so these methods do not perform accurate simulations on an hourly basis, which is why they cannot represent in detail the highly dynamic building energy behavior (Ascione et al. 2021). According to Ali et al. (2021), who include a very interesting review on urban building energy modeling approaches, top-down methods are suitable for an aggregated level large-scale analysis, but bottom-up approaches are instrumental in the identification of plausible efficiency improvements for the urban building sector. As also stated by Ferrari et al. (2019), who carried out a literature review of over 70 studies about methods for estimating buildings' energy demand at district level, there is a great need of having reliable hourly energy profiles to develop accurate energy scenarios in districts, but a great amount of time is needed to do so in detail. For these reasons, bottom-up approaches are potentially more desirable at large scales, but are quite complex to implement.

1.3 Software tools for large-scale building assessments

Dynamic building simulations can be performed with software such as EnergyPlus, ESP-r, TRNSYS, HULC, and so on. Nevertheless, these tools usually simulate buildings individually, since a lot of data is needed to perform the calculations: detailed geometry, orientation, number of floors, window to wall ratio, year of construction, materials, etc. Thus, dynamic urban simulations often face three main challenges: 3D digital city generation, building archetypes creation, and inclusion of urban microclimate impacts due to limited data and computing resources available (Katal et al. 2022). Geographic Information Systems (GIS) are a powerful tool to help modelling districts, since they can manage information of real objects. Several standards such as CityGML are available for modeling 3D building data, which is why 3D city models are increasingly being created around the world.

These 3D models are also starting to be used to perform simulations at urban level. For example, in Schiefelbein et al. (2019) a method is presented to automatically extract basic city district data from OpenStreetMap (OSM), using national building stock statistics to complete the GIS datasets. In Ascione et al. (2021), a GIS tool is coupled with SketchUp to generate geometrical models of the buildings, then DesignBuilder is used for the thermophysical definition of the building envelopes, then EnergyPlus is used to perform the simulations, and lastly Matlab is used to process the results. Also, in Cucca and Ianakiev (2020) a simulation tool coupling EnergyPlus (to model the buildings) and Dymola-Modelica (to model the energy systems) was developed, which allowed them to model a cluster of homes so as to develop different control strategies to reduce the energy consumption from the grid.

To add on this, due to the fast development of computer technology, researchers have developed various Urban Building Energy Modeling (UBEM) tools in recent years, which are a bottom-up approach (Liu et al. 2023). UBEM tools allow to support municipalities in shaping the necessary strategies by estimating energy demand with high spatial and temporal resolution (Issermann et al. 2021). For instance, the paper (Deng et al. 2023) introduces a new UBEM tool to calculate urban building energy demands and to analyze energy retrofits and rooftop photovoltaic potentials. In this case, a building-by-building approach is used to model the buildings and perform the simulations using EnergyPlus. To simplify building interactions and implement multi-thread computations, Zheng et al. (2019b) developed an efficient and reliable parallel computational building-chain simulation model. In Issermann et al. (2021), a Functional Mockup Interface (FMI)-based UBEM that couples EnergyPlus with external models is proposed and tested in a German city, estimating sub-hourly energy demands based on the adjacent environmental conditions of each building. In this regard, to evaluate microclimatic effects in the built environment, one of the most used tools is ENVI-met, a 3D microclimate model which can be integrated into EnergyPlus to quantify the effects on building energy consumption.

Furthermore, as stated by Nutkiewicz et al. (2018), UMI (Urban Modeling Interface) is capable of modeling the conditions of shading and Urban Heat Island (UHI) effects apart from the energy use, within the context of urban planning. However, the process in UMI to create an urban 3D model, attach all the necessary information and run a stock simulation is labor intensive and time consuming, limiting its usability (Li et al. 2018). Another available 3D tool is SOLENE-Microclimate, which considers unsteady building thermal behaviors, using a thermo-radiative model which may be coupled with outside airflows computed by a Computer Fluid Dynamics (CFD) tool. In addition, an interesting tool based on a dynamic thermal model that can import 3D geometry of buildings is CitySim, although according to Ascione et al. (2021) it has a proprietary simulation engine that is difficult to couple with other software. Last of all, we would like to mention the tool City Energy Analyst, presented in Fonseca and Schlueter (2015) and Fonseca et al. (2016), which is an open-source computational framework for the analysis of urban energy systems. The tool was initially built as an extension of ArcGIS, and is now available as a stand-alone tool.

1.4 Web-based tools for building assessments

Apart from the previously mentioned approaches, new web-based tools are beginning to be developed for the energy simulation of buildings. A review of available web-based tools for building analysis applications is shown in Forouzandeh et al. (2021). The study states that the reviewed tools may be divided into four groups: tools to define the geometry by drawing, by using simplified numeric inputs, by importing certain types of file or by using datasets of geometry assumptions for existing buildings.

An example of a very interesting and novel web-based framework for large-scale assessments is UBEM.io, presented in Ang et al. (2022). By uploading a GIS file and using building archetypes, the tool may be used to create UBEM models for different scenarios, which may then be simulated to visualize the results. The tool does not implement its own energy simulation: it interfaces with other software (such as UMI). However, it is not possible for the users to create the buildings manually based on an online map for instance: they need to previously develop a GIS file with a certain format so that an UBEM model may be then prepared by the tool. This means that the energy modelers require GIS-related experience.

1.5 Aim of this work

As seen in the literature review, performing accurate hourly dynamic simulations of all the buildings in a district is essential when improvement measures or demand side management strategies need to be assessed on a large scale (Romero Rodríguez 2018). In this respect, researchers and practitioners have been exploring new technologies and tools that can facilitate the creation of accurate 3D models of buildings. However, most existing approaches present several limitations, since they either make many simplifications and do not represent the buildings in a precise way, or are too difficult to utilize since they require the use of complex software tools.

Most of the tools are not web-based either, which would facilitate its usability. That is the case of City Energy Analyst for instance (presented in Section 1.3), which is not a web-based but a stand-alone tool that relies on the data availability in the OpenStreetMap platform or in the creation of a compatible GIS file. In fact, in most tools it is not possible to create the buildings' manually: a GIS file is usually needed. Therefore, as far as the authors of the present work know, no previous studies developed an online web-based tool to allow users to easily define the geometry of districts and carry out precise dynamic hourly simulations. Thus, there is a great need to carry out further research so as to be able to assess precisely the energy performance of buildings at a district scale, but in an uncomplicated way which may be carried out by non GIS-related experts.

As an effort in this direction, the present study aims to provide a user-friendly way to create the geometry of all the buildings within a district, considering their mutual shading, so that dynamic simulations may be later performed. For this purpose, a new web-based tool will be presented, using online maps to generate the geometry of districts so that anyone could potentially use the tool to model any neighborhood around the world. Concurrently, an Excel tool was developed to interface with a building simulation software that is already available: HULC (Ministry of Transport Mobility and Urban Agenda 2019), which is a building energy performance evaluation tool frequently used in Spain, available for free, and capable of performing transient dynamic hourly simulations of buildings so as to determine their energy demands.

In Section 2, the procedure and tools developed in this work will be presented, a case study will be described and a validation will be carried out to check the accuracy of the results. Then, in Section 3 several retrofitting scenarios will be considered for the case study district, so as to demonstrate the practical applications of the tool and highlight its potential for supporting evidence-based decision-making in urban planning and policy-making. Last of all, Section 4 will summarize the main achievements and conclusions of this study.

2 Methodology

2.1 Overall description of the method

After conducting the literature review, it became evident that there is a significant need to explore new methods to create precise 3D representations of buildings on a large scale, but in a straightforward way. In the pursuit of this goal, the present work carried out the development of an online map-based tool named "HULCGIS web", using the JavaScript and HTML programming languages. The aim of this tool is to aid in the process of creation of all the buildings within a certain district, using information from Google Maps. Apart from defining the geometry of all the buildings in a district using this tool, the users may input building information such as the year of construction, the window to wall ratio, the number of floors or the height per floor. The surroundings of every building are also considered, since obstacles may be defined. Further information about the tool will be given in Section 2.2.

HULCGIS Web is integrated into the "HULCGIS Excel tool", which was created in parallel to manage all the information flows needed in the process to evaluate the energy performance of a district. Figure 1 shows the Excel tool that manages all the steps, and Figure 2 summarizes the entire procedure.

The procedure in Figure 2, managed by the Excel tool, consists in four steps, each of which have been automated using Visual Basic for Applications (VBA) programming. These steps will be analyzed in more detail in the next sections.

- The first step of the procedure is to open the previously mentioned HULCGIS web tool, so that the user may create the geometry of all the buildings.
- The second step, carried out by the Excel tool automatically, is the creation of a model for each of the defined buildings, with the format required by the tool used in the present study to simulate the thermal performance of buildings, named HULC.
- The third step carried out by the Excel tool is to call the HULC calculation engine iteratively, to simulate the thermal performance of every building in the district.
- In the fourth step, once the simulations have been completed, the results may be viewed in the Excel spreadsheet, allowing to assess the energy demands of the district.

2.2 Description of the online map-based tool

As a first step, the "Create buildings" button of the tool shown in Figure 1 should be clicked to start the definition of a district. This will open the HULCGIS web application in the default browser of the user. To assess the thermal performance of a whole district it is essential to know its precise geometry, which is why the HULCGIS web-based tool uses the Google Maps API to visualize 3D representations of buildings all around the world. A random district in Madrid (Spain) will be used to illustrate the procedure in this section.

When the user opens the web-based tool, they should first approach the area under study, and follow the easy steps provided in the upper part of the map (refer to Figure 3). Then, the user may create a representation of each building

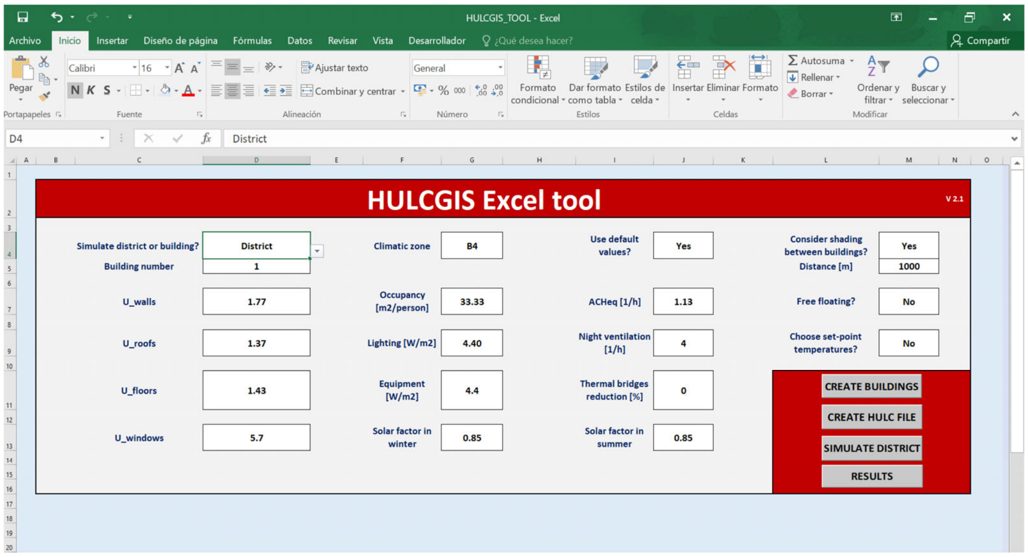

Fig. 1 Interface of the HULCGIS Excel tool

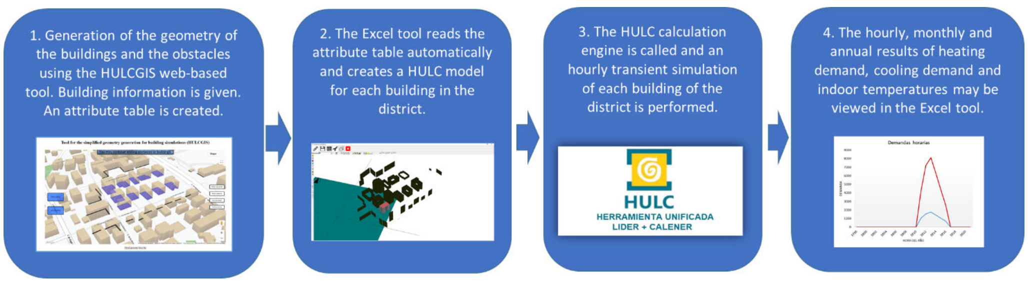

Fig. 2 Summary of the steps in the HULCGIS tool

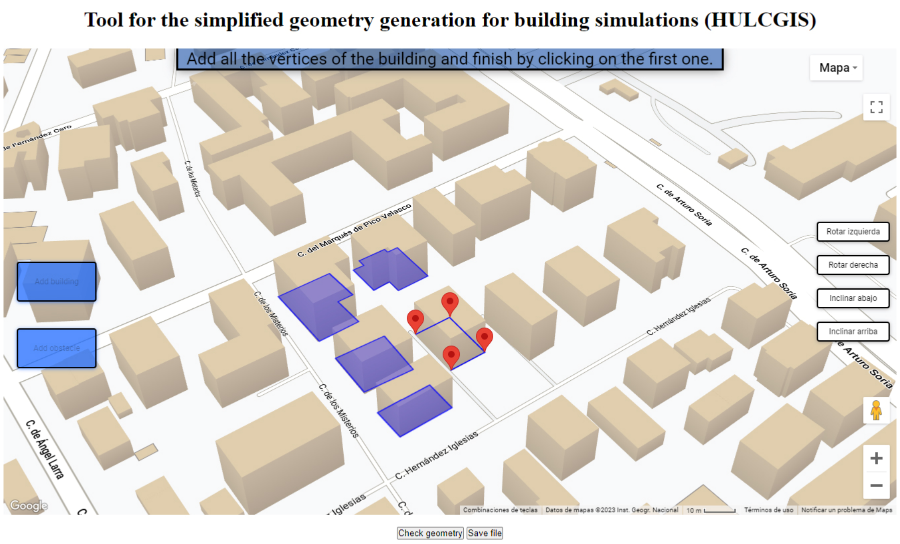

Fig. 3 Buildings already created in HULCGIS web (blue polygons) and vertices of a building that is being defined by the user

footprint within the district using polygons, by clicking on the vertices of the buildings (see Figure 3).

When each polygon representing a building has been created, polylines may also be drawn to account for the shading of buildings that do not need to be simulated, or for any other obstacles in the area (see Figure 4), so that they can be taken into account in the simulations of all the defined buildings in the district.

In parallel, the user should provide information about the buildings (by right-clicking on the polygons): for instance the year of construction, which may be obtained from other open access sources such as OSM or the cadaster. This information (see Figure 5 left) is used to assign for instance the materials of the building envelope, as will be later explained. Also, data about the height of the building per floor, the total number of floors and the glazing percentage (window to wall ratio) need to be provided. On the other hand, the only information that needs to be given by the users in the case of the obstacles is the obstacle height (refer to Figure 5 right).

Once the user has created all the polygons and obstacles within the district, the online map-based tool automatically creates nodes based on the vertices of the polygons and assigns them numbers. Also, the tool performs a calculation to obtain the relative coordinates of the nodes, selecting a reference node. Then, the data can be exported as an attribute table by clicking on a button, and all the information is saved as a text file that will be later used by the Excel tool as input to create the building models. With this file, the information of each building provided by the user is also retained for future simulations and adjustments. By using the HULCGIS web tool, even inexperienced users can create a comprehensive model of the whole district in just a few minutes, which represents a significant time saving compared to the several hours typically required to develop such detailed models.

2.3 Creation of the building models

As mentioned before, the HULCGIS Excel tool created in the present study controls all the information flows of the proposed approach, and once it has received the file with the geometry and characteristics of the district indicated by the user in the previously explained step 1, in step 2 it creates a HULC model for each building in the district. HULC is the tool available in Spain since 2016 for the energy certification of buildings, since it allows to run thermal simulations based on detailed 3D building models. Many research studies have previously used HULC to simulate the energy performance of buildings, such as Aparicio Ruiz et al. (2014); Rosselló-Batle et al. (2015); Herrando et al. (2016); Marta and Belinda (2017); Romero Rodríguez et al.

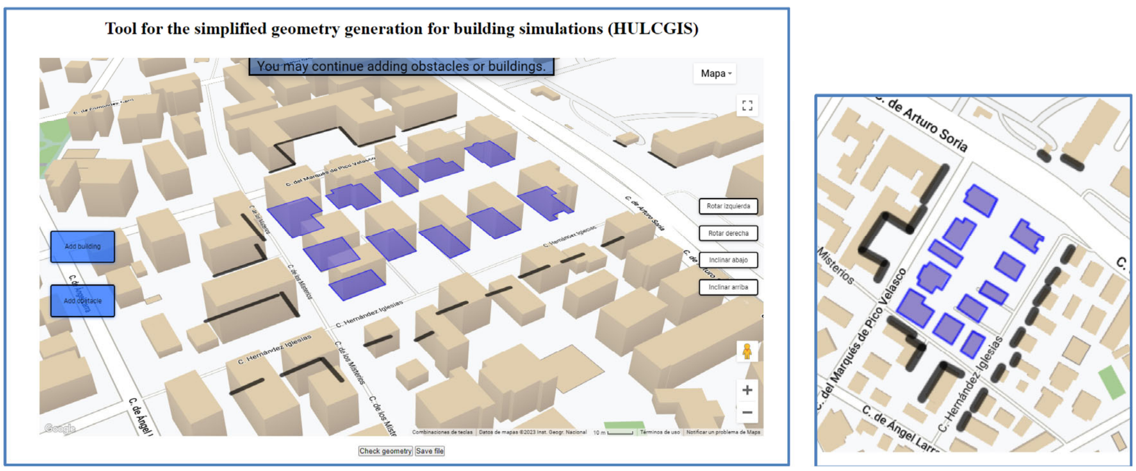

Fig. 4 Buildings (blue polygons) and obstacles (black polylines) defined in the district. The image on the right shows the planimetric view

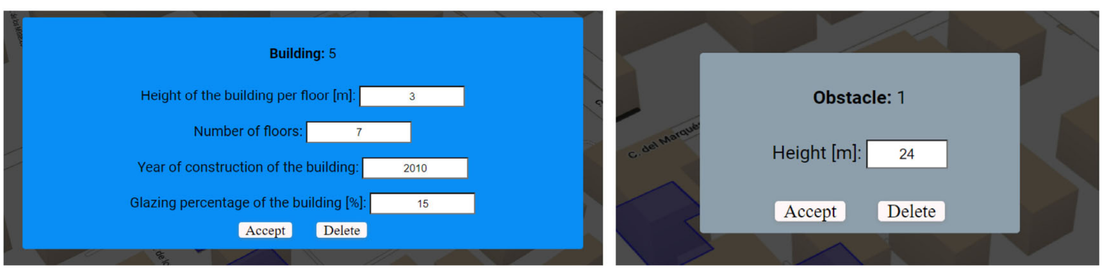

Fig. 5 Information provided by the users for each building (left) or obstacle (right)

(2022). HULC is also used to obtain the official Building Energy Performance Certificate of hundreds of thousands of buildings in Spain. Apart from the fact that it performs precise hourly dynamic simulations, another advantage of this software is that mutual shading may be accurately considered for all the buildings in the district. The simulations carried out by HULC were also previously validated via the BESTEST (Judkoff and Neymark 1995), ensuring its accuracy.

The procedure to create each building model will be now explained in detail. Let us remember that among the information provided by the user was: the geometry of the building footprint, the number of floors and the height per floor. With these data, the HULCGIS Excel tool creates the 3D geometry of the building with the format required by HULC, including roofs, floors and walls with different orientations. The tool is constrained to modeling the roofs as flat, which could be a limitation for cases with tilted roofs (that would require more complex information to be accurately modeled). Then, the window to wall ratio is used to create a window located in the center of each façade. Also, adjacent buildings would be identified, in which case the walls would be modelled as adiabatic and with no windows.

Regarding the materials of the windows, floors, roofs or walls, they are assigned depending on the year of construction indicated by the user for each building, using a database of typical construction materials in Spain for different periods. As for the internal gains, ventilation, operating schedules and use of the building, they are set by default with the values of the Spanish Building Technical Code for residential buildings, although they may be changed by the user as will be later explained.

The obtained building models are uni-zone for each floor, which means that the total number of thermal zones is equal to the number of floors. The aim is to simplify the definition for the users, although this implies that internal partitions are thus not considered. Figure 6 shows an example of building model generated by the HULCGIS tool, using the district displayed in Figure 4 as a case study. As may be seen, only one building is included in each simulation, with an accurate consideration of the geometry of the rest of the buildings and obstacles so as to account for the shading effects precisely, which affect the incident direct, diffuse and reflected solar radiation of each building element in every hour of the year. In step 2 of the tool, a model is thus created for each building in the district, which will be later simulated iteratively in step 3.

As mentioned before, although the usual procedure would be to use the default values provided by the tool depending on the year of construction, the users may change any of them manually. This can be seen in the interface of the HULCGIS Excel tool shown in Figure 1. If the user indicates that the default values should be used, then the materials of the walls, roofs, floors, windows, etc. are assigned depending on the year of construction. The same applies to the internal gains or the ventilation, which are set by default. On the other hand, the user may indicate that default values should not be used, in which case the desired values for each variable should be indicated: thermal transmittances, internal gains, solar factors of the windows, ventilation and so on. This option allows to potentially simulate any retrofitting measure. In addition, the user could choose to perform free-floating simulations, in which case the air conditioning systems would never be activated to modify the indoor temperatures. Also, if the tool was to be used in other countries, two options would be possible: either the database that assigns the building materials depending on the year of construction could be changed, or the option to assign specific values for each building component could be used.

2.4 District thermal simulation process

To perform the thermal simulation of the whole district once each building model has been created, in step 3 the HULCGIS Excel tool calls the HULC simulation engine

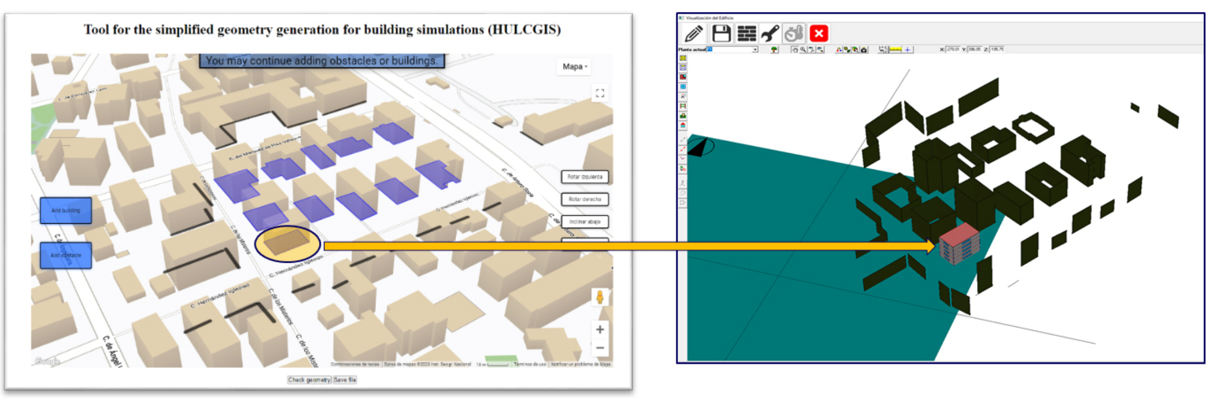

Fig. 6 Example of building model created by HULCGIS, including the shading of the rest of the buildings and obstacles of the district

iteratively, once for each building in the same order they were created. A standard weather file similar to a Typical Meteorological Year (TMY) is used for the weather inputs: the closest one available for the area where the district is located. This file may also be changed by the users if needed, creating for instance a custom weather file that considers the microclimatic conditions surrounding the buildings or the UHI effect. Thus, it is possible to perform the simulations under different weather conditions.

Since HULC performs hourly transient dynamic simulations, it needs some time to perform the calculations, depending on the shape of the building and other parameters. Nevertheless, all the process is done automatically. Once every building in the district has been simulated, in step 4 the user may click on the "Results" button of the HULCGIS Excel tool, and the results of each building and the summary for the whole district are gathered in the spreadsheet with one tab per building.

The results for each building are the hourly heating and cooling demands, as well as the hourly temperatures of each building thermal zone (each floor). Also, the monthly and annual heating and cooling demands of each building are shown. As for the summary of the district, it includes the hourly, monthly and annual results of heating and cooling demand for the whole district. These are shown to the users in a simple way, through tables and graphs that may be later used by them to perform additional calculations (see Figure 7).

2.5 Description of the case study

To demonstrate the usefulness of the tool developed in this work, it is essential to provide a real-world case study. For this purpose, we will consider a neighborhood at risk of energy poverty in Morón de la Frontera (Seville, Spain), so as to evaluate the impact of different retrofitting interventions. The aim is not to discuss the specific values of energy demand reduction obtained in this district, but to illustrate the procedure.

To show that the neighborhood under study is indeed at risk of energy poverty, data of the hourly temperatures measured in five dwellings within the district for the whole year 2017 was collected. In this way, we can better understand the challenges faced by the residents and make informed decisions about how to support them in the best possible way. As may be seen in Figure 8, despite the very high temperatures during the summer months and low during the winter months that the residents had to endure, none of the dwellings made use of air conditioning systems. In fact, the five dwellings were outside the comfort range (between 20 and 25 °C as suggested in the Spanish Technical Building Code) around 80% of the time throughout the year. This suggests that the residents were either unable to afford having air conditioning systems, or were consciously choosing to forgo them to save on energy costs. Several visits to the district confirmed these issues.

This lack of access to cooling and heating systems can have significant impacts on health and well-being, particularly

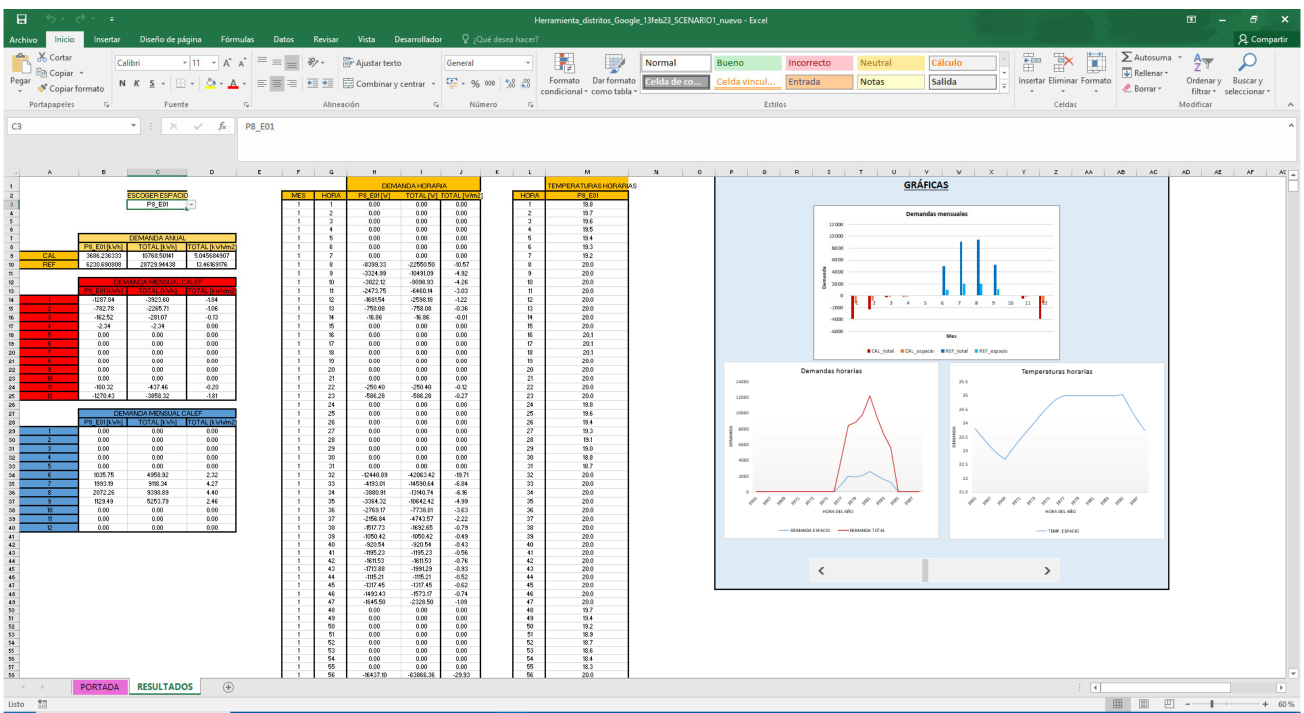

Fig. 7 Results gathered by the HULCGIS tool

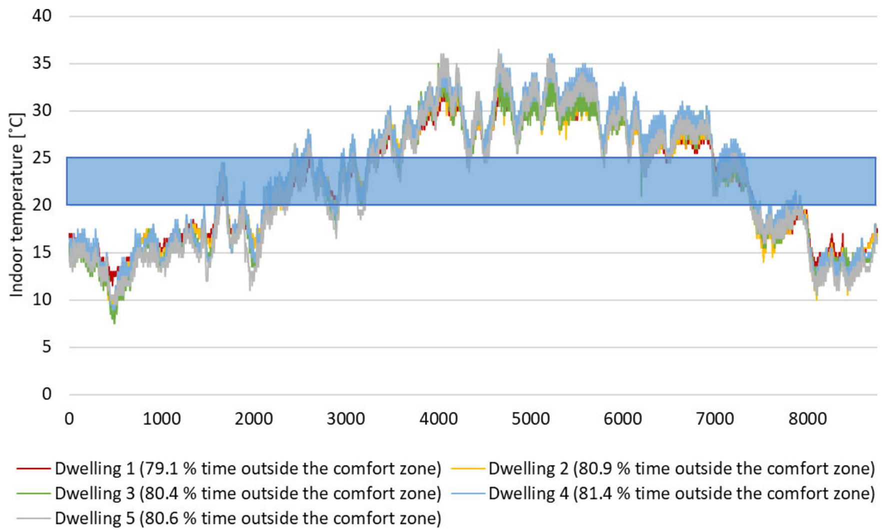

Fig. 8 Hourly temperatures measured in 5 dwellings of the district for a whole year

for vulnerable populations such as the elderly and those with pre-existing medical conditions. Additionally, it may indicate a broader issue of inadequate energy efficiency measures in the neighborhood, further highlighting the need for retrofitting interventions to address energy poverty.

By comparing pre- and post-retrofitting energy demand results, thanks to the HULCGIS Excel tool it would be possible to measure the effectiveness of retrofit interventions in this neighborhood, and assess their impact on reducing energy poverty. In Section 3, an example pertaining to this case study will be presented, exploring various retrofitting measures.

2.6 Validation of the tool

Before using the proposed procedure to perform estimations of the energy demands in a district and draw conclusions for a real case study, a validation is necessary to ensure its accuracy. This validation has been carried out in two different ways, explained in the following subsections.

2.6.1 Validation of the energy demands

Since the building models created using the HULCGIS web tool include some geometry simplifications compared to the real buildings, a very detailed model of a representative building of the case study district was first developed and simulated in HULC. Its real geometry (the building plans were available) and actual construction materials were considered. Then, HULCGIS web was used to create a simplified model for the same building, which was simulated with the same weather conditions. Their geometries may be compared in Figure 9.

Once both building models were simulated using HULC, the comparison of the hourly energy demands obtained for both cases may be seen in Figure 10. Negative values show the heating demands, and positive values the cooling demands. As may be observed, the results provided by the detailed model are slightly lower than those of the HULCGIS model. Nevertheless, despite the assumptions regarding the shape of the roof, the materials or the location of the windows made in the process, the results obtained for both models are very similar and the correlation is very good, so the simplified model can be considered accurate enough for large-scale assessments.

2.6.2 Validation of the free-floating temperatures

In certain situations, instead of obtaining the heating or cooling demands of a building the free-floating temperatures

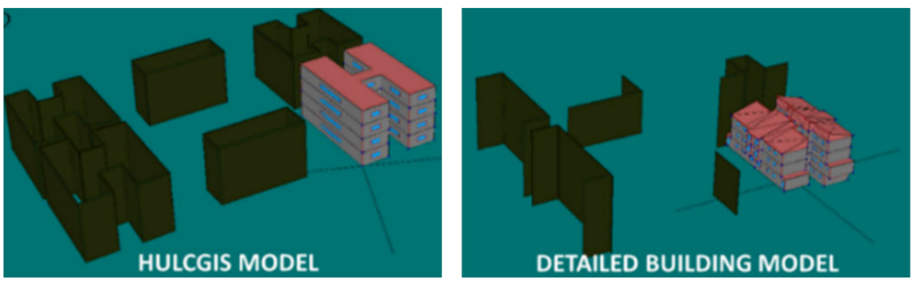

Fig. 9 Comparison of the geometry of the detailed and the HULCGIS building models

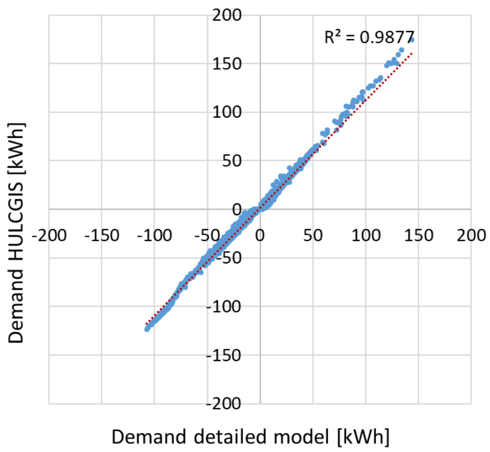

Fig. 10 Comparison of the heating and cooling demands of the detailed and the HULCGIS building models

could be more convenient. That would be the case of buildings at risk of energy poverty for instance, whose residents may not have the means to power the air conditioning systems (or may not even have them). Since the real energy consumptions would be zero, in these circumstances it would be more suitable to consider the free-floating temperatures.

To answer the question about whether the HULCGIS tool is capable of replicating the real behavior of a non-air-conditioned building in an accurate way, the measured hourly temperatures of a dwelling (Dwelling 3 of the case study presented in Section 2.5) were retrieved for a whole year. Then, a model of the building where the dwelling is located was developed using HULGIS web, and a free-floating simulation was performed. In this case, the weather file was modified to account for the real hourly solar radiations and outdoor temperatures measured in a nearby weather station during the same period. This creation of the modified weather file was done following the procedure explained in Romero Rodríguez et al. (2020).

Once the free-floating simulation of the building was performed, the temperatures of the thermal zone where Dwelling 3 is located (fourth floor) were retrieved and compared to the real measurements. Figure 11 shows a comparison of the hourly temperatures for a period of 3 weeks. As may be seen, the estimations carried out by the HULCGIS tool are quite precise. Figure 12 shows the correlation for the whole year of hourly estimations, comparing the temperatures of the simulated HULCGIS model with the real temperature measurements of the dwelling. In this case, the values differ at certain times due to the simplifications made in the process, but the correlation is good and the estimation can also be considered accurate for assessments at large scales.

3 Results: illustrating the utility of the tool

3.1 Simulated scenarios

With the purpose of showing the type of results that may be obtained using approaches such as the HULCGIS tool, in this section different retrofitting scenarios will be proposed. The case study at risk of energy poverty presented in Section 2.5 will be considered. First of all, the geometry of the district was created using the HULCGIS web tool (see Figure 13 for some images). Then, the scenarios shown in Table 1 were simulated for the whole district. The simulations were performed using a TMY weather file in all cases, for the climatic zone B4 in Spain.

The base case scenario corresponds to the actual situation of the district, whose buildings were built in 1983 and are in need of refurbishment, as justified by the measured temperatures in Figure 8. Then, two different scenarios were also simulated: S1 includes measures to improve the heating needs of the buildings, and S2 adds solar control and night ventilation strategies to address the cooling needs. The specific values used for the thermal transmittances of walls, roofs, floors and windows in these two scenarios are those suggested for residential buildings in the last version

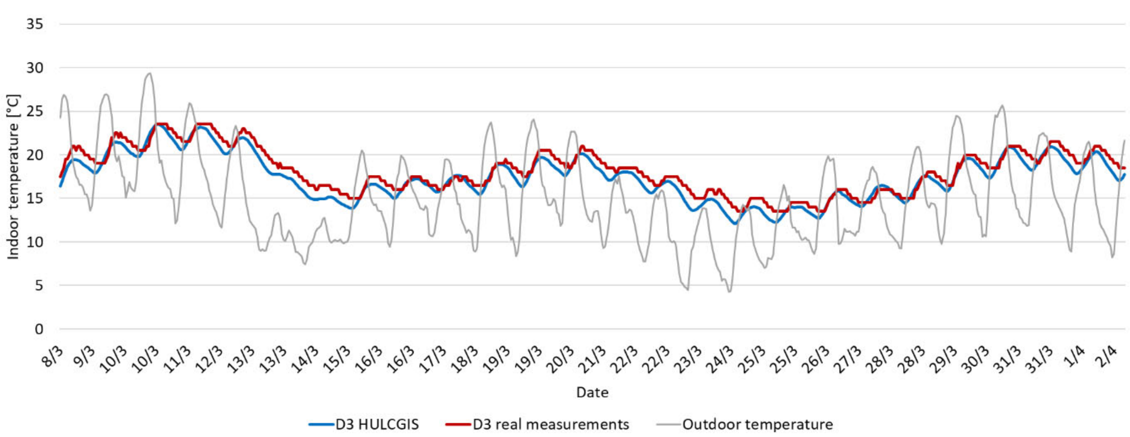

Fig. 11 Comparison of the temperatures measured and estimated in Dwelling 3 in March. The outdoor temperatures are also shown

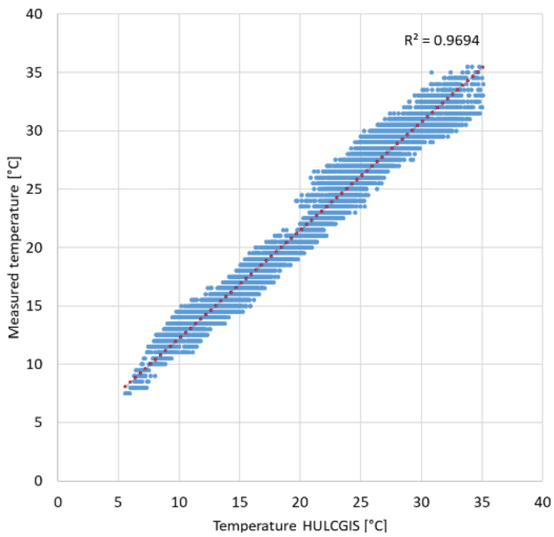

Fig. 12 Correlation between the temperatures measured and estimated in Dwelling 3 for the whole year

Table 1 Different scenarios considered for the simulations of the district. The values changed in each scenario have been highlighted

Variable	Base case scenario (Technical Building code in 1983)	Scenario 1 (S1)	Scenario 2 (S2)
U-value exterior walls	1.49	0.38	0.38
U-value floors	1.88	0.69	0.69
U-value roofs	1.43	0.33	0.33
U-value windows	5.7	2.0	2.0
Solar factor winter	0.85	0.8	0.8
Solar factor summer	0.77	0.7	0.2
Treatment of thermal bridges	—	30%	30%
n50	10	3	3
Night ventilation	4 ACH	4 ACH	12 ACH

of the Spanish Building Technical Code, so as to comply with the newest requirements when refurbishments are carried out. As for the night ventilation, it is performed in summer months during 8 hours at night in every scenario, with the Air Changes per Hour (ACH) indicated in Table 1, so as to take advantage of the lower outdoor temperatures at night and thus reduce the indoor temperatures of the buildings.

The simulation of every scenario shown in Table 1 allows to obtain the heating and cooling demands of each building in the district in those situations. Additionally, free-floating simulations were also carried out in the 3 scenarios, so as to analyze the thermal comfort improvements in cases where the air-conditioning systems cannot be used, such as this neighborhood at risk of energy poverty. In this district consisting of 11 buildings, 6 scenarios were therefore calculated, leading to a total of 66 building simulations.

3.2 Energy demands of the buildings: base case scenario

First of all, the results of the simulation of the whole district in the base case scenario will be shown. As may be observed in Figure 13, the energy demands of the buildings of the district range from 30.3 to 50.0 kWh/(m^2·year) in the case of heating, and from 12.1 to 17.9 kWh/(m^2·year) in the case of cooling. These differences are explained mainly due to two reasons: first, the different geometries in the case of buildings 6 and 11 compared to the rest, and second, due to the influence of the remote obstacles. As may be observed, the heating demands of buildings 6 and 11 are the highest ones, since they are more exposed and the surrounding buildings limit their solar access. Also, building 9 is the one with the lowest heating demand despite its similar geometry compared to other buildings. This is explained by its lack of obstacles in one direction and its three adjacent façades to buildings 8 and 10, which are modelled as adiabatic.

3.3 Monthly energy demands of a building in every scenario

As an example of monthly energy demands, Figure 14 presents the results of building 1 for every scenario. Several conclusions may be drawn from these results. First of all, the heating demands are considerably reduced in the winter months due to the implemented retrofitting measures in S1 and S2, which involved decreasing the thermal transmittances of walls, roofs, floors and windows, as well as the improvement of the thermal bridges and the air-tightness of the building. In fact, the heating demands are the same in S1 and S2, since the changes in S2 of solar gains and night ventilation only affect the cooling demands. Last of all, it may be observed that the cooling demands are higher in S1 due to the increase in thermal insulation of the building, but S2 is capable of reducing the cooling demands compared to the base case scenario thanks to the solar control and night ventilation strategies.

3.4 Heating demands of the buildings in every scenario

This section presents the results of heating demand reduction for each of the 11 buildings in the district. It can be observed in Figure 15 that S1 and S2 are capable of achieving from 79.6% to 83.3% of reduction in the heating demands. These results allow to prioritize which buildings would benefit the most from retrofitting interventions in the neighborhood. It is true however, that the differences among buildings are not very noticeable in this particular district, due to the similarities between the buildings. Nevertheless, that may not be the case of other districts

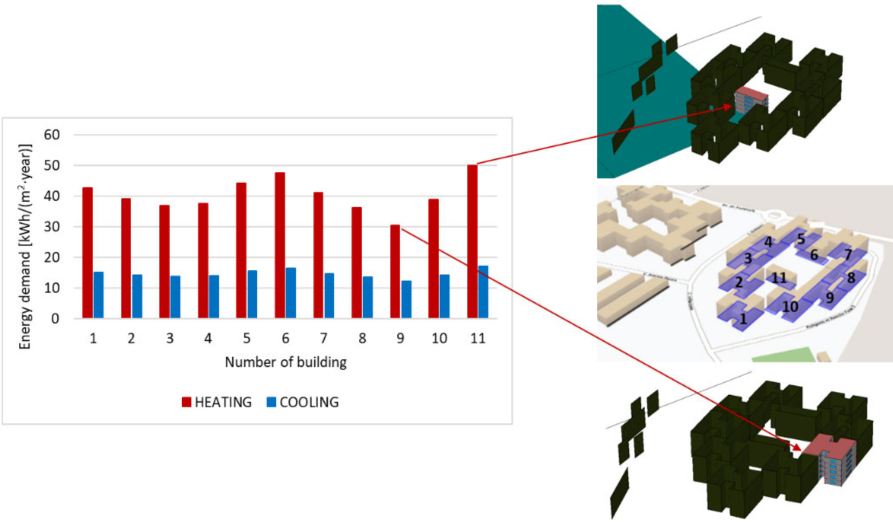

Fig. 13 Heating and cooling demands of the district for the base case scenario

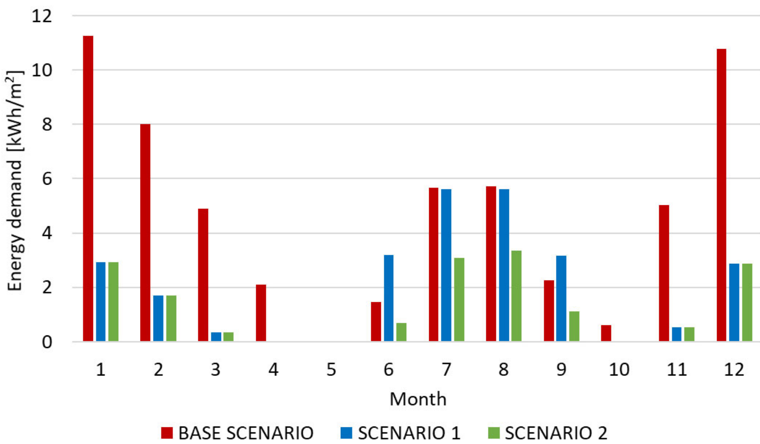

Fig. 14 Monthly heating and cooling demands of building 1 for all scenarios

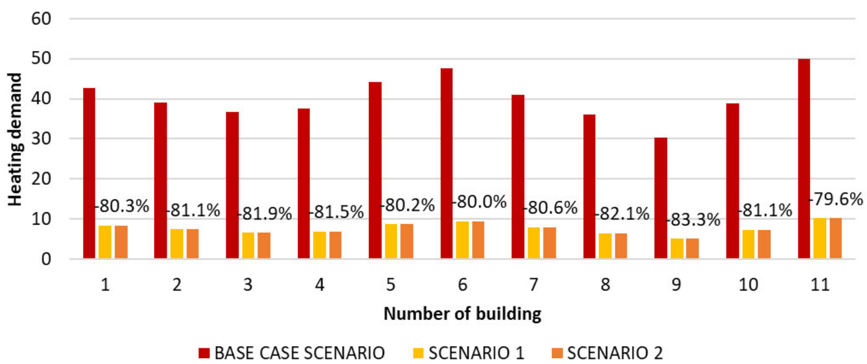

Fig. 15 Heating demands of the district in kWh/(m^2·year) in every scenario. The percentages show the reduction of heating demand in scenarios 1 or 2 compared to the base case

where the buildings are different in geometry, use and construction materials.

3.5 Cooling demands of the buildings in every scenario

As for the cooling demands, Figure 16 shows that savings from 44.8% to 49.7% may be obtained in S2 compared to the base case scenario. Again, the differences in this case are not very noticeable among buildings, but the results show a considerable reduction in the cooling needs of the district by implementing the proposed retrofitting measures in S2.

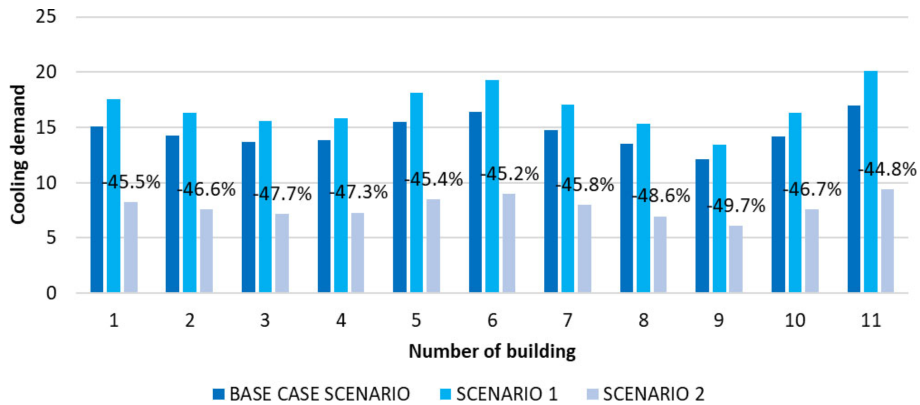

Fig. 16 Cooling demands of the district in kWh/(m²·year) in every scenario. The percentages show the reduction of cooling demand in S2 compared to the base case

3.6 Overall comparison of the district in every scenario

Once the results of the simulations of every building were available for each scenario, the results for the whole district were also automatically gathered by the HULCGIS Excel tool. Figure 17 shows that the retrofitting measures implemented in S1 would mean a reduction of 81% in the total heating demand of the district, but an increase of 15% in the cooling demand. Additionally, including solar control and night ventilation measures, S2 would be capable of obtaining the same reduction of 81% in the heating demand, and a reduction of 47% in the cooling demand compared to the base case scenario. All in all, it may be concluded that the proposed retrofitting scenarios would substantially decrease the energy demands of the district.

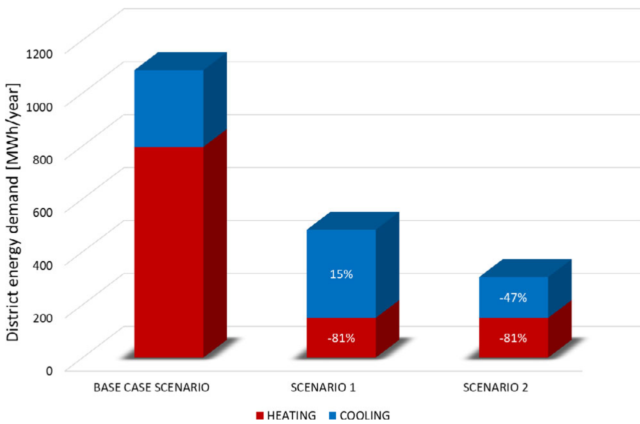

Fig. 17 Total energy demands of the district in every scenario

3.7 Free-floating simulation of a building

As mentioned before, in certain cases the residents of a district may not have the means to pay for their energy needs, even if the thermal comfort conditions inside their buildings are inadequate. In such cases retrofitting would be even more recommendable, but it would be more useful to consider the free-floating temperatures (with no air-conditioning systems). For this reason, free-floating simulations were performed in all the scenarios, so as to estimate the indoor temperatures if no air-conditioning systems were present.

To illustrate these kind of simulations, Figure 18 shows for instance the hourly temperatures of one of the thermal zones inside building 1, comparing the free-floating simulations of the base case scenario and S1 in February. As may be seen, the retrofitting interventions of S1 would improve the thermal comfort conditions of the residents

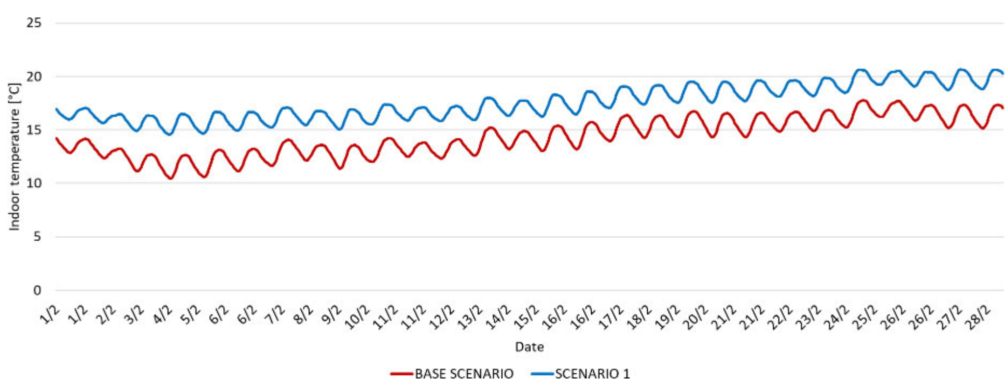

Fig. 18 Hourly free-floating temperatures of building 1 in February

between 2.5 and 4 °C. As for the conditions in cooling months, Figure 19 shows that the changes in summer would not be so noticeable, although the temperatures would be up to 2.5 °C lower in August with S2.

3.8 Free-floating simulation of the district

As for the free-floating simulation of the whole district, Figure 20 shows the results of the heating Excess Degree Hours (EDH) for each building. As may be observed, in S1 (or S2) there is a reduction between 60.7% and 70.0% in the heating EDH. Regarding the summer months (see Figure 21), S2 would mean a reduction between 33.4% and 46% in the cooling EDH. Overall, in S2 there is a 64.5% average reduction in the heating EDH of the district, and 38.9% in the cooling EDH, which means that the thermal comfort conditions of the residents after the retrofitting interventions would greatly improve.

4 Conclusions

The literature review carried out in this study showed the drawbacks of current approaches for estimating the energy performance of buildings at large scales, due to the fact that most methods make many assumptions and simplifications that affect the accuracy of the estimations, or are very complex to use. That is the reason why new procedures and tools are emerging to perform such studies more accurately on a large scale, but there is still a lack of user-friendly methods. In this context, the present work proposed a new

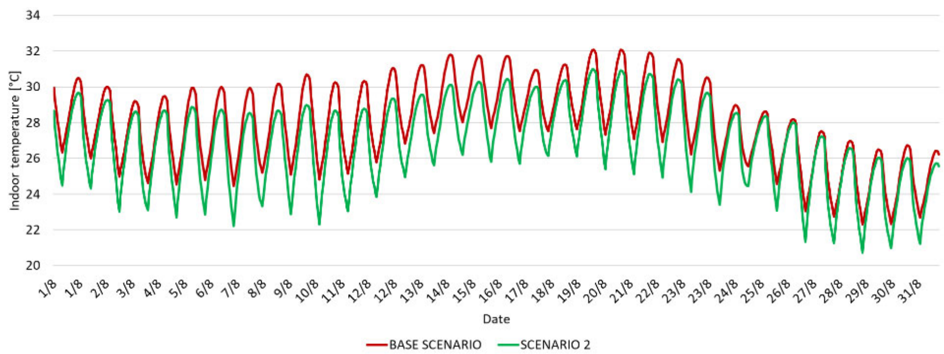

Fig. 19 Hourly free-floating temperatures of building 1 in August

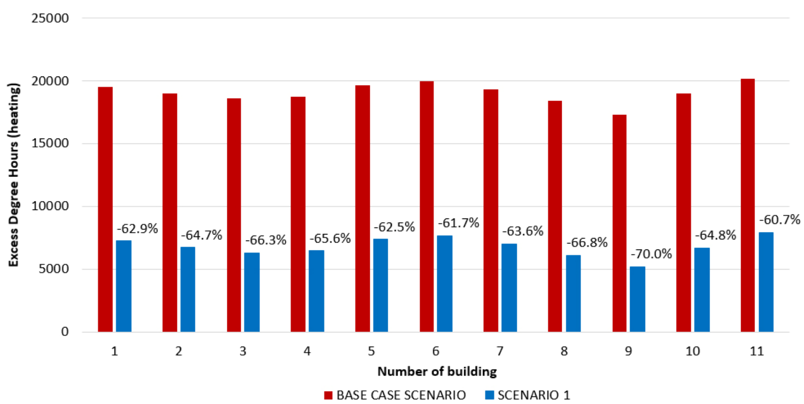

Fig. 20 Heating Excess Degree Hours of every building in the district

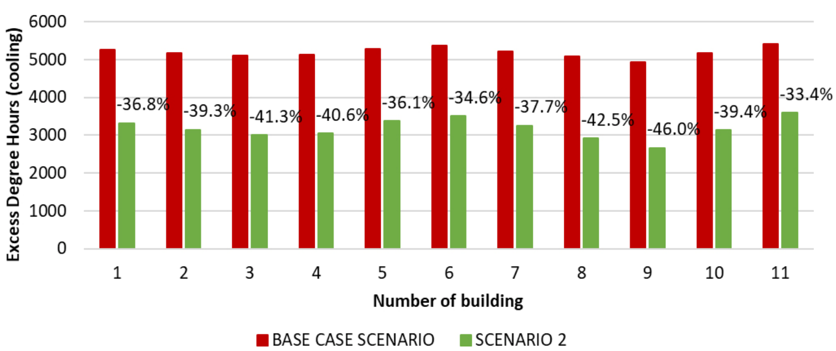

Fig. 21 Cooling Excess Degree Hours of every building in the district

tool to couple online maps with detailed dynamic simulations of the thermal performance of districts.

The presented map-based online tool would allow any user around the world to define the geometry of a whole district in a very simple way, helped by the great availability of geometric information provided by the Google Maps database. After defining the geometry of any district with this tool, transient dynamic hourly simulations of each building in the district may be performed. A validation was carried out using real data from a district in Seville (Spain), to figure out whether the results of the tool were comparable to those of a detailed building model and also to check that it estimated accurately the real indoor temperatures of a building, obtaining satisfactory results.

To illustrate the usefulness of the tool, this work also included the results and comparison of different retrofitting scenarios in a case study district at risk of energy poverty. The objective was not to discuss the specific values obtained, but to show the usefulness of this kind of tools. The outcomes showed that the differences of energy demand between buildings could be explained by their different shapes and solar access. Also, the results demonstrated that the proposed retrofitting scenarios could achieve 81% reduction in the heating demand of the district, and 47% in the cooling demand, with differences among buildings not very prominent in this particular case. Free-floating simulations were also carried out for each scenario so as to figure out whether the buildings could also benefit from retrofitting measures if no air conditioning systems were available, concluding that the heating and cooling EDH throughout the year could be greatly reduced.

All in all this work effectively showcases that, utilizing web-based tools such as the one proposed in this work, it is possible to greatly reduce the workload for users and researchers in evaluating the energy demands of districts, while retaining the accuracy of the estimations. The proposal has the potential to address the barriers identified in the literature, and enhance the usability of UBEM methods. In fact, by using tools such as HULCGIS web, even non GIS-related experts may create comprehensive models of whole districts in just a few minutes, which represents an important contribution towards the availability of urban energy demand assessments. In addition, these tools may potentially be used anywhere in the world, as long as there is open access data available. This means that shifting the focus from individual buildings to groups of buildings to consider large scales no longer means having to sacrifice either a lot of time or the accuracy of the obtained results, which is a significant improvement to support evidence-based decision-making in urban planning and policy-making.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Laura Romero Rodríguez, José Sánchez Ramos and Servando Álvarez Domínguez. The first draft of the manuscript was written by Laura Romero Rodríguez and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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