ENERGY EFFICIENCY ASSESSMENT IN URBAN ENVIRONMENTS USING GIS

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ABSTRACT

Energy simulation tools are commonly used in building design processes. Their calculation methods are comprehensive and widely accepted. However, the increasing requirements imposed to comply with low emission urban scenarios demand a wider scope analysis, taking into account not only the building, but also the interactions between urban elements (buildings, green areas, urban lighting…). GIS technology seems suitable for this purpose, but current solutions do not include deep energy demand calculations. On the other hand, building simulation tools do not consider the city environment and terrain influence. To evaluate a district by manually adding single building simulations results is an overwhelming process, prone to errors and very time-consuming.

In this scenario, urban planners demand Decision Support Systems that go beyond traditional building-scope simulation engines and consider both building and urban-level variables in order to assess the energy efficiency of the urban design.

Aware of this issue, the platform presented in this paper fills this gap between building and city approaches. It consists of an ArcGIS customisation, implementing energy simulation models for radiation, energy demands, consumption, energy costs and CO_2 emissions. The results are simulated and visualized at different levels (façades, buildings and city). Thus, it is possible to benchmark the district against a reference scenario and certify the sustainability of a district. It has been validated with a new urban development scenario in northern Spain.

The platform seamlessly integrates CAD cartography, GIS geoprocessing and the calculation strength of excel sheets, enhanced with 3D energy mapping outputs which can be seen in Google Earth. It does not require deep technical knowledge, being suited for multicriteria analysis. Its modularity allows extending it with future extensions.

Keywords: GIS, energy efficiency, low carbon cities, urban planning, simulation.

1. INTRODUCTION

Urban environments are great consumers of energy. In Spain, housing and services are responsible for 27% of the country's total energy consumption (Eurostat 2008a). In Europe, this figure mounts to 41%, highlighting the relevance of the housing-services sector when compared to industry and transportation, which represents 28% and 31%, respectively, of the total energy consumption (Eurostat 2008b).

In order to get these energy consumptions decreased, the EU has set "20 / 20 / 20" targets for 2020:

- A reduction in greenhouse gas emissions by at least 20% compared to 1990 levels.
- To develop renewable energy resources so that they account for 20% of our final energy consumption.

- A 20% increase in energy efficiency.

In Spain there are many initiatives towards the reduction of energy consumption in buildings, which range from regulations, such as the building code (Código Técnico de la Edificación 2009), to incentives, such as those proposed in the Spanish Energy Efficiency and Saving Action Plan (IDEA 2007), to best practices, such as bioclimatic architecture.

However, many of the alternatives are diminished due to a lack of a holistic approach in the planning, design, and building of new communities. In other words, by the time energy efficiency initiatives are applied, much of the community's potential for these has already been missed, unveiling a critical need to integrate energy efficiency concepts early on and throughout the planning, design, and building process of urban communities (Romero, A., Barreiro, E., Perea, E. et al. 2009).

This paper contributes to this notion through the definition of a novel Design Support Tool that integrates energy efficiency concepts into the urban design and planning process of new urban developments.

Regarding the technical aspects of the project, the energy efficiency analysis of urban environments must cope with a vast number of potential variables, which are not relevant in single buildings analysis. Therefore, the scope of the study must be clearly determined, balancing calculation accuracy and data requirements to characterize buildings and environment. Scenarios defined with a great degree of detail would be undoubtedly more accurate in their results, but the simulation resources and user effort would make the tool not very friendly to use, making difficult its adoption in the market.

On the other hand, lightweight energy models, with a low definition degree would be easy to use and to manage by a software tool, but the validity of the results would be doubtful. Thus, it is mandatory to reach a consensus between these two opposite situations.

2. GENERAL ARCHITECTURE

For the development process, several GIS commercial solutions have been analysed and finally ArcGIS has been selected as a core platform, due to the following reasons:

- It is the most extended platform among professionals, especially in big administrations and city planners. For this kind of users, there is virtually no training period to learn to use the system.
- ArcGIS provides a flexible licensing scheme, adaptable to the users needs and to extend the core platform with specific extensions (3D Analyst, Statistics, Data Interoperability, Spatial Analyst…). Furthermore, it can be used in several environments (desktop, server, mobile) and different operating systems.
- It is highly customisable according to specific business needs, supporting the most common programming languages like Java, Visual Basic or .NET. Particularly, Visual Basic permits its integration with external Excel sheets.

The following figure shows the general architecture of the platform. ArcGIS Desktop is the core tool of the system, whose core functionalities are extended with specific algorithms for energy simulation. The geographic information is stored in a personal Geodatabase (MS Access).

The platform provides an interoperability layer to connect to different data formats and information sources. Thus, the system can import external cartography in DXF format and could eventually be linked to other geometric models like CityGML. In addition, external Excel databases are linked to the system providing climatic data as well as catalogue values (parameters of materials and costs and emissions related to each energy source).

Finally, the system can export the 3D energy maps to KML format.

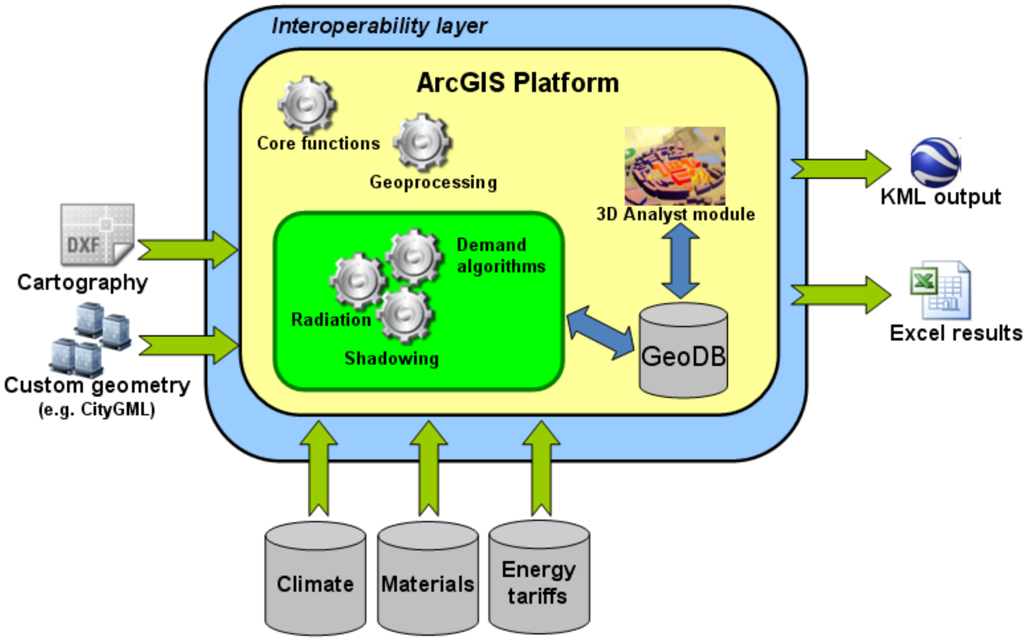

Figure 1. General architecture

All the functionalities of the system are accessed through a custom toolbar created for the project and embedded in the typical ArcGIS toolbars.

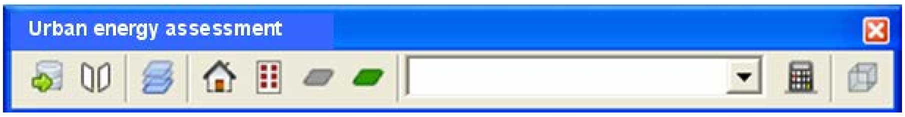

Figure 2. Custom toolbar

System hardware requirements:

- 1,6 GHZ or higher CPU speed
- 2 GB RAM memory or higher
- OpenGL 1.3 or higher compliant video card, with at least 32 MB of video memory.

System software requirements:

- Operating system: Windows XP/Vista/7.
- ArcGIS (ArcView licence) + 3D Analyst extension
- .NET Framework 2.0.
- MS Excel + MS Access
- Google Earth is needed to visualize the exported KML formats, but not mandatory to run the application.

3. MODULES OF THE SYSTEM

The analysis process consists on the execution of the four re main modules of the system, which are invoked sequentially using the above-described toolbar.

1.1 Configuration and Interoperability

The user starts the energy assessment process by configuring the scenario. He selects the location of the city and in case cartography in DXF format is available (which is the most common format in regional administrations and municipalities) he can provide it and will be imported.

The initial installation contains climatic data (e.g. monthly temperatures and horizontal radiation values) as well as the latitude of all the main Spanish cities. If the user wants to study locations not present in the Excel database he can easily extend it with new rows with the required data.

Regarding the cartography, the module automatically detects the layers present in the DXF file and lets the user select the ones to be imported. The only mandatory one is the buildings layer. He can also import common areas (green areas, etc.) and in case the DXF has elevation data (e.g. contour lines) they can be imported to generate the TIN elevation model in ArcGIS. Other data like rivers or roads can be imported, but they do not contribute to any calculation during the simulation process. In case no digital cartography is available or is not complete, the user can always create draw its own buildings using ArcGIS graphical edition capabilities. In this situation, the possible loss of accuracy if we draw manually the buildings will logically affect the accuracy of the results.

Once the digital model is loaded or created, the user must provide some attributes of the buildings, the most important one being the height, which will be internally used to extrude them in 3D visualization and used to calculate shadowing patterns.

The geometrical model needed for the energy analysis at this scope is very simple, only 2D footprints of buildings and heights are considered, so standards like CityGML can be integrated in the system. In fact, ArcGIS 9.3 is able to import CityGML or IFC formats using the interoperability extension. In case other custom geometry definition formats are available specific import processes could be developed in the future.

1.2 Radiation model calculation

Prior to launch any energy calculation, the system automatically creates for each building (polygon type objects) several façade entities (line type objects). In this way, the user can define and analyse individually each façade within a single building. This functionality is one of the main strengths of the system and a step forward in comparison to other GIS-based urban planning tools. Geometric attributes of the façades (coordinates and height) are derived from the building they belong to.

Next, the module estimates hourly shadowing fractions affecting each façade and roof, repeating the calculation for a typical day each month. To perform this operation, the module calculates the sun position according to the latitude of the selected location and the analysis day and hour. Possible sun path obstructions of other façades are considered. In addition, sky visibility from each façade and roof is calculated. Combining these values with the database radiation values for the location and orientation of the façades, the daily effective radiation patterns are calculated (direct and diffuse values).

Once the analysis is performed the user launched the 3D visualization of radiation maps, being able to show extreme situations of a year (June and December radiation), both on façades and roofs. It is also a way for visualizing the potential for solar renewable generation in building roofs.

Taking this radiation map as a basis, the user can define basic shadowing elements in windows through geometrical parameters (length, position and fenestration), allowing the analysis of the self-shadowing effect in addition to the effect of other buildings.

The following figure shows the incident radiation in each façade compared to a reference scenario (isolated buildings), i.e. the maximum possible amount of energy received. The colours represent the decrease of incident radiation due to surrounding obstructions.

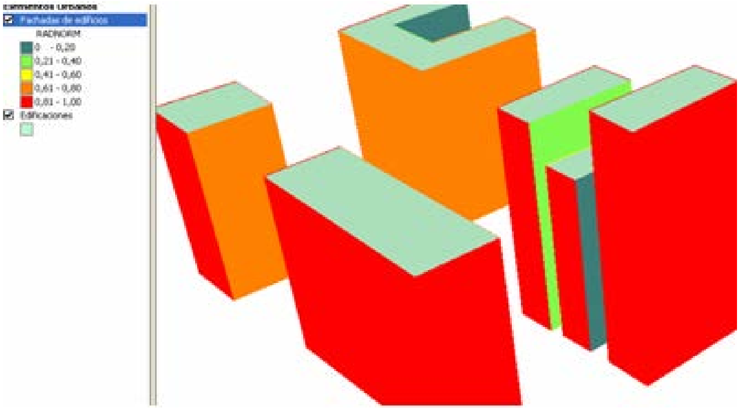

Figure 3. Façade radiation mapping

1.3 Energy demands and consumptions

The simulation methodology consists on the definition of several simulation phases with an increasing degree of detail (Bonilla A., Mediavilla A., Romero A. et al 2008). Each phase permits to concentrate on particular aspects of the design and estimate their influence in the global design. The first phase analyses the influence of geometrical aspects (building distribution, height, orientation, massing and distance), including the possible self-shadowing effects, and main building type (residential, hotel, educational, hospital…). At this stage, default materials (always in compliment with the National Building Code) and usage parameters are considered. Once the volumes are fixed, the next phase consists on specifying individual building usage parameters (occupancy levels, ventilation rates, equipment, comfort temperatures for heating and cooling, etc.) and permits to compare the relevance of different usage patterns.

The next phase considers composition details of the envelopes. Properties for each façade (U values, glazing types, percentage of glazing surface, roof type etc.) must be specified, being able to detect the materials influence and indirectly we can visualize which buildings are more critical, i.e. badly isolated, which means that any change in building parameters will have a greater influence in the global energy demand.

All this process yields a monthly distribution of energy demands: heating, cooling and domestic heat water and general electric demands for lighting and common facilities (lift or garage if present).

To carry out this process of energy demand estimation several algorithms can be used, each of them having its accuracy, data requirements and applicability range. In the case of urban areas study, we are not concentrating on a single building but in a variable set of buildings, so it is not practical to use a complex, dynamic hourly method. Instead, the method implemented in the tool (Claux 1982, Santamouris 1997) is based on the monthly integration of daily heating and cooling average demands.

The algorithm considered takes as a primary input the effective monthly radiation distribution in façades, which is the output of the previous module. This factor has a crucial influence, along with the outside monthly temperature coming from the database.

With this information, as well as all the user-defined values (materials, occupancy values, glazing…) the system calculates heat gains and losses through building envelopes and window glazing. The algorithm considers radiation, convection and conduction factors, based on the daily average indoor/outdoor temperature difference. Heat flow due to ventilation is also considered. The assumption taken is to discard any heat flow through different building storeys (i.e. the whole building has the same use schedules and comfort temperatures). So, internal partitions are adiabatic for analysis purposes. Then, internal gains are added, considering people and internal equipment.

The tool generates 3D visualization models, using the typical energy benchmarking colour patterns (green to red). The user can select a category (heating, cooling, DHW…) or view the total energy demand added up. Moreover, the results can be exported to Google Earth format, taking benefit from its intuitive capabilities as shown below:

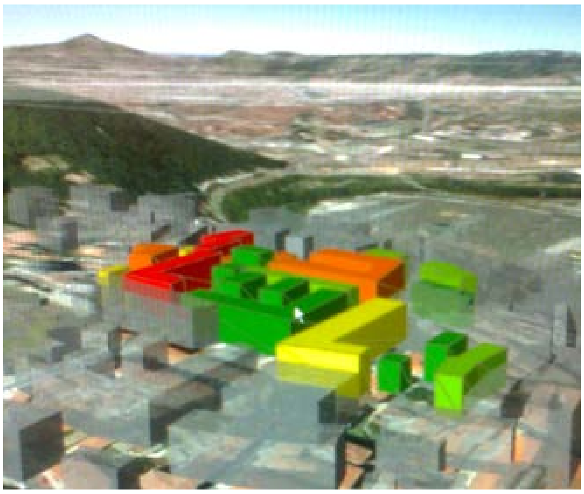

Figure 4. Energy demands mapping in Google Earth

From this monthly demand distribution, it is not difficult to obtain the real consumptions. All the user has to do is to specify the primary energy source (gas, electricity…) for each building and demand type. The user selects a specific building system from a catalogue, which involves an efficiency rate. In addition, the database contains local energy tariffs for each source, being able to generate 3D mappings of buildings for consumptions and energy costs, quite similar to the one shown in Figure 4.

All the output values derived from the different calculation steps (radiation, demands, consumptions and emissions) have been up to now represented in a 3D environment (using 3D Analyst extension), which is very powerful, but the system also generates a MS Excel workbook for each building being simulated. This is very interesting in order to view and store the numerical data. Furthermore, the sheets contain the different formulae used for the demand analysis. In this way, the user can perform custom *what-if* analysis, modifying certain parameters and seeing the effect. He can benefit from the Excel functionalities to exploit the data in a desired way (create graphs, define scenarios, etc.).

1.4 Urban model benchmarking

All the different previous analysis are very powerful in order to visually detect critical buildings or even critical urban areas, being able to compare and select the best design alternative for each building. However, urban planners also demand an overall picture of the built area as a whole, to have a way of referencing the energy performance of urban areas in an objective way. For this purpose, a benchmarking process combines individual building results into a single value.

The most common reference values are the CO_2 emissions. Each energy source type has each KWh to CO_2 conversion rate, thus the tool converts all the building consumptions into CO_2 Kg and normalizes the result to the total built area. The final step is to define a reference value, to detect improvement or deficiencies of our scenario. There is no commonly accepted reference scale for emissions, because the final value depends on the location, building usage and more factors. Therefore, we must find a method to reference the urban model to itself in a certain standard conditions.

The reference scenario in each case is defined as the one with the same geometry and building use distribution as the one being studied, but considering default building envelope materials and glazing (i.e. taking the legal U limit values in each façade according to its climate location) and considering standard installations (average energy losses), instead of the user provided values. The real scenario is then benchmarked to a typical colour scale (A-G), the same used for household appliances. The mean value is the reference one and if the real scenario minimizes the reference emissions it will have a positive score (A to C) and if it is worse it will have a negative score (E to G).

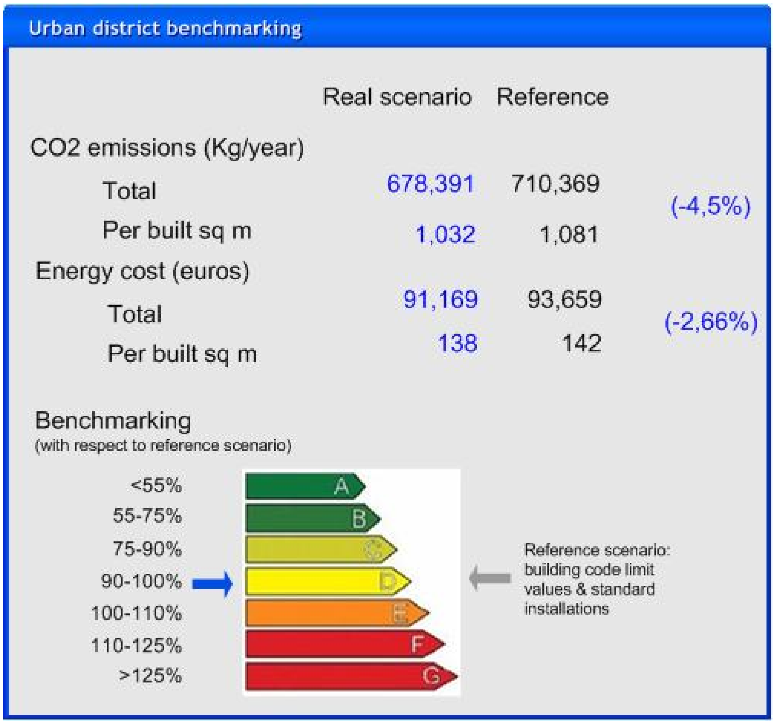

Figure 5. CO2 benchmarking against a reference scenario

4. CONCLUSION

Whereas a wide range of building simulation tools exist, with complex calculation methods accepted among energy efficiency professionals, analysis of complete urban areas lack of simulation tools that consider the multiple factors involved without losing usability. The tool presented in this paper aims to fill this gap by integrating a simplified algorithm in a GIS environment, providing very intuitive input/output interfaces. The simulation of a whole district takes only a few minutes, permitting the comparison of different alternatives and providing visual 3D results at façade, building or city scale. The tool is modular and open to include future capabilities and the databases are easily extensible. Complete set of numerical results of each building is exported to MS Excel for off-line analysis.

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