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GIS-3D Platform to Help Decision Making for Energy Rehabilitation in Urban Environments

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Abstract. One of the main current challenges of European cities is to become energy self-sufficient entities. One of the vectors for this challenge is to improve the energy efficiency of the buildings and to promote the generation of renewable energies in the urban environment. The article describes a tool based on GIS-3D technologies to support the identification of the energy rehabilitation potential of neighbourhoods based on the introduction of renewable energies. The platform is based on a urban 3D model that collects the geometry of buildings, together with relevant information for the identification of rehabilitation opportunities (e.g. surfaces, heights, orientations and slopes). The project includes the generation of a cloud-based repository, which incorporates active and passive innovative solutions with metrics that allow the comparison of the solutions and the applicability of them to the real environment. The identification of rehabilitation opportunities combines information resulting from the diagnosis of the current energy performance of the district's buildings with the potential for renewable generation in the area. A multicriteria analysis process facilitates the identification of the most appropriate rehabilitation solutions for the analysed environment based on different criteria as energy, cost or applicability. The result can be visualized through a web tool that combines 2D and 3D information, with comparative information in a quantitative and geo-referenced manner. The flexibility of the architecture allows the application of the same approach to different urban challenges as the application of energy conservation measures to protected historic urban areas.

1. Introduction

The energy performance of buildings is the most determining factor of global sustainability. The energy consumption of buildings represents approximately 40% of total European energy consumption [1]. The need to improve the energy performance of buildings makes necessary to identify and develop new solutions and technologies. The key aspects to improve the energy performance of urban environments are the envelope of buildings, energy consumption installations and the generation of renewable energy.

Improving the energy efficiency of buildings has become a priority of regional, national and international policies. It has been in recent years when the interest in the energy performance of existing buildings has been awakened and the need to address rehabilitation from the point of view of energy saving, sustainability and emission reduction. The kick-off of this new way of looking at rehabilitation is given by the European Directive 2010/31[1], which already indicates in several of its

[1] Directive 2010/31/EU on the energy performance of buildings-May 2010

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articles the need to extend the concept of sustainable building and energy saving also to the rehabilitation. This guideline is implemented through specific regulations in each member country. In Spain, the guidelines in energy efficiency in buildings are included in the Technical Building Code (CTE). Also through the compulsory nature of the energy certification of buildings for both purchase or lease contracts, as well as those buildings that have to make a Technical Inspection of the Building (ITE) for having more than 50 years old or if they are going to request a subsidy associated with the rehabilitation. The main problem is that certification has been addressed, in many cases, as a mere bureaucratic requirement. Nevertheless, speed and price have been prioritized instead of achieving certain objectives, improvements and rigor.

The world consumption of energy remains very dependent on fossil fuels, although it should be noted that the weight of Asia in total consumption is very high (almost 40 %), while the weight of the European Union does not reach 14 %[2]. Current dependence on fossil fuels is still very high and the substitution by renewable sources is a long and expensive process. However, it is a path that cannot be reversed, above all, because the benefits are considerable, both from the environmental and economic point of view.

Solar energy is the greatest source of energy, it is clean and inexhaustible. The placement of solar energy installations in urban environments, on the roofs of buildings or even on the facades themselves (solar windows, although it is currently a very incipient technology) represents a solution with great potential. Solar energy is, at the moment, one of the energies with more capacity for development in Europe in general and in Spain in particular.

During the last few years, several tools have been developed for energy evaluation at district level. In some of the cases the insertion of the data is manual, requires specific knowledge about energy simulation or manual modelling (e.g.: Dynamic Energy Atlas [2], Neighbourhood Evaluation for Sustainable Territories – NEST [3] and CitySim [4]). Other examples pursue the same objective but are based on basic cartographic information available (EnerCity [5]), however, it focuses on energy diagnosis without offering rehabilitation solutions. Finally, approaches that consider districts as an aggregation of buildings, such as the one described in [6], provide highly accurate simulation results, but they require a large amount of data and a high computational cost that increases exponentially with the number of buildings.

The solution described in this article presents a tool that allows automating the process of diagnosing the energy performance of buildings and the potential for generating renewable energy based on GIS-3D technologies. This process requires a limited number of generally accessible data and little specific knowledge of simulation. It is quite more rigorous than the way it is currently carried out in most cases. Work described in this article is based on an adaptation of the method and model described in [7] for rapid performance assessment. However, the solution proposed in this article includes the implementation in a web-based tool and considers the complementarity between the rehabilitation needs and the generation opportunities based on renewable energies.

2. Rehabilitation Methodology and Workflow

In order to carry out an energy rehabilitation project at urban scale a methodology based on GIS-3D technologies has been proposed, which is structured in three major phases: (1) Digital Survey, it is about carrying out the compilation and analysis of existing information at the municipal level (e.g. cartography, maps or on-site measurements), to obtain a digital representation of the urban environment; (2) Energy Characterization, whose objective is to represent the energy situation of the study area, its problems, needs and potentialities; (3) Improvement Proposals, this stage includes the identification of energy efficiency improvement solutions, the feasibility study on different sources of renewable energy, compliance with regulations and comparisons with real data.

[2] La energía en España 2014. Ministerio de Industria, Energía y Turismo

The proposed methodology is described in more detail through the workflow presented in Figure 1. The generation of the 3D model is carried out through semi-automatic processes based on existing data (mainly cadastre and LiDAR) and the subsequent editing and processing of the generated model allows improving the resolution of such model. Then, the energy characterization of the study area is carried out using the information in the 3D model and combining the result of the calculations of the "Energy Behaviour" and "Generation Potential", together with "Environmental Restrictions". The "Energy Behaviour" module is based on simplified simulations using the available information. The "Generation Potential" considers the characteristics of the buildings, the geographical location and the radiation maps. The result of the characterization is represented by multicriteria indicators (e.g. energy consumption, cost, performance). The identification of proposals and improvement opportunities is based on the multicriteria analysis of the results of the characterization and the complementarity between the rehabilitation needs and the renewable generation potential.

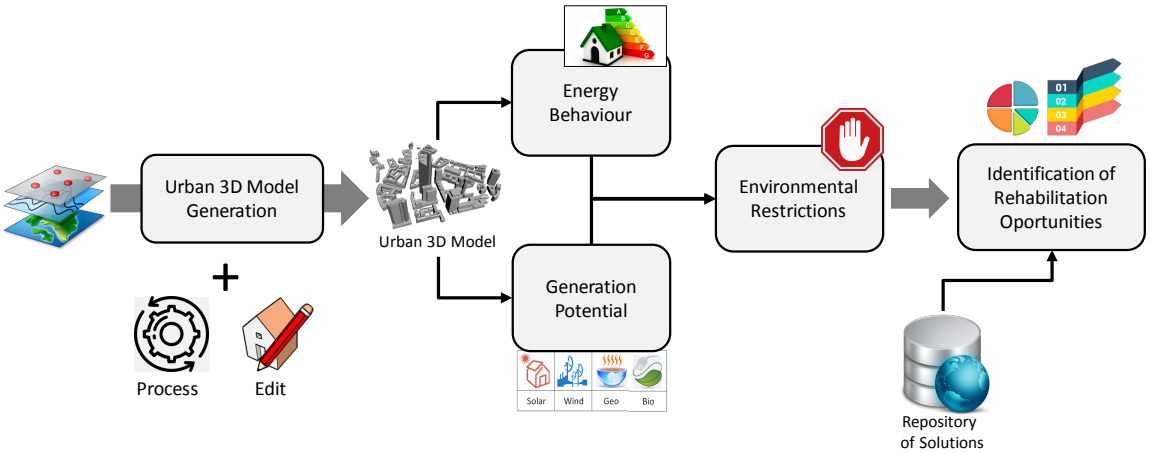

Figure 1. Workflow for the Energy Rehabilitation in 3D

3. Urban 3D Model

Current technologies allow the generation of urban 3D models in a semi-automatic and massive way for a district or even for a small city. For this process, free access data sources are used, complemented by information provided by local agents. The results obtained from this semi-automatic generation present 3D models with low level of detail and insufficient precision. In this project, processes for improving accuracy have been developed by processing existing geometric information. The generation of the urban 3D model has been carried out following the standard data model CityGML. The municipality of Durango (Spain) of approximately 30,000 inhabitants has been chosen as case study.

The process carried out for the generation of the model starts with the identification of existing data sources and data collection, which are listed in the following table (See Table 1) for Durango:

Table 1. Data sources for urban 3D model generation

Data	Source
Geometry of building plot	Municipality Cadaster
Digital Terrain Model (DTM)	GeoEuskadi (2016) – 1m. resolution
Digital Surface Model (DSM)	LiDAR-GeoEuskadi (2012) – 0.5 pt/m^2
Semantic information relevant to the project	Municipality Cadaster and Basque Cultural Heritage Center

The city model includes the geometry of buildings in LoD2 (represented by independent facades and roofs) as well as, semantic data related to energy domain (e.g. building age). All this information is included in the generated CityGML file. The resulting geometric model has been analysed, processed and edited to complete the CityGML model with the following parameters:

- **Building Height:** It is obtained by combining the DSM and the DTM. First a cleaning process is performed in order to discard atypical values (very low and very high values). This is done by eliminating those values below the percentile 5 and above the percentile 95. From the remaining values the percentile 90 is calculated and that value is selected as the building height.
- **Number of floors**: Estimated from the height of the building considering an average height per floor of 3 meters.
- **Roof type**: It is identified if a roof is flat or not from the LiDAR data, by calculating the standard deviation of the altitude of the points that represent the roofs.
- **Roof area**: When the roof is flat, the value is obtained from the area of the building footprint, if the roof is not flat, a correction factor of 1.1 is applied to the base area.
- **Gross floor area**: It is calculated from the floor area multiplied by the number of floors.
- **Façade area**: To calculate the area of the building façade it is necessary to previously identify which of the building's surfaces are facades and which ones are adjoining walls. An envelope surface is considered as an adjoining wall in case both the surface and the adjacent surfaces follow the same direction and overlapping is greater than 50 %. Subsequently, the area of each facade is calculated from the geometry of the building footprint and the height of the building. Finally, it is necessary to add the surface of all facades at the building level. The orientation of the envelope surfaces of the building are also identified, both for the facades and for the adjoining walls.

4. Cloud-based Repository of Solutions

The solutions repository is a dynamic structural database hosted in the cloud that implements a data structure which includes the characteristics of commercial energy rehabilitation solutions. Different types of energy retrofitting solutions are defined: solutions to be applied to the building envelope, and solutions for the integration of renewable energies. For envelope retrofitting solutions, a general data structure has been defined (See Figure 2). The data structure considers sustainability issues (e.g. energy improvement and local production) and installation issues (e.g. solution cost and the compatibility with the protection requirements of the building or constructive element to which each technology is applied).

TITULO		
DESCRIPCIÓN	Descripcion de el sistema	
CONCEPTO	concepto basico de la solucion	imagen
ELEMENTO DE APLICACIÓN	FACHADA	
VENTAJAS	ventajas del sistema	
LIMITACIONES /DESVENTAJAS	limitaciones y desventajas del sistema	
ASPECTOS DE IMPLEMENTACION	aspectos claves de la ejecucion implementacion	
	Edificios Protegidos	
	Medios Auxiliares	SI
	Precio estimado (€/m2 PEC) Base de Datos Precio de la Construcción Centro 2017	precio estimado
ASPECTOS SOSTENIBILIDAD	Mejora energética (kWh/m²/año)	mejora estimada con un ejemplo. Se pueden calcular varias situaciones
	Valor U (W/m2K)	mejora estimada con un ejemplo. Se pueden calcular varias situaciones
	Consumo CO2 asociado	se puede obtener un baremo
PRODUCTO LOCAL	SI	

Figure 2. Data structure defined for retrofitting solutions

For renewable solutions, the main types that are applicable to the energy rehabilitation of urban districts have been identified. Among the existing ones, we have identified: Solar Photovoltaic, Solar Thermal, Aerothermal with heat pump and Biomass. For each of the solutions, the demand curve and the associated production costs are identified as the main characteristic parameters of the solution.

5. Baseline Assessment

5.1. Typological analysis

The information included in the urban 3D model previously generated allows identifying the geographical distribution of the typologies of buildings in the study area. This typological analysis makes possible to identify priority areas or districts for retrofitting, identify synergies between buildings and adjust budget items. The platform integrates a 3D viewer that facilitates the identification and location of the buildings in the municipality. For this visualization, the previously generated 3D model is used. Navigation and interaction is intuitive, as in Google Earth, through the 3D map visualization library Cesium[3]. The typological analysis is done through filters and the combination of several predetermined filters. The visualization of the results is presented through coloured maps and statistical data of the results of each type.

5.2. Project Set-up

The energy assessment of the current state of the district to be analysed begins with the identification and selection of the study area. Then the main properties of the district and the retrofitting project are defined. The main characteristics of the project to be defined at this point include the: climatic zone, types of energy available in the district, electricity prices, availability to place renewable facilities, maximum cost of rehabilitation and level of protection of the buildings in the area.

A 2D viewer is also included in the web application that allows intuitive identification and selection of the boundaries of the study area of the project, while the 3D viewer facilitates the identification and location of buildings in the selected area. In this 3D viewer it is possible to add or remove buildings to the selection made in the 2D view, in order to adapt the selection to the subset of buildings to be evaluated (See **Figure 3**).

Figure 3. 2D and 3D viewers to enable project set-up

[3] Cesium Library https://cesiumjs.org/

5.3. Energy Performance

To calculate the current energy performance of the buildings in the selected neighbourhood, the main energy demand indicators and the energy certification of the buildings are calculated. The list of calculated indicators is presented in the following table (Table 2). The calculation is based on energy demand simplified formulas that provide sufficiently accurate results with low information requirements. The urban 3D model allows obtaining in a precise and standardized way the main characteristics of the buildings. The energy performance calculations are carried out at building scale, however an aggregation on a larger scale is necessary to prioritize actions at the neighbourhood level.

The representation of the values of the calculated indicators can be displayed using 2D graphs or through the 3D viewer on the elements of the model of the study area (See **Figure 4**).

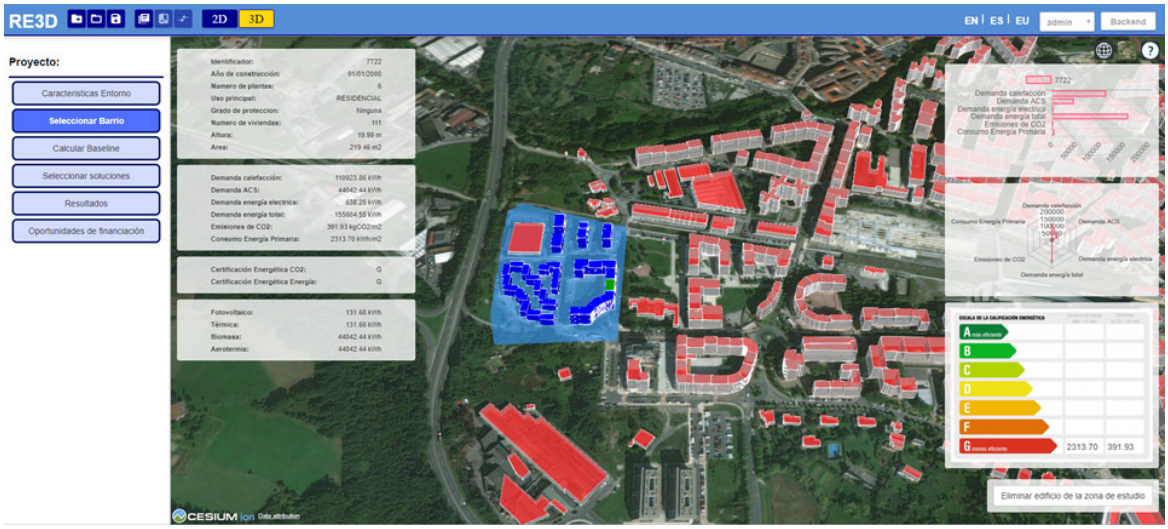

Figure 4. GIS-3D technologies for energy performance assessment

5.4. Potential for Renewable Energy Generation

The main renewable sources that can be applicable in urban environments are: solar, biomass and aerothermal. The potential of each renewable sources is also calculated as indicators. In the followed approach, the generation potential of the biomass and aerothermal solutions has been adjusted to the power required to cover only the DHW demand, while the potential for solar generation has been calculated based on the characteristics of the building roofs. Both the biomass and the solar need space for the installation of accumulators and in the case of biomass additional space for the silo and possibility of periodic discharge of the fuel (See Table 2).

6. Identification of Rehabilitation Opportunities

The platform helps during the process of identifying rehabilitation opportunities by comparing solutions, comparing the energy indicators proposed in the baseline with the results of application of rehabilitation solutions and the calculation of economic indicators.

The solutions repository is connected to the platform, which allows an easy comparison between the main features and behaviour of each technology and provide users with the identification of solutions associated with each technology and the selection based on user needs and requirements. Figure 5 shows the comparison between different thermal insulation solutions.

The indicators related to the energy performance of the neighbourhood are compared with the result of simulation by applying the repository solutions compatible with the environmental restrictions. The results are shown graphically in Figure 5. The results represent aggregated values of the buildings of the selected neighbourhood. The economic indicators (see Table 3) are calculated from the data available in the model and the solution repository, as well as the previously calculated indicators.

Table 2. List of indicators calculated for the baseline assessment

Indicators			**Required Data**		
IND_ID	**Indicator**	**Units**	*IND*	*Project*	*Urban 3D Model*
IND_1	Energy Demand for Heating & Cooling	kWh	-	Climatic Zone	Building Surface Number of Floors Orientation Façades Year of Construction
IND_2	Energy Demand for DHW	kWh	-	Climatic Zone	Dwelling Units
IND_3	Electricity Demand	kWh	-	-	Building Surface Number of Floors Dwelling Units
IND_4	Total Energy Demand	kWh	IND_1, 2 and 3		
IND_5	Primary Energy Consumption	kWh/m^2*year	IND_1, 2 and 3	Fuel used	-
IND_6	CO2 Emissions	kgCO_2/m^2*year	IND_1, 2 and 3	Fuel used	-
IND_7	Energy Certificates	A-G	IND_5 and 6	Climatic Zone	-
IND_8	Solar Potential (Thermal or PV)	kWh	-	Climatic Zone Accumulation	Roof Surface Orientation Slope
IND_9	Biomass Potential	kWh	IND_2	Silo Storage Accumulation Unloading	-
IND_10	Aerothermal Potential	kWh	IND_2	-	-

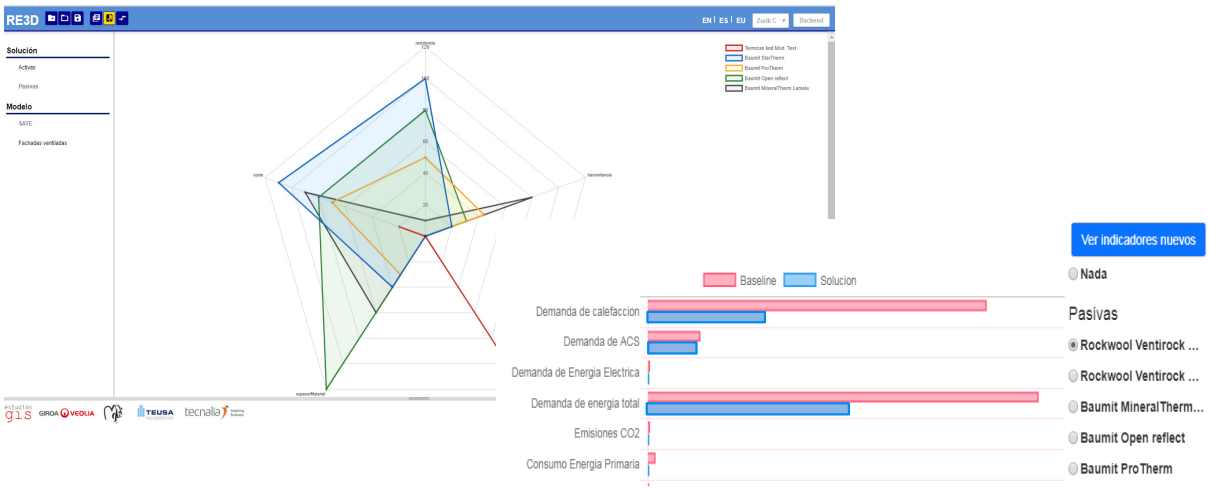

Figure 5. Solutions comparison and energy performance improvement for rehabilitation opportunities

Table 3. Economic indicators for rehabilitation opportunities identification.

Indicators			Required Data			
IND_ID	**Indicator**	**Units**	*IND*	*Project*	*Urban 3D Model*	*Solution*
IND_11	Cost of Retrofitting	€	-	-	Facade Surface	Unit Cost Dimension
IND_12	Renewable Cost	€	-	-	Roof Surface	Unit Cost Dimension
IND_13	Energy Saving Cost	€/kWh	IND_11, 12 and 4_REH	-	-	-
IND_14	CO2 Reduction Cost	€/kg CO_2	IND_11, 12 and 6	-	-	-
IND_15	Return of Investment (ROI)	Years	IND_11, 12, 6 and 4_REH	Fuel Price	-	

7. Conclusions

The article describes a web platform based on GIS-3D technologies for supporting the management of the energy rehabilitation potential of urban environments. The platform helps to analyse geographically the behaviour of buildings and the grouping and prioritization of interventions by neighbourhoods.

The solution presented in this article calculate and visualize energy performance of current state and rehabilitation scenarios based on a low resolution CityGML model and a repository of rehabilitation solution. The processed scenarios consider compatibility with the environment, complementarity between rehabilitation solutions and viability of the investment.

The target audience of the proposed platform are energy managers and city planners, who can benefit from the ease and intuitiveness of use to identify highly vulnerable areas or intervention priorities, and then obtain initial estimations of the benefits of different rehabilitation strategies, considering complementarity between rehabilitation needs and renewable generation potential.

The assessment of current state and the rehabilitation solutions, once the data are included in the tool is an automated process and almost real-time. Although the time required for collecting data and generation of data model is very much dependent on the availability of data and the size of the area to assess, since the process depend of easily accessible databases it is significantly faster than other methods (from the beginning of the process until the final results are obtained, an estimated average time would be around 2 weeks for a municipality similar to the one presented in the case study).

The proposed methodology and workflow could be highly beneficial for the early stages of an urban energy retrofitting process, and its flexibility allows the application of the same approach to different urban challenges as the application of energy conservation measures to protected historic districts.

Further research is still needed in order to assess the results provided by the tool in comparison with other performance calculation methods, also it will be necessary to improve accuracy of results including user behaviour. Finally, additional feedback from the final users are expected to improve functionalities and usability of the tool.

Acknowledgments

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