A decision support tool for the co-design of energy and seismic retrofitting solutions within the e-SAFE project

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Abstract. The innovation project e-SAFE, funded by the EU under the H2020 Programme, is developing a new deep renovation system for non-historical reinforced concrete (RC) framed buildings, which combines energy efficiency and improved seismic resistance. The present paper describes the main functionalities of a Decision Support System (e-DSS) that is being developed by e-SAFE experts, aimed at guiding the technicians and the building owners through a conscious preliminary co-design activity, and leading to the choice of the most suitable renovation solution amongst those envisaged by the e-SAFE portfolio. The e-DSS allows assessing – with a reasonable degree of approximation – the energy performance of the building before and after the proposed renovation action, the environmental benefits in terms of decarbonization (i.e. reduction in CO_2 emission for space heating, space cooling and DHW preparation), the expected costs and time for the building renovation and the expected time of Return of the Investment (ROI), based also on the savings in the annual operating costs. The paper explains the criteria used by the tool to identify those solutions that are not suitable for the selected building, and discusses the degree of approximation behind the calculation of energy, cost and environmental performance.

Keywords: energy renovation, seismic renovation, decision support, energy saving, decarbonization.

1 Introduction

The topic of combined energy and seismic upgrading of buildings has become increasingly important because of the growing attention to the economic, social and environmental sustainability in the real estate sector. However, often retrofit actions are not chosen based on a detailed evaluation and comparison of the several possible alternatives, but rather on the designer's experience and widespread best practices. In addition, the building process can be particularly complex from both a technical (e.g. because of the low number of companies specialized in combined seismic and energy retrofitting) and an administrative point of view (e.g. because of bottlenecks in the approval process for renovation actions in apartment buildings).

For these reasons, there has been a growing interest in the development of Decision Support Systems (DSS) to guide the decision process of various retrofit interventions. As an example, some authors [1-3] analyzed and grouped the most common decision-making methods and found that multi-criteria approaches are widely used in DSSs within the construction sector. In addition, some companies and universities have already started developing decision support tools themselves. Amongst them, Kamari et al. [4-5] applied a hybrid approach based on a genetic algorithm able to define several scenarios and to evaluate their performances in terms of energy consumption, thermal comfort, and investment costs.

Another interesting reference can be found in the RENO-EVALUE tool [6], which is meant as a basis for dialogue among building professionals and building users while also supporting the formulation of specific objectives for renovation projects. This system can also be used for comparing alternative project proposals and to follow-up on a project and assess its actual performance.

Furthermore, Campos and Neves-Silva developed a DSS tool called EnPROVE ("Energy consumption prediction with building usage measurements for software-based decision support") that supports investors in the selection of the most suitable renovation scenarios by considering budget, technical, and usage constraints [7-8]. Although being a powerful tool for ranking energy-efficient long-term projects, it needs a technical consultant to define legislation and incentive schemes that can be applied in the specific location where the renovation should take place.

What emerges from the review of existing DSS tools is that several renovation scenarios are first generated through genetic algorithms or user-defined schemes, and then they are assessed and finally ordered according to the stakeholders' priorities.

Differently from such approaches, this paper introduces a new Decision Support System called e-DSS, developed within the H2020 project e-SAFE. Indeed, this tool is specifically designed to support professionals, building managers and residents in choosing amongst the different technologies made available by the e-SAFE project. The main outcome of the tool is the comparison between energy, environmental and economic performance of the building in its current state and after the renovation: these results are helpful to the designer during the preliminary design process, since it allows him/her to show the residents all the potential benefits of the selected solution. Furthermore, the e-DSS guides the designer in the selection of the most appropriate renovation solution amongst those envisaged in e-SAFE, based on a series of checks regarding the shape of the building, the nearby context and the presence of balconies and large glazed surfaces.

The paper describes the main features of the e-DSS in its first release, its current limitations and the criteria behind the selection process for the most suitable renovation solutions. Further developments and functionalities are being implemented and will be available in 2023 in the second release of the tool

2 The e-SAFE renovation system

2.1 Envelope renovation technologies

In e-SAFE, the energy and seismic retrofit of the existing RC-framed buildings will be primarily achieved through two different envelope solutions: (i) timber-based panels including a wood-based insulating material (e-PANEL), and (ii) structural panels made of Cross Laminated Timber (e-CLT) that increase seismic performance through specifically designed friction dampers attached to the existing RC beams. The CLT panels make available additional lateral stiffness, while the dampers dissipate seismic energy in case of moderate or strong ground motions. The e-CLT will also include an outer insulation whose thickness is calculated in order to get the same thermal transmittance of the e-PANEL. The two types of panels will externally clad the existing walls seamless and, as a general rule, the e-PANEL will be applied on those walls including openings while the e-CLT to the remaining façade surfaces (see Fig. 1). Both panels are customizable in terms of size, thermal transmittance, and finishing material; they will be prefabricated through BIM-based design procedures and installed through cranes, without the need of scaffoldings.

Finally, the e-SAFE project envisages also the possibility of applying a metallic exoskeleton (e-EXOS) made of bi-dimensional bracings equipped with dampers and connected to the existing RC frame for increasing its seismic resistance. e-EXOS is installed on the outside of the existing building and does not interrupt the continuous skin realized entirely with e-PANELs to ensure the proper thermal insulation.

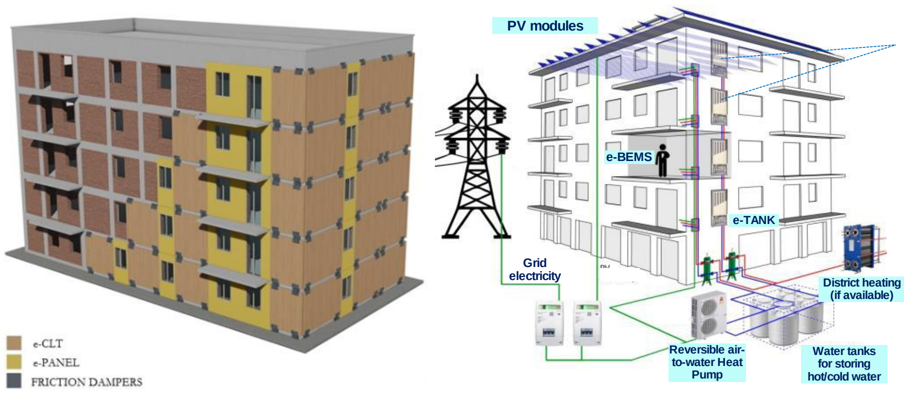

Fig. 1. Left: proposed envelope retrofit solutions. Right: concept for thermal systems (e-THERM)

2.2 Renovation of the technical systems

Apart from acting on the thermal insulation of the building shell, energy savings are also achieved by renovating the technical systems. In e-SAFE, the selected technical solution is named e-THERM: this provides space heating and cooling, as well as Domestic Hot Water (DHW), through highly efficient electricity-driven centralized reversible air-to-water heat pumps (Fig. 1). Fan-coils for space heating and cooling are installed in each dwelling, fed at medium temperature in the winter (45 °C); each dwelling will also be equipped with a modular plug-and-play small-size tank of 140 L capacity to store DHW, called e-TANK and specifically developed within the project.

Roof-mounted PV panels are also included for on-site electricity generation. In order to make full profit of PV-based electricity production, the e-THERM concept appoints a central role to heat storage. A first storage level is provided by large centralized water tanks: the system will be equipped with a programmable control system in order to use the water tanks as a buffer and let the heat pump operate in the most convenient conditions (e.g. when PV electricity is available, or the outdoor air temperature exceeds a minimum threshold). A second level of energy storage is provided by the decentralized e-TANKs. The final aim is reducing peak energy demand and increasing the self-consumption rate by the heat pumps.

3 Looking inside the e-DSS

3.1 Calculating the energy needs

The e-DSS estimates the energy needs of both the current and renovated building configurations within the framework of the quasi steady-state energy balance approach described in the European Norm EN ISO 13790:2008 [9]. Specifics concerning the heat transfer through the envelope and the nominal efficiency value of various mechanical and domestic hot water (DHW) production systems are instead gathered from the Italian Norm Series UNI 11300:2014 [10-12].

Other Italian technical norms are recalled also for the calculation of air change rates and endogenous heat contribution (UNI 10339:1995 [13]), as well as for the outdoor weather data (UNI 10349:2016 [14]). This is done because the demo building of the e-SAFE project is located in Italy, and as such it has to comply with the local building codes and prescriptions. Nevertheless, the quasi steady-state calculation approach is commonly adopted by many European Countries for the assessment of the energy performance of buildings, so the e-DSS tool can be easily adapted to different contexts by simply allowing the users to change the values of some parameters and by selecting different weather data based on a GIS tool: these features will be implemented in the second release, available in 2023.

Since the tool does not aim to provide an extremely precise estimation of the energy needs, and cannot be used for official energy certification purposes, some simplifications are introduced in order to speed up the data input and make the tool user friendly. For instance, heat transfer through thermal bridges is taken into account by a coefficient that multiplies the heat transfer rate through the opaque envelope components: the coefficient ranges between 1.1 and 1.3 depending on the number of facades hosting balconies.

Coming to the technical systems, the e-DSS is able to determine their global efficiency as the product of the efficiency of several sub-systems: generation, distribution, emission, and control. Each efficiency has default values depending e.g. on the water temperature, the presence of thermal insulation in the distribution system, the type of emission terminal. The COP of air-to-water heat pumps is calculated on a monthly basis as a function of the mean outdoor air temperature, according to UNI 11300:4 [12].

Finally, the e-DSS considers the possible presence of solar thermal systems and PV systems, and subtracts from the energy needs the corresponding thermal/electric energy production, in order to asses the non-renewable primary energy demand. In this regard, suitable primary energy conversion factors are considered for electricity and various fuels [15]

3.2 Choosing the renovation solutions

The e-DSS does not aim at assessing the seismic improvement provided by the proposed renovation solutions, since this result comes from a complex structural analysis that goes beyond the scopes of the tool. However, the e-DSS supports the technician in the decision-making process of the most suitable solution for seismic improvement, in relation to the seismic zone, the height and the shape of the building, and the current state of conservation of the reinforced concrete structures.

The seismic risk of the city where the building is located is defined based on the Peak Ground Acceleration (PGA), automatically retrieved through the EFEHR web service [16]. According to the seismic risk, the **e-**DSS suggests either a simple energy refurbishment or a combined seismic and energy refurbishment. In the latter case, a series of questions are posed by the e-DSS, such as:

- level of degradation of the existing structure (RC frame)
- percentage of perimeter occupied by balconies in a typical floor
- number of facades attached to other buildings
- presence of constraints that prevent altering the appearance of the building (e.g., local regulations, cultural heritage restrictions);
- availability of sufficient space for crane's operations around the building.

Based on the responses, but also on the seismic risk and the number of floors, the e-DSS attributes a score to the building, and determines the most suitable combined solution (e-CLT or e-EXOS). In some cases, the e-DSS might exclude one or even both solutions, which happens for instance if the number of floors is above twelve, or when local regulations forbid altering the façade.

Regarding the e-THERM, its concept and architecture is already well defined. The technician can choose if it has to be included or not in the renovation project, but then there are only few variables that should be specified during the preliminary design process and that are relevant to the e-DSS in the calculation of the energy performance.

3.3 Calculating energy and cost savings

In the e-DSS, energy savings are first determined by the reduction of heat losses through the envelope because of the application of e-CLT and e-PANEL to the existing façades. The tool calculates the minimum insulation thickness that must be adopted in order to get a certain target U-value, inserted by the user. The target U-value may come from national regulations, or other performance targets identified by the technician himself. In doing this calculation, the tool considers default values for the thermal conductivity of the various layers of materials composing both panels. The user can then select a specific insulation thickness (higher than the minimum value), and the e-DSS defines the new U-value for the renovated buildings, taking also into account the different surfaces covered with e-PANEL or e-CLT, if this is the case. If the user selects e-EXOS in place of e-CLT as the seismic upgrade technology, the new U-value is estimated for the only e-PANEL.

In any case, the user is also allowed to renovate the roof: after selecting the desired insulating material and its thickness, the **e-**DSS calculates the new thermal transmittance of the roof. As far as the windows are concerned, there is no calculation performed by the **e-**DSS but rather a unique U-value input by the user. The shutter boxes (if any) are assumed to be thermally insulated by default and the windows to be provided with shadings whose shading factor is set by default as well.

On the other hand, energy savings come also from the upgrade of the technical systems. The data regarding the new technical systems (e-THERM) are specified by the user through a series of questions posed by the e-DSS. Many parameters are defined by default according to the specific **e-**THERM concept described in Section 2.2, while others (e.g. type of heat pump, COP value in standard conditions, SEER value, number and type of PV modules). can be inserted by the user. The energy savings achievable through the renovation are then estimated by subtracting the non-renewable energy needs of the retrofit scenario from those estimated for the building in its current state, as already described in Section 3.1.

The e-DSS then computes the renovation costs of both the envelope and technical systems separately. As concerns the envelope costs, they are estimated by multiplying the base unit costs of e-CLT, e-PANEL, windows and roof ($€\cdot m^{-2}$) retrofit by their surface extension (m^2). All unit costs depend on the materials selected during the renovation co-design process, and are reported in the database from which the user selects the materials. The unit costs will be regularly updated in order to follow market prices. Instead, the costs of the heat pump, storage tanks and auxiliary systems are considered proportional to the thermal power of the heat pump, whose size is specified by the technician during the renovation co-design process. Similarly, the size and the cost of the circulation pumps are proportional to the water flow rate, which in turn depends on the thermal power of the heat pump. A similar approach is used for estimating the costs related to the PV system (PV panels and batteries namely), which are considered proportional to the peak power installed.

As a further step, the **e-**DSS also assesses the renovation costs associated to each apartment by splitting the overall installation costs proportionally to the net surface of the dwellings. This information is very useful during the co-design stage, since the building manager can show it to the residents and discuss with them the convenience of the proposed solutions.

Finally, the Simplified Payback Period of the investment is computed by dividing the total costs for the renovation (envelope + technical systems) by the annual cost savings. The last ones are estimated as the annual savings on the energy bill due to the energy savings and are calculated considering the constant unit costs for electricity and natural gas embedded in the database (regularly updated for reflecting cost variations through time). The second release of the tool will include the Compound Payback Period and will quantify also the potential benefits arising from the improved seismic resistance.

3.4 e-DSS architecture, data model and protocols

e-DSS is a web application implemented according to the Model-View-Controller (MVC) [17] architectural design pattern separating an application into three main logical components: the Model, the View and the Controller. The Model component corresponds to the e-SAFE data model, which represents the knowledge base of the building renovation process. The View component is what is presented to the end user, and as such, it is the e-DSS Graphical User Interface (GUI) responsible for the visualization of building's relevant information and for guiding the end user into the building renovation co-design process. Finally, the Controller component is the brain of the application since it implements the needed business logic for the calculation of building's energy needs and the algorithms supporting the co-design and renovation process. The e-DSS tool takes advantage of the main benefits associated to the MVC like the efficient code reuse and parallel development of the application, faster development process, easy modification of the entire application and a simplified testing process. The e-DSS architecture is shown in Fig. 2, where the main functionalities and architectural choices are shown. As it is possible to see, the View component consists in the web application front-end addressing the user interaction whereas the Model and the Controller components belong to the application back-end, manly related to the e-DSS data model and the e-DSS business logic. The front-end relies on HTML, CSS, JavaScript and Vue framework [18], while the back-end is implemented in NodeJS [19]. The Renovation Space Representational Model is delivered as a MySQL database [20], while the interaction between the Client and the Server side is addressed through REST services based on Express framework [21] exploiting the HTTP protocol.

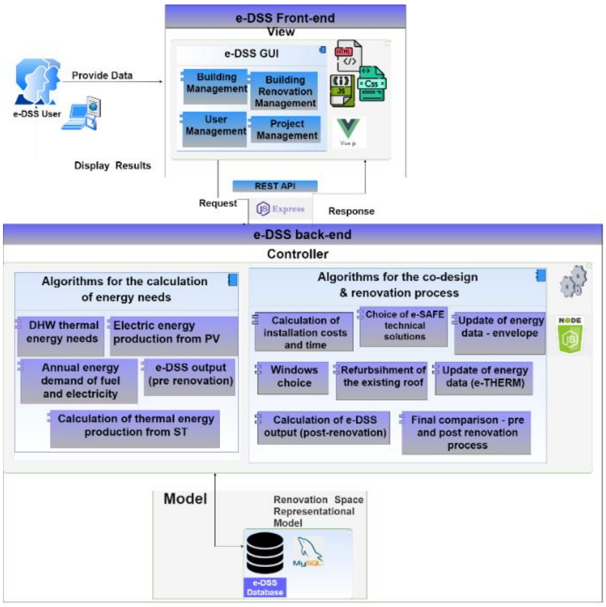

Fig. 2. e-DSS tool architecture.

4 Limitations and further developments

The first release of the e-DSS has several limitations, which will be tackled in the second release ready in the summer 2023.

One of the main limitations concerns the monthly weather data used for calculating the energy needs: now, they are taken from the Italian Standard UNI 10349:2016, and just refer to Catania (Italy), i.e. the city hosting the pilot building. In the second release, the weather data will be extracted from PVGIS EU web-service, starting from latitude and longitude of the site, and after some simple processing by the same e-DSS.

One more limitation affects the data input process for the building geometry: in the first release, the size of the building, including net/gross volume and surfaces, is assigned manually by the user, while in the second release these data will be automatically derived from a BIM-based file. To this aim, the e-SAFE partners are investigating the possible use of IFC and/or gbXML format. Furthermore, the e-DSS considers a standard duration of the heating and cooling seasons in the calculation process, depending on the climatic zone as established by Italian regulations. The second release will adopt a more general approach, where the duration depends on the ratio of the monthly heat gains to the monthly heat losses, but also with the possibility for the user to freely assign these periods.

Finally, the current release of e-DSS calculates the installation costs according to the Italian market as for December 2021. The second release will include updated costs extended to other European countries.

Further information about limitations and future development, together with more details about the e-DSS tool, can be found in the Deliverable D4.2 of the e-SAFE project, available in the ZENODO open access repository [13].

5 Conclusions

A new Decision Support System developed within the H2020 project e-SAFE and called e-DSS is presented with its main features and limitations. The tool is specifically designed to support all the stakeholders involved in combined energy and seismic building renovations in choosing the most appropriate technological solution made available by the e-SAFE project. Indeed, the tool reports as an output a comparison in terms of energy, environmental and economic performances of the building in both its current state and after the renovation, thus allowing for a quick scenario analysis.

The e-DSS does not address the seismic improvement provided by the chosen renovation solutions because this result would require complex and cumbersome structural analysis that are out of the scopes of the tool. Nevertheless, the e-DSS supports the decision-making process of the most suitable solution for seismic upgrading by accounting for the seismic zone, the height and the shape of the building, and the state of conservation of the bearing structure.

In its current release, the tool can only work for building renovations taking place in Catania (Italy), where the pilot building of the e-SAFE project is located and for which weather data and renovation costs are provided in the library of the software.

However, an upcoming release of the tool due on summer 2023 will overcome these limitations and allow the users to analyse the performances of the e-SAFE renovation solutions for buildings located everywhere in the EU by extracting the relevant weather data from PVGIS EU web-service and considering nation-specific renovation costs. Further improvements are also planned concerning the use of the gbXML format for automatically deriving the main geometric features of the building and thus simplifying the users' modelling tasks.

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