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***Abstract*—In the early stages of building renovation projects, the lack of information on the existing building and an unclear definition of project objectives have been identified as critical bottlenecks. An early decision support tool has been developed to mitigate or overcome these barriers. The tool provides initial estimates tailored to the specific building and climate being assessed, and can be used to guide the renovation design at an early stage, even from very limited information. It includes the automatic generation of potential renovation scenarios, a dynamic energy simulation of existing and renovated cases, integrated economic and environmental assessments from a life cycle perspective, and a multicriteria analysis that ranks renovation alternatives to meet the interests of the stakeholders involved. The user obtains an initial indicative budget and the expected potential benefits of several renovation projects over comfort, energy consumption, economic cost and environmental performance. One of the main assets of the tool is the reduction in time and cost at initial phases of the renovation process, avoiding the need of site visits and the use of more laborious simulation tools.**

Keywords—building renovation, decision support tool, energy simulation, life cycle assessment, multicriteria analysis

I. Introduction

The implementation of nearly-zero energy renovation packages for the residential building stock is a key priority for the European Union. However, the energy renovation of existing buildings is a complex process involving multiple stakeholders with diverging interests, as well as technical, environmental, economic, social, cultural and health aspects that are often in conflict with each other. In addition, digitalization is becoming an integral component of the renovation process, transforming traditional methods, and enhancing efficiency across various stages of project development. From initial planning to execution and post-renovation maintenance, digital tools and technologies are profoundly impacting every aspect of the renovation workflow. One significant aspect of digitalization lies in the realm of design, decision-making and planning [1]. Advanced software applications enable architects and designers to create detailed 3D models, allowing stakeholders to visualize proposed changes. This not only facilitates better decision-making but also minimizes the risk of costly errors by identifying potential issues before construction begins. Digital tools streamline communication and collaboration among project teams, contractors, and clients. Furthermore, the digitalization process enables new opportunities and enhances the efficiency of the construction process by creating intangible resources which turn into more cost-effective and rapid design and production [2].

The ENSNARE project aims at accelerating the transition to Nearly Zero Energy Buildings (NZEB) in the residential sector through a systemic methodology combining a toolkit of digital solutions and a modular envelope mesh incorporating active functionalities (e.g., photovoltaic and solar thermal collection, heat recovery ventilation). A questionnaire-based study carried out in the project [3] identified critical bottlenecks in the early phases of existing renovation projects. The outcomes from this work, together with previous studies [4], led to the development of an Early Decision Support Tool (EDST) in the framework of the ENSNARE project, to support and accelerate renovation processes in their initial phase.

TABLE I. BARRIERS AT EARLY STAGES OF RENOVATION PROJECTS

Current Barrier	Responding Feature of EDST
Limited information on the characteristics of the existing building, e.g., construction type, layers of envelope, actual insulation levels.	Possibility of performing initial assessments from limited information, including a library of likely characteristics based on building type, age and location.
Large time and costs associated with initial surveys and assessments, including travel to site.	First iterations can be performed using online data from cadastral or open mapping services.
Unclear definition of renovation objectives.	Clear indicators evaluate comfort, cost and environmental performance, and a multicriteria assessment is performed to suit these to user preferences.
Lack of interest from building owners and users due to limited awareness on the potential benefits of building renovation solutions.	The EDST can be used as a marketing or divulgation tool to learn about innovative renovation solutions, providing fast estimations of their potential impact on a specific building and climate.
Limited number of design proposals, hindering decision-making ability from clients.	Automatic generation and evaluation of renovation scenarios to empower clients, who can compare these options and ask the design team to fully or partially incorporate these into design proposals.
Limited or unreliable information on the implications of different solutions in term of actual energy performance and cost-efficiency.	Database with cost, thermal and environmental performance data for renovation solutions. A life-cycle environmental and cost assessment is performed early in the project.
Uncertainty of predictions for cost and energy performance. Post-renovation energy consumption and associated costs might not match expectations from simulations.	This uncertainty is primarily attributed to the lack of reliable data on the building and its use patterns. The EDST simplifies the building model while supporting accurate input of usage data.

In most current projects, building energy simulations, environmental assessments and annual cost estimations are not carried out until the latter stages. Energy calculation tools are often used for checking compliance with energy performance regulations [5] once a design has been finalised, with little to no impact of any potential learnings on the actual design. In contrast to the usual approach, the tool presented in this study is designed for the early stages of building renovation projects, when there is greater potential to impact the design. It is therefore not a substitute or competitor for detailed simulation software tools, but a complement to be used at early stages of renovation projects to support and accelerate the decision-making process. Barriers identified at these early stages and the key features of the EDST addressing these are listed in TABLE I.

II. USE CASES

The EDST has been designed to work from data with varying levels of detail, thus allowing several use cases at different design stages. Four possible use cases are presented below:

- Before a brief has been set up, the tool can be used for the initial exploration of renovation solutions. Building owners, users or managers with limited expertise or information can use the EDST as a user-friendly tool to explore the renovation potential of their building. It might thus encourage clients to attempt an energy-focused renovation, eventually leading to a contract with a design team.
- Once a design team is on board, designers can make use of the EDST for comparison of design alternatives. Architects, engineers and consultants can exploit their expertise and knowledge of building technologies to assess the implications of different solution kits on comfort, cost, energy and environmental performance, to inform and enhance the design of a renovation project.
- The EDST can serve as a marketing tool for product manufacturers and suppliers, in informing clients and demonstrating the viability and benefit of their solutions when applied to specific buildings and climates, thus enhancing both their market penetration and the overall building renovation rate.
- Finally, the EDST can be of use for architecture or engineering students or professionals as a research or educational tool to test the performance of design alternatives over specific buildings or representative archetype buildings.

III. ARCHITECTURE AND WORKFLOW

An illustration of the conceptual workflow of the EDST is provided in Fig. 1. The user experience is handled by the front end (left), while the calculation components (right) process the data and perform all simulations with no direct interaction required from the user.

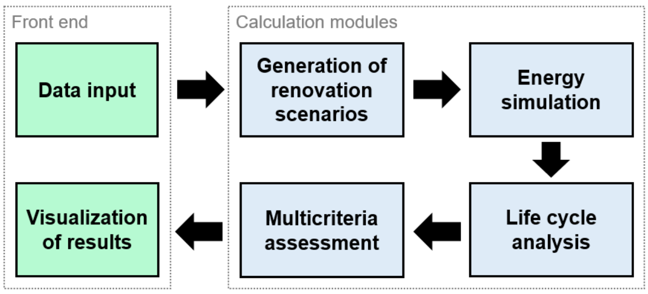

Fig. 1. Conceptual workflow of the early decision support tool.

The software architecture relies on the sequential operation of calculation modules interacting with a common database. A back end interacts with the database and manages communications with the calculation modules. The different processing modules and the data layer communicate through representational state transfer application programming interfaces (REST API). The modular architecture allows each submodule to be developed independently using the most suitable language and software stack for each case. The front end makes use of standard web technologies (HTML5, CSS3 and JavaScript), while the relational databases are developed using PostgreSQL.

The sequence diagram in Fig. 2 describes the operational workflow in more detail. Columns indicate the different components of the tool, while arrows describe the operation sequence. Initially, the user fills in basic parameters about the building such as location, age and building type (1). These are processed by a reference module estimating the most likely features and parameters (3) of the existing construction and building systems. The user can accept these defaults or provide more specific information when available (5). These parameters are used to run an initial simulation (7) which can be presented to the user (9) for feedback on comfort levels and energy bills. This feedback can be used to adjust and recalibrate the model (11). The next step is the automatic generation of a set of proposed renovation scenarios (14), featuring combinations of technologies that are among the most suitable for the building and climate assessed. The user can decide to simulate the whole set of alternative scenarios or discard some of these (16) based on personal preferences or other constraints (e.g,. structural, regulatory, heritage, feasibility). A dynamic simulation (18) is performed for all accepted scenarios to estimate their energy and comfort performance. Results from energy simulations, together with data on costs and environmental performance of each solution, are used to feed an economic (21) and environmental (22) life cycle analysis. Finally, a multicriteria assessment (25) is performed to rank the renovation scenarios according to adjustable user preferences (27) on comfort, financial and environmental performance.

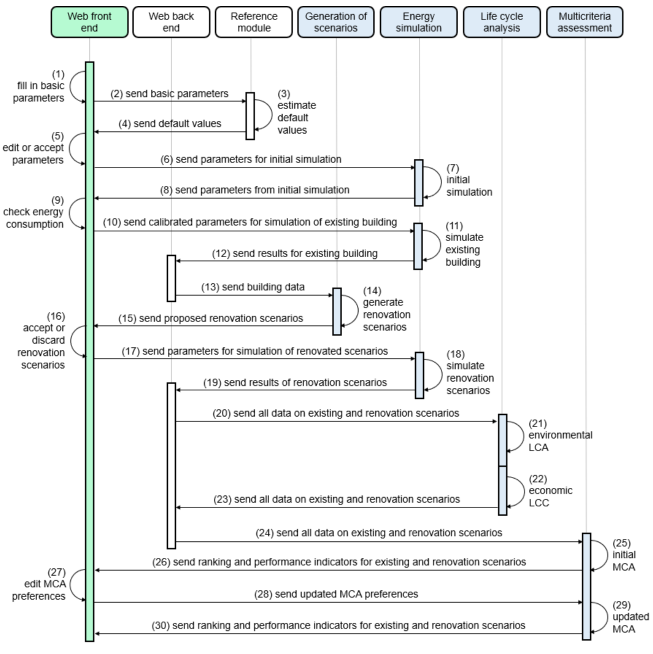

Fig. 2. Detailed workflow of the early decision support tool.

The user interacts only with the web front end (left column in Fig. 2), while the back end triggers the sequence of reference and calculation modules with no intervention required from the user. Hence, the user perceives the EDST as an integrated tool, with no need of engaging with the complexities of the underlying submodules.

IV. User Input

The data input process has been specifically designed to allow the use of the EDST with input data of varying levels of detail, from very limited to exhaustive. Initially, the user is requested with a minimal set of input parameters. The location and the geometry of the building can be sourced from cadastral data or online mapping sources [6]. Location data is processed to identify the country and the euro region (used for estimating likely construction characteristics), as well as selecting the most suitable climate file for estimating preliminary energy demand and running dynamic simulations. Depending on the available data, the level of detail of the geometry can vary from a simple extrusion of the building footprint to a detailed 3D IFC model including the shape, size and location of all windows and protrusions [7]. In addition to the calculation of volume and floor areas, geometric data is used to model each surface of the building envelope with its area, orientation, and inclination, for computing heat exchanges with the ambient and solar radiation. Window areas can be retrieved from the model (if available), assumed as a percentage of wall area, or manually input by the user. An automatic visibility analysis is performed for each elevation, considering the horizon line (terrain shape and geographical features), neighbouring buildings and self-shading from other surfaces in the building. Results from the shading algorithm can be overridden if more precise knowledge is available, e.g., for trees or other shadowing elements not considered in the cadastre or mapping sources.

The user is prompted for the age band of the original construction of the building, and additionally for any partial renovations like window replacement, insulation of roof or walls, and changes in heating or cooling systems. The combination of location, age and building type (e.g., detached or collective building) is used to estimate likely values for the construction characteristics of the building, i.e., thermal transmittance (U) of walls, roofs and floors, frame and glazing type of windows (and associated U and g values), heat capacity, thermal bridge heat loss, and unintended air infiltration. The EDST also identifies the most likely devices and energy carriers (fuel or electricity) for space heating and cooling (if present), as well as layouts, storage elements (if present) and emitters.

User behaviour is known to be a major source for the deviation between building energy simulations and measurements [8]. In standard building energy simulations, detailed data is required for heat transfer calculations, but standard usage patterns are usually assumed [9]. In contrast, the EDST is built on a simplified physical model but allows for a more detailed consideration of the interaction of the occupants with the building. The user can refine the standard assumptions for the number of occupants (usually based on floor area for energy certification purposes), setpoint and setback temperatures, as well as their operation schedule, which usually differs for residents of different ages and lifestyles. Predefined default schedules (e.g., always at home, out at working hours) are available to support the tool users.

V. Calculation Modules

A. *Generation of renovation scenarios*

One of the main assets of the EDST is the automatic generation of renovation scenarios (combinations of building envelope and active technologies) to be further simulated and evaluated. The generation of renovation scenarios provides an initial filter, attempting to identify a limited set of solutions with greatest potential from the set of all possible scenarios. For this purpose, the module processes the available data considering building and climate data as well as project constraints (e.g., energy target, available budget). Scenarios of different ambition levels are generated, from passive renovations scenarios based on insulation and window replacement to nearly-zero or positive energy scenarios, incorporating active technologies such as photovoltaic and solar thermal technologies in combination with heat pumps.

The generation of renovation scenarios is built on a data model comprising the existing building, the objectives of the renovation project, and the considered interventions (including their sizing defined as U-value, area or power). Inference rules are used to compute a finite set of scenarios forming a flatten decision tree. After retrieving the energy needs of the existing building, the scenarios are generated in a two-step process. First, a set of passive, insulation-based scenarios are considered, which are limited to the thermal envelope of the building. Different insulation levels are considered, which are climate-dependent. In a second step, solar active technologies (photovoltaic, solar thermal and hybrid) are incorporated and sized to cover fully or partially the thermal and/or electrical needs of the building. Considering the exposure to solar radiation, and depending on shading from neighbouring buildings or elements, most often south-oriented facades are found to be the most suitable.

The outcome from this module is a limited set of approx. 20 to 25 renovation scenarios, which are defined as a combination of technologies and associated sizing values (e.g., U value for passive envelope technologies, panel area for active technologies).

B. Energy simulation

The dynamic energy performance of the building is estimated using two independent models of hourly resolution: (1) a transient building model and (2) simplified steady-state models for renewable and non-renewable energy generation and storage technologies. Decoupling energy demand and supply avoids the need for iteration loops and co-simulation, resulting in a faster and more efficient calculation. Only a limited number of building model simulations is required, determined by the combinations of passive envelope technologies, while their energy demand can be fulfilled through different technologies and strategies.

The building energy model (represented in Fig. 3) builds on previous work [10] and follows the German guideline VDI 6007 [11]. It belongs to the class of lumped parameter or resistance-capacitance models. The linear nature of such models allows fast calculations while accounting for the dynamic behaviour of building structures. Opaque areas of the building envelope are assigned a thermal resistance and a capacity, while windows are modelled as steady-state thermal resistances. Internal walls and slabs are considered adiabatic structures linked to a thermal capacity. Heat gains from solar radiation are considered over external surfaces (using a sol-air temperature formulation [12]) and internal surfaces (through a solar admittance). An equivalent linear formulation is used for computing long-wave radiative heat exchanges with the sky vault. The model allows the hourly calculation of indoor temperature or heating/cooling demand, and can be operated in different modes (free-floating, ideal power, limited power).

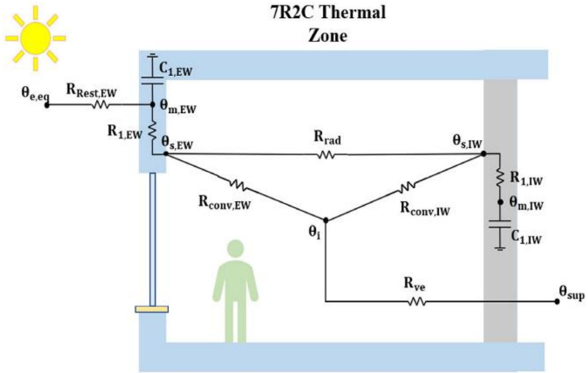

Fig. 3. Scheme of the thermal zone lumped parameter model [10].

The resulting energy demand is fulfilled by a combination of renewable technologies applied over the thermal envelope (solar thermal collectors, photovoltaic and hybrid photovoltaic-thermal panels) and backup energy generation devices (e.g. heat pumps). The energy produced and stored in thermal batteries is computed using a collection of calculation routines, considering the energy demand estimated in the previous step together with temperature and solar irradiation data drawn from the associated weather file.

The main outcomes from the energy simulation are hourly and annual energy consumption, renewable thermal and electrical energy production, as well as subheating and overheating discomfort indices based on cumulated deviation from a comfort temperature range [13].

C. Environmental and economic life cycle assessment

Estimates of annual energy consumption enable the prediction of operational fuel costs and associated global warming potential (GWP). This data is used as part of a broader assessment performed from a life cycle perspective, spanning the service life of the renovated building [14].

An environmental life cycle assessment (LCA) is performed based on ISO 14040 [15] and EN 15978 [16], calculating GWP for the whole life of renovation projects (in units of kgCO2e). The assessment comprises the following stages: production (A1-A3), transport (A4) and installation (A5), maintenance (B2), replacement (B4), operational energy use (B6), and end of life (C1-C4), as well as benefits and loads beyond the system boundaries (D), such as the potential for reuse, recovery and recycling. This calculation is fed by a comprehensive database containing the environmental impacts of renovation technologies as a function of their sizing (e.g., m2, kWh).

The life cycle costing (LCC) follows the framework of [17]. An economic analysis is performed computing upfront investment costs against fuel and electricity costs during the operation phase, together with associated operation and maintenance fees. Life cycle stages and system boundaries are consistent with the LCA methodology to provide comparable performance data and to enhance decision making. The LCC is complemented by a financial analysis that assesses the *bankability* of potential renovation scenarios that go above the maximum available budget by calculating metrics such as internal rate of return (IRR), net present value (NPV) or debt service coverage ratio (DSCR).

D. Multicriteria analysis

The multicriteria analysis method aims at scoring and ranking the assessed renovation scenarios considering the often-conflicting criteria of comfort and cost (the latter is understood as a combination of economic and environmental penalties). In contrast to usual approaches built over an analytic hierarchy process (AHP), which only take account of relative performance, an absolute weighting scheme is developed relating cost and comfort.

Results from previous calculation modules are summarised using three key performance indicators (KPI) for each scenario measuring discomfort, economic performance, and environmental performance. Namely, these are (1) cumulated deviation from a comfort temperature range (K·h), (2) life-cycle financial cost considering upfront and operational expenses (EUR), and (3) life-cycle global warming potential considering embodied and operational impact (kgCO2e). All three KPIs are formulated to be minimised for optimal performance.

These KPIs are normalised into comparable units, building on the concept of a generalised reward function [18] based on a set of fixed relations between KPIs. Normalisation factors are grounded on the *acceptable* economic and environmental costs for achieving comfort that would be representative for a standard user and can be calculated for any specific country and period based on average *per capita* earnings and emissions.

Finally, a relative weighting is applied over discomfort, economic and environmental KPIs, reflecting the objectives and expectations of the different user types. Default weightings are informed by a previous survey work [3]. Interestingly, respondents seemed to be more sincere when asked to evaluate judgements from other actors than when evaluating their own. Private clients reported economic performance as the most relevant aspect for making decisions, followed by comfort. Environmental aspects were only perceived as relevant when tied to economic cost. In contrast, public clients reported a more balanced appraisal of cost, comfort and environmental performance, but keeping this same order of preference.

The *score* assigned by the multicriteria assessment to each scenario is used to generate a ranking of renovation alternatives according to the suitability for the use case and the project objectives. This is useful in presenting the outcomes from the EDST to the user, who is allowed to modify the default weightings assigned to comfort, economic and environmental performance in order to check their impact on the ranking. Users can also inspect each scenario to check or compare more specific indicators (e.g., payback period, renewable energy production, expected annual costs) by means of result tables and plots.

VI. Related Work

The design and development of decision support systems for building renovation is a topic of interest in recent years. These tools cover a wide variety of criteria, simulation approaches and analysis scales (ranging from individual buildings to districts).

In [19], authors present a survey of decision-making procedures targeting sustainable renovation and, as in [20], they compile building assessment methods such as BREEAM, LEED or DGNB. One of their most interesting conclusions, in line with what is proposed in this article, is the need for simplified tools and a robust methodology to initiate discussions and support decision making. This methodology would start from inventories and initial values and an early evaluation of measures based on renovation goals. Another study [21] describes the need for improved decision support tools to suggest renovation alternatives, which in the tool presented here is provided by an automatic generator of scenarios and their further categorization based on suitability and specific scenario objectives. In [22], 19 building assessment tools from 10 different countries are analysed, detailing two interesting shortcomings. The first is that homeowners' preferences are often neglected. The second is that almost all of them focus on energy, financial, and environmental criteria, and social or aesthetic aspects are rarely considered. This same problem is also echoed in [23]. Addressing this shortcoming, the EDST includes user comfort as one of the KPIs for the evaluation and ranking of scenarios.

Regarding relevant decision support tools (DST), it is worth mentioning [24], which although it is largely focused on investments and economic returns, links data with real-time information to consider different scenarios. Also noteworthy is [25], which suggests the use of workflows similar to the one proposed in this paper to explore different renovation alternatives, and includes a multiple-criteria decision analysis (MCDA) in the last step of the workflow. With regards to MCDAs, [26] presents an approach that likewise makes use of building information modeling (BIM) for information extraction, suggesting that the capabilities of BIM are not fully utilized in current DSTs and MCDAs.

Studies are not necessarily limited to the building level; the neighbourhood or district level is becoming more and more common. For example, [20] presents a survey of articles combining geographic information systems (GIS) and MCDA for positive energy districts. One of the shortcomings mentioned in the article is that environmental and social impact costs are generally overlooked.

There seems to be a gradual switch from an energy-based to a carbon-based perspective (in line with EU policy), from single-objective to multi-objective assessment, and from an operational to a life cycle scope. The present tool is well aligned with these trends. Frequently mentioned shortcomings are the need for early calculations, the possibility to categorize results while facilitating discussion, and the necessity for a wides scope beyond purely financial and sustainability criteria. These shortcomings are in various ways addressed in the solution presented in this paper.

VII. Conclusions and Future Work

This paper presents an early decision support tool (EDST) designed to overcome barriers at the initial stages of energy-focused renovation projects for residential buildings. Its aim is not a precise simulation of energy performance for a renovation project (which is arguably unfeasible with the information available at early stages), but rather a fast, user-friendly and cost-effective assessment that is more suited to early-stage uncertainties than current simulation software packages. The EDST can work with limited input information and online mapping tools, avoiding extensive data search and unnecessary site visits. The outcome is a preliminary performance estimation (considering cost, economic and environmental performance) for potential renovation alternatives that can be automatically recommended by the tool. This holistic approach aims not only to address the technical aspects of energy-efficient renovations but also emphasizes the importance of early decision support tools in overcoming prevalent barriers of these projects. The proposal and consideration of many alternatives and performance metrics at early stage allows a greater impact on the design of the renovation project. The underlying design philosophy of the tool focuses on providing users with accurate, comprehensive, and actionable insights from the initial stages of renovation planning.

In this regard, one of the main strengths of the EDST is the integration of a comprehensive set of tools within a user-friendly framework, including the automated generation of renovation scenarios, transient energy simulation, and economic and environmental life cycle analysis (LCC/LCA). In addition to the outlined architecture and operational workflow, it is pertinent to underscore the contribution towards enhancing the modular and interoperable aspects of such decision support tools. Emphasizing seamless integration with diverse digital platforms and BIM systems, the presented methodology underlines the necessity for adaptable and user-centric design solutions in energy renovation projects. This approach not only facilitates broad applicability across different building types and climatic conditions but also encourages the adoption of sustainable renovation practices by simplifying the decision-making process.

Forthcoming work will focus on the validation of the tool in a set of real and virtual demonstration buildings in six European countries, renovated with the technologies developed within the ENSNARE project. The quantitative validation will be based on monitored data for temperature and energy consumption, which will be compared against predictions obtained with the tool presented in this paper and with advanced simulation engines. Additionally, a qualitative validation will be performed by comparing the outcomes of the tool with the learnings from the renovation and decision-making processes of the demonstration buildings.

The library of renovation solutions included in the tool is currently limited to a set of generic passive insulation solutions and the set of active solutions developed within the ENSNARE project. Future work might include extending the scope of the tool through the incorporation of additional (both generic or proprietary) passive and active envelope solutions.

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REFERENCES

[1] Y. Lu et al., "Information and communication technology applications in architecture, engineering, and construction organizations: A 15-year review," J. Manag. Eng., vol. 31, issue 1, A4014010, 2015.

[2] Y. Rezgui and A. Zarli, "Paving the way to the vision of digital construction: a strategic roadmap," J. Constr. Eng. Manag., vol. 132, issue 7, pp. 767–776, 2006.

[3] M. Fuccaro et al., EDST Specifications, ENSNARE D3.1, European Commission, 2021. https://doi.org/10.3030/958445

[4] T. Konstantinou, A. Prieto, and T. Armijos-Moya, "Renovation Process Challenges and Barriers," Env. Sci. Proc., vol. 11, issue 6, 2021.

[5] European Union, Directive 2010/31/EU of the European parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), 2010.

[6] K. Iturralde., A. Mediavilla, and P. Elguezabal, "Automation process in data collection for representing façades in building models as part of the renovation process," J. Facade Des. Eng., vol. 11, issue 2, pp. 123–144, 2023.

[7] A. Mediavilla, P. Elguezabal, and N. Lasarte, "Graph-Based methodology for Multi-Scale generation of energy analysis models from IFC," Energy and Build., vol. 282, 112795, 2023.

[8] E. Delzendeh, S. Wu, A. Lee, and Y. Zhou, "The impact of occupants' behaviours on building energy analysis: A research review," Renew. Sustain. Energy Rev, vol. 80, pp. 1061–1071, 2017.

[9] P. Hoes, J.L. Hensen, M.G. Loomans, B. de Vries, and D. Bourgeois, "User behavior in whole building simulation," Energy Build., vol. 41, issue 3, pp. 295–302, 2009.

[10] E. Prataviera et al., "EUReCA: An open-source urban building energy modelling tool for the efficient evaluation of cities energy demand," Ren. Energy, vol. 173, pp. 544–560, 2021.

[11] German Association of Engineers, Calculation of transient thermal response of rooms and buildings - Modelling of rooms, VDI6007-1. Düsseldorf: Beuth Verlag GmbH, 2015.

[12] P. W. O'Callaghan and S. D. Probert, "Sol-air temperature,", Appl. Energy, vol. 3, issue 4, pp. 307–311, 1977.

[13] CEN, Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6, EN 16798-1:2019.

[14] T. Konstantinou et al., "The role of LCA in the renovation's early decision-making for the design of a multifunctional, modular building envelope system", J. Phys.: Conf. Ser., vol. 2600, 152024, 2023.

[15] ISO, Environmental management - Life cycle assessment - Principles and framework, EN ISO 14040:2016

[16] CEN, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, EN 15978:2011

[17] CEN, Sustainability of construction works - Assessment of economic performance of buildings - Calculation methods, EN 16627:2015

[18] R. Mulero, B. Arregi, I .Mendialdua, and R. Garay-Martinez, "Designing a generalised reward for Building Energy Management Reinforcement Learning agents," SpliTech 2021, pp. 1–6.

[19] L. Thuvander,, P. Femenías,, K. Mjörnell., and P. Meiling, "Unveiling the process of sustainable renovation," Sustainability, vol. 4, issue 6, pp. 1188–1213, 2012.

[20] A. Bisello, M. Bottero, M. Volpatti, and T. Binda, "Multicriteria Spatial Economic Decision Support Systems to Support Positive Energy Districts: A Literature Review," in Smart and Sustainable Planning for Cities and Regions: Results of SSPCR 2022, pp. 15–31.

[21] A. N. Nielsen, R. L. Jensen, T. S. Larsen, and S. B. Nissen, "Early stage decision support for sustainable building renovation–A review," Build. Environ., vol. 103, pp. 165–181, 2016.

[22] M. Seddiki et al., "Review of Existing Energy Retrofit Decision Tools for Homeowners," Sustainability, vol. 13, issue 18, 10189, 2021.

[23] N. Hashempour, R. Taherkhani, and M. Mahdikhani, "Energy performance optimization of existing buildings: A literature review," Sustain. Cities Soc., vol. 54, 101967, 2020.

[24] E. Neves-Silva and L. M. Camarinha-Matos, "Simulation-based decision support system for energy efficiency in buildings retrofitting," Sustainability, vol. 14, issue 19, 12216, 2022.

[25] S. D. Mangan, "A Performance-Based Decision Support Workflow for Retrofitting Residential Buildings," Sustainability, vol. 15, issue 3, 2567, 2023.

[26] T. Tan, G. Mills, E. Papadonikolaki, and Z. Liu, Z, "Combining multi-criteria decision making (MCDM) methods with building information modelling (BIM): A review," Automat. Constr., vol. 121, 103451, 2021.