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OptEEmAL: Decision-Support Tool for the Design of Energy Retrofitting Projects at District Level

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Abstract. Designing energy retrofitting actions poses an elevated number of problems, as the definition of the baseline, selection of indicators to measure performance, modelling, setting objectives, etc. This is time-consuming and it can result in a number of inaccuracies, leading to inadequate decisions. While these problems are present at building level, they are multiplied at district level, where there are complex interactions to analyse, simulate and improve. OptEEmAL proposes a solution as a decision-support tool for the design of energy retrofitting projects at district level. Based on specific input data (IFC(s), CityGML, etc.), the platform will automatically simulate the baseline scenario and launch an optimisation process where a series of Energy Conservation Measures (ECMs) will be applied to this scenario. Its performance will be evaluated through a holistic set of indicators to obtain the best combination of ECMs that complies with user's objectives. A great reduction in time and higher accuracy in the models are experienced, since they are automatically created and checked. A subjective problem is transformed into a mathematical problem; it simplifies it and ensures a more robust decision-making. This paper will present a case where the platform has been tested.

1. Introduction

The Energy 2020 strategy highlighted increasing energy efficiency as one way to tackle the challenge to lower EU GHG emissions, which stems from the fight against Climate Change, as highlighted in the Paris Agreement and in the latest IPCC report [1]. One of the main approaches proposed to obtain this objective is tapping into the biggest energy-saving potential sectors: the built environment.

This necessity to improve the current built environment poses a challenge for technical stakeholders who are obliged to implement these directives in their building retrofitting projects. Building-as-usual approaches are usually highly ineffective, insomuch as they tend to consider retrofitting projects in an isolated manner without taking into account possible interactions among buildings, trade-offs or synergies. Moreover, whenever any parameter related to energy-efficiency or sustainability is considered it is usually focused on a very specific aspect, such as "energy consumption", once again ignoring a wide variety of impacts a retrofitting project may have, ranging from environmental issues to social ones. However, if there is the desire to evaluate the energy performance of the project it is usually performed through simulation tools, which can be more or less accurate, but which usually imply

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generating ad-hoc simulation models. This process is always prone to human error both in the definition of the simulation models and when implementing ECMs or other kind of modifications in the models. Other projects have developed similar platforms but the users have to introduce the number of solutions manually [2]. Furthermore, this process is extremely tedious and time-consuming; therefore a limited number of solutions are taken into consideration, hindering the possibility to find an optimal retrofitting solution, and are applied to individual buildings, due to the considerable complexity of the problem.

2. OptEEmAL overall approach

Bearing the problems encountered in the design of retrofitting projects, OptEEmAL proposes a platform which tackles the three most relevant aspects to effectively contribute to EU Energy Directives and to their goal of GHG emissions reduction: holistic take of the problem, collaboration among stakeholders and technical complexity.

First of all, the OptEEmAL platform provides a **holistic take of the problem** at hand. Analysing the energy performance at building level is not enough, since many of the possible impacts of a certain action are missed. A wider scope should be aimed for, that is the reason why OptEEmAL places its focus at district scale and models the interactions among the different buildings encountered in an area of study. This idea permeates the whole platform, in particular, the Energy Conservation Measures catalogue, which is not constrained to the measures to be implemented at building level, but also considers district level measures, such as District Heating.

Secondly, and extremely crucial for the platforms' success, is to assure the **collaboration among stakeholders**. The flow of information and the inclusion of stakeholders in the decision-making process, in particular, when establishing the main objectives or criteria to be followed is of the utmost importance. Thus, the collaboration framework established within Integrated Project Delivery (IPD) is consistently followed in all the steps of the platform.

Finally, the **technical complexity of the platform**, which is inherent to the ambition of OptEEmAL is tackled. It includes the use of standards, such as IFC or CityGML, in addition to other sources of data; which need to be checked and be interoperable among each other. Moreover, this information should be adequately transferred among the modules of the OptEEmAL platform in processes such as the simulation (energy, environmental, economic, etc.) or the optimisation. In the next sections a particular focus will be placed on these two modules of the platform.

However, before delving into the specificities of these modules, it is important to have a basic understanding of the functioning of the platform. OptEEmAL works in 5 steps in order to provide the functionalities described above. Firstly, it integrates and processes input data from various sources, being some uploaded by the users and others automatically retrieved from existing data sources (for example climate or economic data) (1). Once input data is integrated and processed, the baseline is calculated in the fields of energy, comfort, environment, economic, social and urban performance of the district, launching a set of simulation tools and algorithms for which input files are automatically generated from the data inserted at the beginning (2). After the calculation of these baseline performance indicators, the platform generates sets of candidate retrofitting scenarios (3) based on the information provided through an Energy Conservation Measures (ECMs) catalogue that is connected to the OptEEmAL system. These candidate scenarios (combination of ECMs – passive, active and renewable measures) are simulated –as in (2) for the baseline– and optimised (4) using the simulation toolbox. This process is repeated in a loop (generate scenarios – simulate – evaluate – optimise – new scenarios, etc.) until some stopping criteria is met and finally the set of best scenarios are obtained. These are exported to the stakeholders of the retrofitting project (5). Therefore, the core of the tool is a simulation and optimisation loop that allows obtaining this rank of best candidate scenarios.

Within this framework, the **Simulation toolbox** is the responsible of creating simulation models of the candidate retrofitting scenarios, which then are sent to their corresponding simulation tools to calculate the set of District Performance Indicators (DPIs), while the process is completed with a **Multi-objective Optimisation Algorithm** that considers barriers from the district and buildings under study and targets defined by the end user to generate the best ranking of candidate retrofitting scenarios.

3. Simulation toolbox to assess the district performance

The Simulation toolbox is supporting two key processes in the OptEEmAL platform: the data insertion and diagnosis process; and the scenarios generation and optimization process. In both processes, data retrieved from proper Data Models (Energy, Energy Carrier, Urban, etc.) comply with certain groups of transformation rules to generate the required simulation input files: (1) an XML file for every building of interest to be used as input to NEST [3] for the environmental DPIs calculation; (2) ECO tool inputs for the economical DPIs calculation; (3) Input Data Files (IDF) files for every building of interest, to be used as input to EnergyPlus [4] for the building envelop thermal simulation and computation of its energy loads; and (4) multiple configuration files to be used as input to the HVAC tool for the energy and comfort DPIs calculation. Note here that within OptEEmAL, SimModel [5] has been chosen as the Energy data model. To achieve functions like data retrieval, data transformation, execution of the simulation tools and computation of DPIs, new (or modification of existing) components have been developed. The need for most of these components, was stipulated in the design of the simulation toolbox, while the need for others, like the BIM exporter modifications, became apparent later when the quality of data obtained from commercial tools was not acceptable.

Related to data management and simulation functionalities, the components developed are shown in Figure 1. The CBIP tool [6] enriches the IFC file with geometry information that is required for Building Energy Performance simulations (BEPs) (namely, generates the 2nd-level space boundary information). The DNS tool [7] retrieves information from the CityGML and generates a set of surfaces that have shading effect to the buildings under investigation (these buildings define the district). The automatic zoning tool [8] aims at generating zoning information if this is not available from the supplied IFC file. These three supporting tools belong to the enrichment layer and interact with the Data Management Module (DMM). The SimModel Enrichment tool retrieves the output of the ETL2 process (a mapping process from IFC RDF to SimModel RDF) and enriches the energy data models with additional information required for energy simulations. Simulation Input Data File Generation, Cluster Computing and DPI Calculation comprise core components of the simulation input model generator module. The Simulation Input Model Generator Module retrieves data from the Instance Creator (DMM), generates input files for specific simulation tools (e.g. EnergyPlus and HVAC tool), and submits these files to the Cluster Computing tool for simulation, results of which are retrieved by the DPI Calculation tool, and after some aggregation operations DPIs values are computed and stored at the project repository.

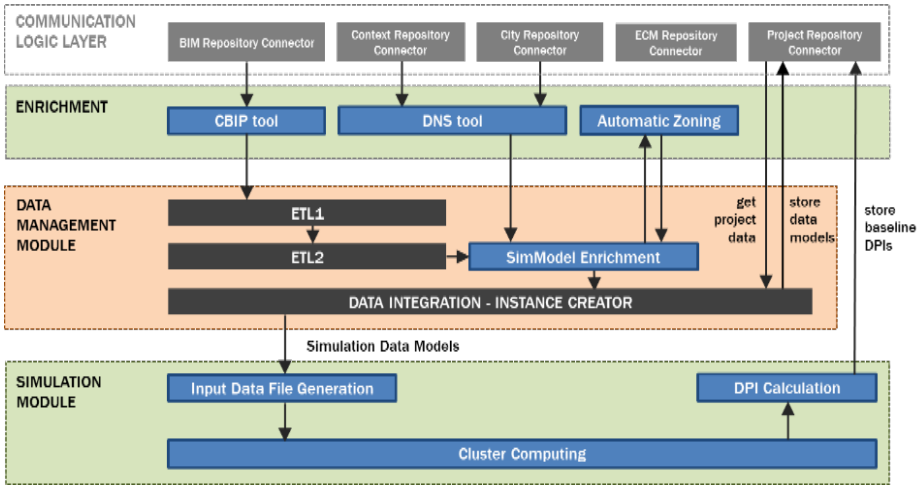


Figure 1. Data Management Module and Simulation Functionalities.

Tools that have been developed for the EnergyPlus input data file generation and for the energy and comfort DPIs (HVAC tool) have been selected to be presented here, since their proper execution and implementation to the simulation toolbox have been the most challenging tasks of this module.

Concerning the EnergyPlus IDF generation for the building envelop simulation, it has been observed that EnergyPlus-oriented input parameters (e.g. time-step, run period, simulation control, etc.) cannot be captured following the ETL2 process while, the data generated as a result of such process are not directly usable for an energy simulation input data file generation since, by default, there is no enough information to infer the required level of specification for some of the elements. Hence, certain rules to enrich the Energy Data models with more specific objects for the EnergyPlus input data file generation have been implemented in a new service, named SimModel Enrichment for EnergyPlus service.

With the enriched SimModel at hand, towards generating the IDF of a specific building, a set of mapping rules have been defined that transform data of the respective, enriched SimModel file to IDD classes' objects and writes a text file according to the IDD specifications. This set of rules forms the EnergyPlus Simulation Input Data File Generation service.

Concerning the energy and comfort DPIs computation, the HVAC tool takes as input the output of EnergyPlus tool (ESO file) and SimModel XML files with parameters for energy systems, controls and renewables. The tool performs system sizing, selection and application of one or more HVAC units available in the SimModel such that the thermal demand is fully supplied. In case the considered refurbishment scenario includes more than one HVAC unit, the system-level control logic is taken into account to determine how the HVAC units share the load and the final consumption of each unit given the variable efficiency models included in the tool. Additional control models estimate the variation in the total energy demand when the system schedules (start and stop times) are varied with respect to the baseline values such that energy consumption can be reduced, and thermal comfort maintained or improved. A key feature of the tool, compared to existing tools, it assesses actual costs and energy performance of commercial HVAC units and use a comprehensive set of high-fidelity simulation models and tools to determine district level DPIs.

The HVAC service includes models of supply and demand systems. The supply systems currently supported include: hot water boilers condensing and non-condensing (natural-gas, diesel and bio-mass), combined heat-power-units, heat pumps, geothermal heat pumps, chillers and solar-thermal panels. The models of demand systems are efficiency-based models applicable to different building demand systems, namely: baseboard heating systems, fan-coil systems, constant air-volume (CAV) systems, variable air-volume systems (VAV), variable refrigerant flow (VRF) systems, packaged terminal heat pumps (PTHP) and air conditioning units (PTAC), air to water heat pumps (A2W HP), underfloor heating systems. The models include zone-level consumption of water circulation pumps and fans. A number of system-level controls applicable to the energy supply and demand systems are supported. These are: system scheduling, optimal start-up & stop, thermal load following, weather compensation for hot and chilled water loops and sequencing control for boiler and chiller plants. The tool generates report that are communicated to the optimizer with a set of DPIs and that are needed to determine the Pareto-optimal points and also a set of selected HVAC and control ECMs for each retrofit scenario.

4. Proposed Multi-objective Optimization Algorithm for District Retrofitting Problems

This section presents a multi-objective algorithm based on the MOHS (Multi-Objective Harmony Search) that simultaneously optimizes cost and benefit fitness functions at district level. Thus, the proposed multi-objective algorithm does not converge towards a unique solution; a set of solutions which represent best trade-offs (related to the bi-objective optimization) that comprise the Pareto optimal front is proposed instead.

The MOHS approach is a populated-based algorithm based on the Harmony Search algorithm (HS) [8] in which a set of candidate solutions P(k), with k = [0,..,K] are iteratively improved by means of the application of certain probabilistic operators. Following the notation stated, it will be hereafter denoted each possible candidate solution as *harmony*, whereas each of the N entries of such vector is called *note*. Within this optimization problem, each harmony states the energy refurbishment strategy to be applied and indicates the percentage of application of each refurbishment strategy.

The improvisation procedure of the MOHS is driven by three parameters that will be explained above: 1) Harmony Memory Considering Rate, HMCR; 2) the Pitch Adjusting Rate, PAR and 3) the

Random Selection Rate, RSR. After generating new candidates, the quality of such new solutions is analyzed in terms of the objective functions (cost and benefit). The best K melodies, among the newly produced ones and the ones stored in the Harmony Memory (HM) from the previous iteration, will be kept for the next iteration. The entire process is repeated until a fixed number of iterations is reached. Concretely, the steps of the proposed multi-objective algorithms are the following: initialization, improvisation, evaluation, multi-objective sorting and stop criteria step.

The **initialization** step is just executed once; at the first iteration the N entries of P(k) are randomly generated taking into consideration the ECM type. Passive ECMs are defined with a numerical number (nº of ECM type), renewable strategies also contain the percentage of application from the subset [0, 5, …, 100]% considering the useful surface covered. Active and control ECMs are set to 1 if they are applied and to 0 instead. It is important to remark that the simultaneous application of the refurbishment strategies must accomplish the symmetric matrix (i.e. symmetric matrix representation in which the strategies that can be employed together are set to 1 and those that cannot be combined to 0) and the application of renewables strategies cannot exceed the total useful roof surface.

The **improvisation** process is composed by three different probabilistic operators that are sequentially applied to each note of the harmonies in order to produce a new improved set of K harmonies. Note that the probabilistic operators have been specially designed for this problem and that the different encoding procedure per ECM has forced to work in a different way depending the position (note) of the harmony that is being improvised, i.e. the specific ECM to which the probabilistic operators are being applied.

- The **Harmony Memory Considering Rate**, HMCR in [0, 1], sets the probability that the new value for a certain note is randomly selected among the values of the same note in all the other K-1 harmonies. That being so, the ECM type and the percentage of application of each refurbishment strategy is combined with the information of the remaining harmonies.
- The **Pitch Adjusting Rate**, PAR in [0, 1] aims at introducing subtle modifications in the harmony by establishing the probability that the new value for a given note is taken from its neighboring values, instead of among the values stored in the HM. Thus, for passive ECMs a step of 1 is added or subtracted with probability 0.5 in order to produce slight changes to the ECM type in the new improvised solution. For renewables ECMs a step of 5% is added or subtracted with probability 0.5 and for active and control ECMS 1 is set to 0 and vice versa if possible.
- The **Random Selection Rate**, RSR in [0, 1], sets the probability to pick a random value for the new note from their feasible ranges.

It should be noted that during the improvisation process, the level of compliance of the newly improvised solutions is checked in order to determine if the generated set is valid in terms of the combination of refurbishment strategies. For example, regarding the renewable strategies it must be checked that the sum of the total useful roof surface is less or equal 100% and in all cases the district strategies' constraints (symmetric matrix) must be fulfilled.

Table 1. List of DPIs per evaluation group.

Cost	Benefit 1	Benefit 2
ECO02.2 Investments (in €)	ENE 01.Energy demand	ENE 14.Energy use from Biomass
ECO03.Life cycle cost	ENE 02.0 Final energy consumption	ENE 15.Energy use from PV
ECO05.Payback Period	ENE 06.Net fossil energy consumed	ENE 16.Energy use from Solar Thermal
ENV01.Global Warming Potential – GWP (kg.CO_2)	ENE 09.Energy demand covered by renewable sources	ENE 17.Energy use from Hydraulic
ENV04.Primary energy consumption	ENE 13.Energy use from District Heating	ENE 18.Energy use from Mini-Eolic
ENV06.Energy payback time	COM01.Local thermal comfort	ENE 19.Energy use from Geothermal

In the **evaluation** the new harmonies are evaluated in terms of cost and benefit fitness functions. For the evaluation 18 DPIs have been taken into account. These DPIs, which have been calculated in a previous simulation stage, have been classified into two main groups: those which imply a cost and those which represent a benefit. Additionally, a third category has been created within the benefit group in order to ease the establishment of the prioritisation criteria, as explained in the following section. Thus, the evaluation criteria is divided into three groups as shown in Table 1:

- Cost group: it contains the DPIs that indicate the environmental or economic cost for the scenario.
- Benefit 1 group: this group involves the DPIs that could show a benefit for the scenario (reduction of energy demand or consumption, increase of the energy demand covered by renewable sources, increase of the comfort…).
- Benefit 2 group: This group takes into consideration the benefits obtained when increasing the contribution of renewable energies: photovoltaics, solar thermal, hydraulic, mini-eolic, geothermal and biomass. It represents a disaggregation of ENE09 (in the benefit 1 group), where the energy demand covered by renewable sources can be further analysed.

The DPIs are normalised in order to be able to make a comparison between them. For the normalising step relative values compared to the baseline situation are used, since it is not possible to know a priori all possible DPI results. After calculating and normalising the DPIs, these are aggregated following a dynamic weighting scheme that varies according to the user priorities. The user can define his/her priorities introducing the prioritization criteria through two different mechanisms: (1) objectives can be inferred from the pairwise comparison of the 18 indicators, performed by the user, indicating the importance of each DPI over the others and (2) the user can select one scheme form the pre-defined scheme, which are based on possible objectives to be pursued according to directives, such as having a “nearly Zero Energy District” or “generation through renewables”. In this step we have finally a cost value, obtained as the weighted aggregation of the normalized DPIs belonging to the cost group and the benefit value generated as the weighted aggregation of the normalized DPIs belonging to benefit 1 group and benefit 2 group.

Multi-objective sorting: Once the quality of the fitness functions is evaluated each solution is assigned with two new values: the rank and the crowding distance. Then, as explained in [9], each current and improvised harmony is associated with a rank equal to its non-dominance level (1 for the best level, 2 for the next-best, and so on). Then, within each front, a specific crowding measure representing the sum of distances to the closest harmony along each objective is used to define an ordering among the solutions. In order to keep stored in the HM for next iterations, solutions with less rank value and largest crowding distance value are preferred. If two different solutions have the same rank, i.e. belong to the same front, then the point located in a region with lesser number of solutions (larger crowding distance) is preferred. The main idea is to select the solutions that optimize cost and benefit metrics while provide a wider Pareto front formed by diverse solutions.

Stop criteria: The entire process continues until the maximum number of iterations is completed. The algorithm iterates to step 2 until the last iteration in which the algorithm stops and the set of solutions stored in the memory that conform the dominant Pareto front is provided as possible results.

5. Case study validation

In order to ensure the reliability, trustworthy, accuracy and final usability of the OptEEmAL solution, a validation of the developed platform in different operational environments is being demonstrated in the final stages of the project. With this aim, the OptEEmAL platform is being validated in three different Technology Readiness Levels or TRLs, from TRL5 to TRL7. TRL5 has already been demonstrated, where the platform modules and components were integrated and deployed to validate the technology in relevant environments. In this case the global functioning of the platform was tested using a fictive example of a district in the city of *Santiago de Compostela* (Spain) with two fictive buildings called Demo4. This scenario was validated successfully and the complete process for this fictive project was

covered by starting with the creation of a new project and IPD group and finalizing with the selection of an optimal scenario from the Pareto front and the exportation of the documentation generated.

Currently TRL6 (platform prototype demonstration in relevant environment) has been demonstrated for 3 already existing/performed district retrofitting plans: *Cuatro de Marzo* district in Valladolid (Spain), *Mogel* district in Eibar (Spain) and *Polhem* district in Lund (Sweden). The purpose of this TRL is to demonstrate the platform prototype on real districts. In this case is of particular importance to validate that the platform fulfils its technical requirements (correct calculations, relevant calculation time, useful Graphical User Interfaces, etc.) and answers end-user needs (provide relevant and useful information in a time efficient process). All this information obtained from the platform is later compared with the existing and available information of the real retrofitting plans in order to fine-tune the OptEEmAL prototype.



Figure 2. View of the *Cuatro de Marzo.*

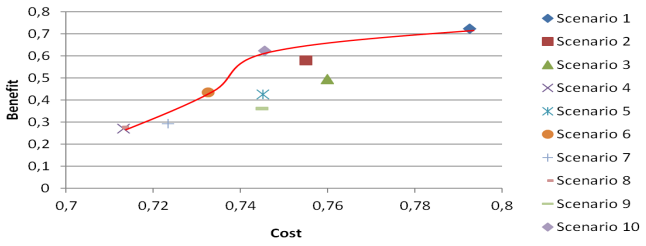


Figure 3. Pareto front for *Cuatro de Marzo* district.

In the case of the *Cuatro de Marzo* district, a complete execution of the platform prototype has been obtained. The validation has been launched for 5 residential buildings (3 individual blocks and 2 towers – see Figure 2) being necessary to upload into the platform one CityGML of the district, one BIM model per block and one BIM model for the two towers. After checking the correctness of these files, they have been enriched with the information needed to be later transformed into the DDM. Simulations of the baseline condition and the different scenarios containing passive, active and renewable ECMs (45 ECMs in total) have been run to provide the appropriate DPIs to the Optimization module with the execution of 10 iteration and 10 scenarios in each iteration. For the iteration 10, the Pareto front presented in Figure 3 has been obtained by the Optimization module. In this case, the optimal scenario is the scenario 6 or 10. A comparison between the real ECM implemented for one of the buildings in the retrofitting project developed by the R2Cities project and the ECMs selected by the OptEEmAL platform is shown in Table 2. The differences between the real ECMs and the ECMs selected by the platform is due to the user selection in the prioritization criteria (cost/benefit).

With this complete execution of the real case of *Cuatro de Marzo* district, the OptEEmAL prototype has jump to a new scale of complexity demonstrating its feasibility, scalability and adaptation to real cases. This achievement is essential to cover the final TRL7.

Table 2. Comparison of the ECM implemented and selected by the OptEEmAL Platform.

Real ECM implemented in the R2Cities project in one of the buildings	ECMs selected by the OptEEmAL platform	
	Scenario 6	Scenario 10
Roof insulation below top slab (Rockwool 100mm)	Passive Roof Pitched Internal Insulation (Mineral wool 100mm)	Passive Roof Pitched Internal Insulation (Mineral wool 60mm)
Façade External Thermal Insulation Composite system (ETICs) EPS 120mm	Passive Façade Internal insulation + plasterboard (Mineral wool 40 mm)	Passive Façade Internal insulation + plasterboard (Mineral wool 40 mm)
Solar thermosiphon collectors for DHW	Monocrystalline photovoltaic panel connected to the grid, 320 W	Monocrystalline photovoltaic panel connected to the grid, 320 W
Efficient condensation low-temperature boiler for heating and support of DHW, 24kW	Condensing natural gas boiler with 24kW of nominal capacity	-

6. Conclusions

This paper has presented the core elements of a tool developed to support designing energy efficient retrofitting projects: a simulation toolbox and an optimization algorithm. These two components combined provide the functionalities to evaluate the baseline of existing districts and the performance of candidate retrofitting scenarios, while optimizing them in order to find the most suitable combination of ECMs to achieve the expected goals by the stakeholders involved in the process.

The simulation toolbox integrates functionalities to generate the models and simulation engines that allow calculating the indicators at building level and at aggregated district level. The adoption of the proposed simulation method allow a more comprehensive evaluation of retrofitting projects compared to business-as-usual processes. The optimization algorithm offers functionalities to generate the candidate retrofitting scenarios and optimize them allowing the identification of the most suitable retrofitting scenario among them considering for that the priorities of the stakeholders that belong to the value chain of the retrofitting project. This optimizer is able to consider a wider range of alternatives against the business-as-usual where a limited number of scenarios need to be considered due to the limitations inherent to the time consumed in the process.

The work developed and its demonstration within a fictive case and within a real environment (*Cuatro de Marzo*) show the suitability of this platform to support the design of retrofitting projects for districts considering a wide range of ECMs combined in an optimized manner to maximize the benefits and reduce the costs of the project.

To conclude, the tool has demonstrated its potential for entering into the retrofitting business value chain, offering more comprehensive evaluations with reduced errors and time and, therefore, costs required in the process.

Acknowledgments

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