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Multi-objective optimization algorithms applied to residential building retrofitting at district scale: BRIOTOOL

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Abstract

The design of district and urban energy efficient retrofitting projects is a major challenge if contrasted solutions want to be implemented. From the establishment of the criteria to the calculation of indicators, there are several aspects to be considered, such as evaluating a series of refurbishment solutions or establishing an adequate method to select the optimal solution. Apart from this process requiring a high number of time and resources, it can result in a number of inaccuracies, leading to inadequate decisions or designs.

The main achievement of the BRIOTOOL solution proposed is the transformation of a subjective problem (what the best combination of energy conservation measures to implement is) into a mathematical problem, which ensures a more robust decision-making process. In particular, by analysing which multi-objective optimization method (NSGA-II, IHS, MHACO or NSPSO) is the most appropriate, based on execution time, number of different and optimal solutions, and hypervolume of the Pareto front generated.

As a result, the time reduction and the increase in the accuracy of the process compared to business as usual practices shows the benefits of the solution in designing energy efficient retrofitting projects at district level.

Introduction

The EU's non-energy efficient building stock is a fundamental sector to be addressed with a view to achieving EU's Climate Target Plan in 2030. Overall, buildings account for 40% of EU's total energy consumption and 36% of their greenhouse gas emissions. These, together with the currently low building refurbishment rates, are the main focus points of the Renovation Wave. Namely, this strategy aims "to at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations" (EC, 2020).

In this challenging context, and once a potential set of buildings to refurbish has been identified, decision-makers are confronted with a plethora of challenges to address: what energy conservation measures to consider? In what order to implement them? How many should be simulated and how can it be assured that the optimal solution is chosen? How to encompass the objectives of the decision-makers and measure if they have been achieved?

To address these questions, a decision-support mechanism based on the concept of Trias Energetica can be applied (EC, 2021), which is aligned with the principle of "energy efficiency first" supported by the European Commission. As a result, the following steps in the application of Energy Conservation Measures (ECMs) are derived:

1. **Energy demand reduction:** through the application of passive energy conservation measures (affecting the building envelope).
2. **Energy consumption reduction**: by making a more efficient use of the energy. First, by implementing energy systems that are more efficient, and also by combining them with renewable energy sources.
3. **Energy management and optimisation**: through the implementation of management systems, control actions can optimise the energy use of the building further.

This application of measures should be applied in a consecutive manner and the specific combination of measures should be determined to achieve specific objectives. However, if business as usual processes are applied, the selection of ECMs and their simulation is a time-consuming process: a model has to be generated for each building; for finding the best combination of the ECMs the models have to be redefined; and finally, the simulation launched for each one of the combinations. As a consequence, a fewer number of ECMs combinations (scenarios) are assessed, potentially not leading to the optimal solution that addresses the decision-maker needs. Besides, the whole process is highly prone to human errors due to all the modelling steps required. Therefore, the automatization of the process is paramount.

However, also the definition of the problem should be supported. In particular, an analysis of the previously mentioned objectives is required, since based on them an evaluation criterium is generated upon which to contrast the results. These evaluation criteria can be complex and consider multiple dimensions, as is the case of the OptEEmAL project (Hernandez G, 2017), or be based on a fewer number of indicators.

Another important aspect is that for the moment there is no much research in the optimization performed at district level, being the current state of the art focused on a building by building basis (Rey E, 2004)(Fialho A, 2012)(Wang B, 2014).

It is important to note that in this work the well-known gap between simulated and real performance is not addressed by the tool.

All in all, BRIOTOOL will provide a decision-support system to reduce time, improve accuracy and facilitate the assessment of energy conservation measures in sets of buildings. Thus, contributing to support energy refurbishments and increasing the renovation rates.

This paper includes an optimization method to determine the best passive measures from a catalogue, so that the greatest energy savings are achieved at an affordable cost for the user.

The rest of this paper is organised as follows. First, the importance of the context is highlighted: why is such a tool needed. Secondly, the solution proposed (BRIOTOOL) and the steps it follows are explained. Then, the demonstration carried out is presented, focusing on a district in the city of Valladolid (Cuatro de Marzo). Finally, some lessons learnt and conclusions are presented, as well as next steps.

BRIOTOOL solution

The design and development of the BRIOTOOL solution is based in three principles: (1) using open and public data as inputs, (2) automation of the different processes, and (3) reduction of time for finding the optimal solution.

By using open and public data as inputs, the tool can be applied without having to collect building-specific data, making it more accessible. The automation of the different processes will help to eliminate potential failures, improving the final results. Also, this automation will allow decreasing the time of the different steps, thus, achieving the time reduction of the third pillar.

The tool works in an iterative manner as can be seen in the Figure 1.

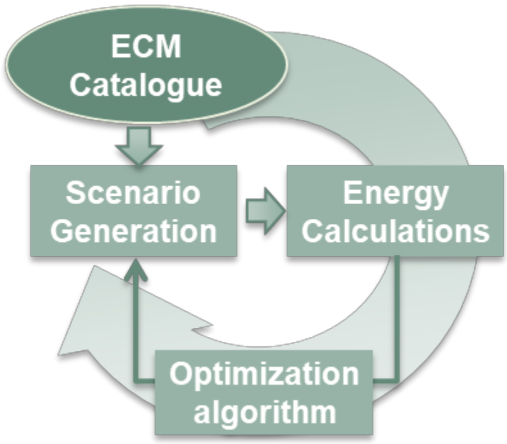

Figure 1: Scheme of the processes.

First, the tool needs information about the buildings to be included in the analysis. The required data is geometrical information of the buildings, year of construction and use of the building. In BRIOTOOL, this information is collected from the Spanish Cadastre, which provides all the needed data following the INSPIRE directive for Buildings (Serna V, 2021). Other information needed (as for example openings or thermal bridges) is estimated. This information is combined in the tool with data from construction catalogues in order to obtain a model of the buildings that allows to calculate the energy baseline of each of the buildings. Specifically, in the BRIOTOOL solution the indicator calculated is the energy demand.

Once the baseline is calculated, the iterative process starts with the execution of the three key modules of the tool: (1) optimization algorithm module, (2) scenario generation module, (3) energy calculations module and, to complement them all, Energy Conservation Measures (ECM) catalogue.

For each building different measures can be applied. These combinations of measures applied to one or more buildings represent a scenario. Thus, once the baseline calculation of the buildings to be analysed is ready, the optimisation algorithm proposes a set of scenarios to be analysed in each iteration. Then, in the scenario generation module each scenario proposed by the optimisation algorithm is managed and used in order to modify the model of each building and apply the selected measures, by using the parameters and characteristics of these measures that are stored in the Energy Conservation Measures catalogue. The modified models are processed in the energy calculations module to obtain the energy demand savings and the economic cost for each scenario. The results are sent back to the optimization algorithm that analyses them and guides the optimization process by proposing a new set of scenarios.

This iterative process continues until some stopping criterium is met: maximum number of iterations, execution time, etc. BRIOTOOL provides the results by representing the benefits versus costs. The results of interest for the user are those that offer the greatest energy savings and at the same time the least economic cost of implementing the measures indicated in the scenario.

Below, the Energy Conservation Measures Catalogue and key modules of the process are described in more depth.

Energy Conservation Measures catalogue

The Energy Conservation Measures catalogue is a fundamental component of the BRIOTOOL. Within it, a series of generic measures are categorised and characterised, including all the relevant parameters that allow to assess them. In particular, it is structured into the following levels:

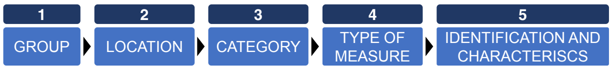

Figure 2: Levels in the BRIOTOOL catalogue.

1. **Group**: there are four main groups in the catalogue: passive, active, renewables and control measures. For instance, a refurbishment measure applied in the façades will be in the "passive" measures group.
2. **Location**: identifies where in the building the measure will be applied. This enables to establish rules on the type of actions that can be performed on every building element. Also, it allows not overlapping measures in the same element, which would be unfeasible in the real world. In the case of measures applied in the façade, the location would be "wall".
3. **Category**: creates groups of measures depending on the element where they are applied. For instance, for the location "wall", the categories of "external insulation", "internal insulation" or "intermediate insulation" exist.
4. **Type of measure**: the type of measure specifies further the measure within the categories depicted in the previous level. One example of type of measure for the location "wall" and the category "external insulation" would be "ventilated façade".
5. **Identification and characteristics:** at this level, specific characteristics of the ECM are defined, which allow to assess its cost, dimensions, or thermal characteristics. For measures that need the definition of sublevels (for instance, layers in a wall), the possibility to add further levels is enabled.

With the combination of these five levels, a unique code is generated for each of the measures, which facilitates their identification.

In addition, for all the parameters, the multiplicity is defined (by specifying if they are optional, mandatory, if more than one element could exist, etc.), as well as the unit used to define each characteristic and the format.

For the moment, the BRIOTOOL catalogue is restricted to passive measures and contributes to analysing how to reduce the energy demand in buildings.

Optimization algorithm module

The method used to solve the set problem is multi-objective optimization (MO). In general, the purpose of MO is the simultaneous optimization of several parameters. In this case, these parameters are the cost of the measures to be applied and the energy savings obtained by the users. To deal with this type of problem there are three main approaches (Cortez, 2014): weighted-formula, lexicographic method and Pareto. BRIOTOOL is based on the Pareto approach, since the results this method offers are the best possible ones and the necessary computational memory is affordable.

In order to find the optimal solution of this problem without known mathematical expression, four evolutionary algorithms are considered: Improved Harmony Search -HIS (Mahdavi, 2007)-, Multi-objective Evolutionary Algorithm Based on Decomposition -MOEA/D (Zhang, 2007)-, Multi-objective Hybrid Ant Colony Optimisation –MHACO (Zheng, 2020)- and Non-dominated Sorting Genetic Algorithm II -NSGA-II (Deb, 2002)-. All of them are available in pygmo (pagmo, 2021), a scientific Python library focused on solving massively parallel optimization problems. BRIOTOOL uses Python and pygmo in order to perform the optimizations.

Evolutionary algorithms operate as follows (Back, 1996): first, an initial population of individuals is initialized by the method determined by the type of algorithm used, and then it evolves through successive improved search regions by random processes of recombination, mutation, and selection, guided by the result obtained in each generation.

In BRIOTOOL, the optimization algorithm generates a collection of scenarios (combinations of measures to be applied on each building) in each generation. The collection of scenarios is used by the scenario generation module in order to adapt the models taking into account the measures indicated.

Scenario generation module

The scenario generation is one of the crucial steps of the BRIOTOOL functioning. In this step the simulation model is modified considering the ECM proposed by the optimization algorithm, adapting different parameters of the model using the information in the catalogue.

For the energy calculation in BRIOTOOL a validated Energy Performance Certificate software tool, specifically CE3X (IDEA. 2012), is used. Then, the simulation model is based on the information needed for this tool adding information about the cost of implementing the different measures.

It is important to note that for this version of the BRIOTOOL solution only passive measures have been taken into account, selecting those that change the envelope and the openings, improving the thermal insulation. So, the simulation model will change the insulation of the envelopes, considering the thermal transmittance once the measure is introduced. Also the parameters that are needed for the implementation cost calculations are added, mainly the cost in €/m^2 and €/unit provided by the ECM catalogue and the façade surface or number of openings changed in the building.

After that, the new simulation models are ready to be sent to the energy calculations module.

Energy calculations module

As soon as the tool starts functioning, the energy calculations module begins to calculate the energy demand for all the buildings considered using the simulation models of each building without any ECM applied. This energy demand calculated will be considered as the baseline of buildings and will be used as basis for calculating the savings, subtracting the energy demand of the building without ECMs from the scenario energy demand.

As it has been commented, energy calculation engine CE3X software tool has been used. This tool allows calculating the energy demand of a building by comparing it with reference buildings, taking into account the characteristics of the building (Hernandez G, 2018). The execution of this tool has been automated (Hernandez G, 2019).

In successive iterations the energy calculation module calculates the new energy demand of the buildings taking into account the measures applied and, after that, the savings obtained. Besides, the implementation cost is also calculated.

The results are calculated for each scenario separated by building, and after that, the energy demand savings and the calculated economic cost are aggregated, obtaining one value for the benefit and other for the cost for each scenario. These values will be used by the optimisation algorithm to start a new iteration if the stopping criteria defined have not been met.

Finally, in the last iteration, the optimal solutions found by the optimisation algorithm are distributed in the Pareto front. The user can select the scenario (ECMs combination) considering his or her preferences and experience, and focus on ECMs that are known to be important and effective.

Demonstration

The characterization of the case study is relevant in order to analyse and understand the results obtained. For this, not only the selection of the demo-site is important, but also the demonstration framework.

Although the tool can work at district level, the demonstration has been carried out with only two buildings in order to better asses the results.

Cuatro de Marzo demo-site

The tool has been demonstrated in one district: *Cuatro de Marzo* district in Valladolid (Spain). This district counts on many buildings that share the same typology. In this case, the demonstration has been launched for 2 residential buildings (individual blocks) that can be seen in the Figure 3.

Figure 3: Location of the buildings used as demo-sites

The characteristics of the two buildings can be seen in Table 1.

Table 1: Cuatro de Marzo selected buildings' characteristics

Characteristics	**Building 1**	**Building 2**
Gross floor area	1007.9 m^2	1013.7 m^2
Use of the building	Residential	Residential
Year of construction	1960	1960
Façade transmittance	2.38 W/m^{2}K	2.38 W/m^{2}K
Window transmittance	2.81 W/m^{2}K	2.81 W/m^{2}K
Cooling demand	12.45 kWh/m^2	12.36 kWh/m^2
Heating demand	116.17 kWh/m^2	116.84 kWh/m^2

In the case of the ECMs to be considered in this experiment, only passive solutions have been taken into account, specifically the application of external insulations (ETICS and ventilated façade) and changes in the openings (double glass, triple glass and double window). The characteristics of the ECMs used in the test can be seen in Table 2 and Table 3.

Table 2: Façade ECMs used in the demonstration

Category	**Type of measure**	**Main characteristics** (mm insulation and final layer type)	**Code**
u	V e	50 mm – polymer	PA.FA.EX.VE.01

		100 mm – polymer	PA.FA.EX.VE.02
		150 mm – polymer	PA.FA.EX.VE.03
		200 mm – polymer	PA.FA.EX.VE.04
		100 mm –ceramic	PA.FA.EX.VE.05
		100 mm –ceramic	PA.FA.EX.VE.06
	ETICS (CS)	50 mm – EPS	PA.FA.EX.CS.01
		100 mm – EPS	PA.FA.EX.CS.02
		150 mm – EPS	PA.FA.EX.CS.03
		200 mm – EPS	PA.FA.EX.CS.04

Table 3: Openings ECMs used in the demonstration

Category	**Type of measure**	**Main characteristics** (layers of glass included)	**Code**
Openings (OP)	Double glass	Coat + Gas + PVC 5 chambers	PA.OP.DG.DE.01
		Coat + PVC 5 chambers	PA.OP.DG.DE.02
		Coat + Gas + Aluminium frame with TBB	PA.OP.DG.DE.03
	Triple glass	Coat+ PVC 6 chambers	PA.OP.TG.DE.01
		Coat+ PVC 7 chambers	PA.OP.TG.DE.02
		Coat + Gas + PVC 6 chambers Passivhaus	PA.OP.TG.DE.03
		Normal + PVC 7 chambers	PA.OP.TG.DE.04
	Double window	Existing window + Coat+ PVC 6 chambers	PA.OP.DG.DW.01
		Existing window + Coat+ PVC 7 chambers	PA.OP.DG.DW.02

The real Pareto front was calculated by evaluating all possible combinations of measures in this problem, that is, 1296 scenarios, and selecting those that offer the greatest benefit and at the same time the lowest cost. It was obtained in 82846.7 seconds. In this Pareto front 31 optimal solutions are present for the experiment (see Figure 4).

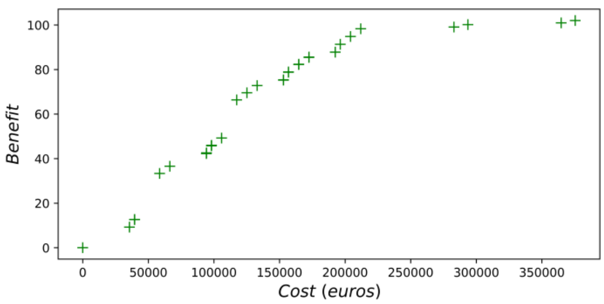

Figure 4: Real Pareto front of Cuatro de Marzo demo-site.

Discussion and results observation

The verification of the correct operation of BRIOTOOL has been accomplished by comparing the real Pareto front of Cuatro de Marzo (Figure 4) with the Pareto fronts calculated by the optimization algorithm. Several of them have been calculated for each optimization algorithm considered: NSGA-II, IHS, MHACO and NSPSO. In order to homogenize the results and be able to compare them, each of the executions has been performed with particular values in the algorithm parameters, which are the number of individuals and the number of generators. So, the executions are divided into three rounds: 24 individuals and 50 generations (Round 1, Table 4), 24 individuals and 25 generations (Round 2, Table 5), and 12 individuals and 50 generations (Round 3, Table 6). In addition, three additional executions have been performed with IHS, since it has been observed that its operation is different from the rest with respect to the number of calls to the objective function to be optimized (Round 4, Table 7). In order to operate, the MHACO algorithm needs to set an extra parameter called *kernel*, which is a variable referring to the number of solutions stored internally. To accomplish these tests, it has been determined that this value is the same as that of the population of individuals.

The comparison between algorithms has been made based on the execution time, the number of different solutions, the number of different optimal solutions and the calculated hypervolume. The number of different solutions and the number of different optimal solutions may be dissimilar, as not all the solutions found by the algorithms have to be optimal. Hypervolume (pagmo, 2021) is defined as the scaling of volume to more than two dimensions. In the case of the problem addressed by BRIOTOOL, hypervolume is equal to volume, since the Pareto front is limited to two dimensions. The hypervolume is calculated between the Pareto front and a reference point. For these tests, the reference point selected was [0, 452256], in order to encompass all the calculated solutions. The higher the hypervolume, the better the quality of the result.

Table 4: Round 1 results

Execution nº	**Algorithm**	**Function evaluations**	**Time (s)**	**Different solutions**	**Different optimal solutions**	**Hypervolume**
1	NSGA-II	1224	78306.8	18	14	33961875
2	IHS	74	3002.4	12	1	29371739
3	MHACO	1224	72791.2	21	4	31775579
4	NSPSO	1224	72591.7	12	0	21780827

Table 5: Round 2 results

Execution nº	Algorithm	Function evaluations	Time (s)	Different solutions	Different optimal solutions	Hypervolume
5	NSGA-II	624	37854.8	18	14	33911783
6	IHS	49	1612.7	10	0	29950189
7	MHACO	624	38902.0	21	5	31725316
8	NSPSO	624	38016.0	18	0	23824543

Table 6: Round 3 results

Execution nº	Algorithm	Function evaluations	Time (s)	Different solutions	Different optimal solutions	Hypervolume
9	NSGA-II	612	38962.9	10	3	32936069
10	IHS	62	3230.8	6	1	28687388
11	MHACO	612	38185.4	12	4	31593173
12	NSPSO	612	38283.5	7	0	19544356

Table 7: Round 4 results (IHS algorithm)

Execution nº	Individuals	Generations	Function evaluations	Time (s)	Different solutions	Different optimal solutions	Hypervolume
13	24	1220	1244	78178.0	10	3	31874187
14	24	610	634	40823.2	13	4	32241454
15	12	1220	1232	78893.5	7	2	30299577

In view of the results, NSGA-II provides the best solutions: its hypervolume is always the largest, it is the algorithm that calculates the higher number of optimal different solutions, and the number of different solutions it finds is high.

Another interesting algorithm is MHACO, since it is the one that calculates a greater number of different solutions. However, its hypervolume and the number of optimal different solutions calculated are far from those of the NSGA-II.

The execution time is similar in all the algorithms except in the case of IHS, since, with the same number of individuals and generations, it evaluates the objective function fewer times than the rest. For this reason, an additional round has been carried out with IHS considering other parameters, so that the number of executions of the evaluator is similar to those of the other algorithms. In this way, a better comparison can be made between IHS and the rest of the methods. Thus, it can be seen that IHS provides relatively good results, although it does not stand out in any of the indicators that measure performance quality.

Lastly, the solutions obtained through the NSPSO method are not acceptable because the resulting Pareto fronts show dominated solutions, which implies there are not preferable solutions for any of the two optimisation objectives considered.

In all cases, it can be seen that better results are obtained by halving the number of generations compared to halving the number of individuals, despite the fact that in both situations the same number of function evaluations are made. In test rounds 2, 3 and 4, it is observed that, in general, the optimization algorithms obtain good results even though the number of function evaluations with respect to the calculation of the real Pareto front and the execution time are about the half.

Computation times in executions nº 1, 3, 4, 13 and 15 are close to the time needed to obtain the real Pareto front, as the number of function evaluations performed is quite similar in both cases. This coincidence was made on purpose in order to ease the comparison between the BRIOTOOL solutions and the brute force result. Nevertheless, in problems with more buildings and more measures considered, evaluating all the existing possible solutions would not be a real option due to its expensive time cost.

Replication possibilities and Lesson learnt

The results obtained by BRIOTOOL in the different tests are positive, which means that a base has been obtained on which to introduce and test more complex characteristics. Some ways in which BRIOTOOL can be replicated are the following:

- **Increasing the number of buildings:** in the tests presented in this paper, only two buildings have been considered. This allows a greater understanding of the results and eases their interpretation in the first stages. However, the approach and the tool can be applied on a bigger number of buildings without any problem. In fact, it is in contexts with a large number of buildings where such a solution has the most potential.
- **Varying the typologies included in the analysis:** apart from considering more than two buildings, to increase the complexity by adding more typologies would be an interesting next step. For the moment, the buildings considered share the same typology, are built in the same year and have the same orientation. Further age ranges and building shapes can be considered

within the residential sector without any problem; nevertheless, expanding the tool to cover tertiary buildings would require additional changes in the energy calculations, since currently this module is only covering residential building calculations.

- **Considering another calculation engine:** the calculation engine used in the present solution is based in certification tools. Replacing the calculation engine with a more advanced one could improve the quality of the results. For this purpose advanced simulation tools could be used.
- **Extending the number of indicators in the evaluation:** for the evaluation of the results the solution only considers the energy demand savings and the economic cost. However a multi-objective optimisation could be applied taking into account other parameters as for example reduction in the greenhouse gas emissions, inclusion of renewable energy, return of investment, etc.

- **Increasing the number of measures:** the Energy Conservation Measures catalogue is currently structured to contain not only the passive measures considered in these tests, but also active, renewable and control measures. Following a similar process to the one presented in this paper, the main characteristics of the measures should be defined in the catalogue, and the way to apply them in buildings defined. This does not only refer to the element where they are applied (for instance, façades or roofs), but also, if they cannot be applied together with another measure. In addition, the sequential application of measures (first passive, then active and renewable and finally control measures) should be contemplated in order to maximise the efficiency of the solution proposed.
- **Adding new algorithms**: BRIOTOOL is prepared to perform these larger simulations easily, but when complexity is increased, the execution time also increases, which is an important aspect to be considered. Moreover, due to this fact, also the inclusion of different algorithms should be considered. This would enable to test their efficiency and validate their effectiveness when confronted with more complex problems.

Conclusion

BRIOTOOL allows the generation, evaluation and optimization of measurement scenarios adapted to the characteristics of the buildings examined within a district. The tool combines existing public data, validated calculated methodologies and multi-objective optimization methods to offer a robust solution in designing energy efficient retrofitting projects at district level. BRIOTOOL is in charge of deciding which scenarios are the best, opening up to the user a range of sets of measures to adopt, maximizing the benefit obtained and minimizing the cost.

Regarding the possible optimization algorithms, the best observed one is NSGAII, since it provides a large variety of different optimal solutions. Additionally, MHACO and IHS deserve also to be considered, especially the first one due to the large number of different solutions calculated.

BRIOTOOL can be improved with the aim of providing a stronger knowledge base for energy planners. Some of the ways the tool can be improved or the test can be expanded are: evaluating a greater number of energy saving measures and of a different type (introducing energy systems, as well as renewables and control measures), making a more complete evaluation with a wider set of indicators, considering another calculation engine, and introducing more complex typologies of buildings in the evaluation.

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