Two-Step Optimization of Envelope Design for the Reduction of Building Energy Demand

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Abstract

The path towards nearly-Zero Energy Buildings has enforced stricter constraints in construction design while promoting the investigation of new architectural solutions, in residential and producing sectors. Energy simulations, integrated with machine learning, helps academics and professionals to investigate novel strategies for energy saving.

We present here a 2-step methodology based on genetic algorithms, aiming to reduce the energy consumption for indoor heating and cooling, while identifying the most suitable commercial solutions for external wall and roof constructions. We compare it with a 1-step optimization algorithm with the goal to determine pros and cons of both methodologies. Even if the two methodologies are comparable in terms of energy reduction, the 2-step algorithm is less computationally expensive and finds several plausible architectural solutions, with equivalent energy profile.

Introduction

The building industry is facing a challenging period between impelling needs and new opportunities.

The growing warnings on climate changes has highlighted the depletion of non-renewable resources concerning the construction sector. Since the Kyoto's protocol (United Nations, 1998), national laws and regulations have followed a renewed environmental policy oriented to reduce the use of natural resources. Nations pursue this goal imposing stricter limits to building energy consumption for heating and cooling needs, that, represents the 40% of total energy consumption and the 36% of CO₂ emissions for the European Union (European Commission, 2018).

To reduce the energy consumption we need to improve the building technology by optimizing the energy exploitation, both for new constructions and existing ones. With this purpose, the European Parliament developed the concept of *nZEB* (nearly Zero-Energy Building), a reference building that requires very low amount of energy, and that should be covered mainly by renewable-energy sources, including on-site and nearby productions (European Parliament and Council, 2010).

Even if the aim of *nZEB* is straightforward, the lack of consistent reference indicators for the building sec-

tor allowed each European Union Members to define them independently. Different local needs worked against an unified calculation framework valid in the whole European Union territory. Despite the unavoidable differences in the methodologies, all the regulations must consider the building as a whole, differently from some old and current regulations, such as Italian energy saving law (Presidenza del Consiglio dei Ministri, 2013), that require the compliance of each single element.

These forthcoming changes demand from firms, professionals, academics and designers, new materials and architectural solutions in agreement with the *nZEB* criteria.

Remarkably, besides the traditional insulation material, firms now investigate high-technology and nature-based new materials for the building envelope, increasing the possibilities to design and realize low-energy-consumption buildings (Ahangari and Maerefat, 2019; Lachheb et al., 2019).

Rural buildings are suitable constructions for nature-based material application, mainly applied for food processing and storage buildings. These structures are often not required to meet energy-saving regulation constraints, even though the indoor climate control plays a fundamental role to preserve food safety and improve quality (Mazarrón et al., 2012; De Rosi et al., 2014). Thanks to high incidence in production costs and increased customers' awareness of environmental sustainability issues, energy saving has recently gained increasing attention in farm building design and construction as well, with a particular focus on food - and wine - processing buildings. (Benni et al., 2013; Torreggiani et al., 2014).

In summary, the new energy saving requirements in the building sector are driving to stricter and stricter constraints and at the same time new opportunities in terms of building solutions, from residential to producing buildings.

The appropriate design of the building envelope is a key aspect of energy saving. Remarkably, Fan and Xia (2017) showed that over 50% of energy consumption in the buildings is related to the heat losses through the shell, so energy efficiency in envelope design becomes a priority. The preliminary energetic assessment of new building solutions is now com-

monly analyzed by computational simulations (Barbaresi et al., 2014; Ramos Ruiz et al., 2016). For instance, Chen et al. (2019) employed a hybrid generalized pattern search particle swarm optimization (HGPSPSO) and sensitivity analysis to evaluate the effects of the urban contexts and various envelope features to optimize the energy needs and to define accurate guidelines for high rise buildings. With the focus on improvement of existing buildings, Risholt et al. (2013), modelled a house in Norway, by employing passive components and renewable energy resources and evaluating the optimized condition among energy and home quality indicators. With similar intent, Hong et al. (2019) developed a multi-objective methodology through genetic algorithm to optimize the energy design of a library in a university located in Seoul, by considering window type, set point temperature and ventilation to optimize economic, environmental and energetic criteria. In summary, the literature provides multiple examples of energy simulations tailored to optimize single building instances, but lacking easy generalization and adaptability (Longo et al., 2018). The main goal of this work is then to optimize the building envelope to reduce the energy consumption for heating and cooling, while retaining several material solutions for external wall and roof constructions. In the following, we compare our 2-step optimization protocol, based on an initial analysis over the theoretical thermal properties of the building envelope, with a 1-step procedure, dependent on the selection of a given database of construction materials.

Methods

The present Section describes the hardware, the software and the programs chosen for this work, the case-study, the simulation parameters, the class of algorithms, the solving procedures defined by the Authors, the database of materials and finally the analyses and indicators used to compare the procedures.

Hardware, software and programs

The method in this paper is based on the analyses of energy simulations' results, achieved and analyzed by two main programs: *EnergyPlus 8.1* (U.S. Department of Energy, 2018) and *MatLab 2017b* (Mathworks, 2017). The first is a program for dynamic energy building simulations widely used in scientific literature (Longo et al., 2018), the second is a multi-paradigm numerical computing environment developed to solve iterative analyses. Several works take advantage of those programs and of their interactivity (Torreggiani et al., 2017; Escandón et al., 2019). More in detail:

- MatLab is used to code and calculate the optimization procedure, create EnergyPlus models, launch EP simulations (with a comprehensive EnergyPlus wether file), run the optimization al-

Figure 1: The case-study building. South view

gorithm and performs the data processing;

- EnergyPlus is the dynamic energy simulation engine.

Both these programs are among the most reliable in their application domain, thus they ensure high accuracy of the results. Summing up, EnergyPlus models can be managed, and simulations launched, directly from MatLab environment, allowing simple managements of iterative procedures such as genetic algorithms. Other software used in this work are OpenStudio, AutoCad, Trimble SketchUp and text editors for the realization of the first model of case study building, called hereinafter *BaseModel*. The computer used in this work is provided with Intel® Xeon® CPU, 3.06 GHz, 6.00 GB RAM, Windows 10 Pro.

Case study

The case study chosen for this work is a wine-making and storage building located in the central part of Italy, specifically in Bologna countryside. The building, shown in the Figure 1, is 30 m long and 20 m wide, the height varies between 5 and 7 m. The main axis is 32° NE oriented. Internally, it is virtually divided in two parts by a row of pillars located in the centre, along the longitudinal axis. One part is dedicated to wine-making (non-conditioned area), the other is used as wine storage area. The latter is conditioned; the analyses in this work will refer to this volume only.

This building was chosen for two main reasons:

- *Simulation reliability*: the building indoor conditions, ground temperatures and the meteorological data were recorded for 2 years. Collected data allowed to realize, calibrate and validate an EnergyPlus thermal model for software simulations (Barbaresi et al., 2017; Tinti et al., 2015);
- *Specificity reduction*: the building geometry and thermal needs are simple, precisely the storage area thermostat requires the same temperature range (12°C - 18°C) throughout the whole year (Marescalchi, 1965; Vogt, 1971). This solution reduces the singular effects due to specificity of building shape or thermal needs during the simulation process, easing the comparison between

Figure 2: The case-study model. North view. (1) wine-making area, (3) wine storage area, (1) and (4) roof areas.

the two approaches, aim of this work.

The building is modelled in EnergyPlus as a four-thermal-zone construction as shown in the Figure 2. Beside the wine-making area and storage, other two volumes under the roofs were modelled, since these parts of the buildings exhibit different thermal behaviour of the underlying volumes, as analyzed in Barbaresi et al. (2017).

The stored wine was modelled as thermal mass objects with same surface and volume of wine bottles and with wine thermal properties as reported in Boulton et al. (1998).

Simulation inputs

The EnergyPlus BaseModel was created on the basis of the validated model. A few input parameters of the BaseModel will be changed creating new models whose final energy demand will be used to evaluate their energy efficiency. All other input parameters are considered constant.

- *(main) constant parameters*: building shape and dimensions, thermostat setting, weather conditions (.epw file), ground temperature, floor slab;
- *variable parameters*: external walls, roofs, building orientation (degree), windows U-value (W/m^2K) and air infiltration (air changes per hour).

External walls and roof are input in two different ways according to the chosen procedure, as better specified in the following Sections. The weather file was created gathering on-site weather data for more than two years. For this work, data from 01/01/2013 until 31/12/2013 were used. EnergyPlus program, among several outputs, returns the energy demand (kWh) of the wine storage area, the only output considered in this work.

Matlab codes were created to generate building models starting from BaseModel, to launch the simulations in EnergyPlus environment, to run the solving algorithms and to modify the models according to algorithm results. Finally, it was used for the result analyses as well.

Genetic Algorithms

Genetic algorithms (GAs) are solving procedures based on the Darwinian evolution theory and related natural selection (Holland, 1975). They are designed and developed to optimize and generate high-quality solutions starting from an initial population (randomly created) and, using operators such as mutation, crossover, selection and generations, GAs create more performing individuals driven by a specific criterion defined by a fitting equation.

More in detail, GA starts creating a *population* of n individuals (energy models) called first *generation*. The individuals differ for specific characteristics called *genes* (simulation variable parameters). Values of genes are randomly attributed. GA randomly chooses two sets of t individuals and assesses their individual performances (energy need) according to a *fitting equation* (minimum energy need). The best individuals of the two sets have higher probability to be selected as *parents* to create a new individual for the following generation. The new individual is created using the genes of the parents. For each gene of the new individual, a *mutation* can occur with a probability of m ; if a gene mutation occurs, that gene is substituted with a randomly chosen new gene. This operation is repeated n times in order to complete the next generation. This procedure is intended to create more and more efficient individuals and will repeated until a fixed number of generation g is reached or a specific individual performance achieved.

For both the solving approaches used in this work, starting from the BaseModel, several different models of the building are created assembling an initial population, called Generation 1. The models differ for the variable parameters - as defined in the previous Section - randomly assigned in the first Generation. The algorithm chooses the most (energy saving) solutions for the creation of a new population of models (reproduction), according to a fitting equation that identifies the lowest energy consuming models.

Solving approaches

The thermal performance of a building is strictly dependent on its envelope, in particular on external walls and roof (Torreggiani et al., 2017). According to EnergyPlus input phase, walls and roofs are inserted as constructions (layers of materials). For each material, the user enters the main thermal properties, such as thermal conductivity, specific heat and density. The program automatically calculates the global thermal characteristics of the constructions. The main ones are the thermal transmittance, the superficial mass, the thermal lag, the attenuation coefficient etc. These values are used in the simulations to calculate the thermal behaviour of the building. The present work proposes two different input phase for external walls and roof:

- *1-Phase procedure*: the code generates building

constructions as combination of 3 materials with their thickness, picking materials from a given database. These constructions are directly inserted in EnergyPlus models. At the end of the solving algorithm, simulations return the most energy performing model that contains walls and roof as 3-layers (i.e. 3-materials) constructions.

- **2-Phase procedure:** the generating code creates constructions as theoretical values (Phase 1) inputting a 20-cm-thick fictitious material and its thermal characteristics: conductivity, density and specific heat. At the end of the solving algorithm, simulations return the most energy performing model that contains theoretical values of walls and roof only (no material is considered in this phase). A second genetic algorithm (Phase 2) creates 3-materials constructions - picking from a material database - that best fit the theoretical values identified in the Phase 1.

The two approaches have the same aim: finding the most energy saving solution for the case-study building. At the end of both procedures, the final solutions contain the construction materials to be used as external walls and roof. While the first approach inserts in EnergyPlus the materials taken from a database returning wall and roof materials at the end of energy simulations, the second approach splits the problem in two phases: the first run energy simulations with construction theoretical values only, then the second identifies the proper constructions (materials).

Material database

A research in the building market supply and in the scientific literature (Sassoni et al., 2014; Asdrubali et al., 2017; Bourdot et al., 2017; Lamrani et al., 2017) allowed to create a database of materials containing 94 materials with related thermal properties. For each material minimum and maximum thickness are reported. Summing up, each database line contains:

- code and extend name;
- main thermal properties: thermal conductivity, density, specific heat;
- secondary properties: thermal, solar and visible absorptency;
- minimum and maximum thickness and increment step for model constructions.

The included materials have mineral (34), vegetable (37), synthetic (2), composite (20) and animal (1) origin. Both procedure refer to this database to create constructions: the 1-Phase procedure since the creation of the initial population, the 2-Phase procedure in the second phase only.

Analyses and indicators

The main aim of this work is to compare the two proposed approaches to identify the most effective one.

The approaches are evaluated according to different indicators:

- **Final energy:** the best solutions (models) achieved by the two approaches will be compared in terms of final energy need (kWh);
- **Initial space of thermal characteristics:** for the energy simulation, constructions are combinations of thermal characteristics; this indicator globally compares the initial walls and roof (belonging to the Generation 1) as combination of thermal resistance (m^2K/kWh), superficial mass (kg/m^2) and thermal lag (h);
- **Material presence:** A limited number of insulation materials are usually used to build walls and roofs, related to the construction market supply. Finding constructions with same thermal characteristics made by different materials, can give more opportunities to professionals and firms involved in the construction sector. This indicator evaluates the probability of each material to be present in the constructions of the most performing solutions achieved by the 2 approaches.

Simulation constraints

To make comparable the results achieved by the two approaches, a few constraints were imposed equal to the both procedures:

- maximum thickness of constructions;
- minimum thermal transmittance of constructions;
- GAs' parameters (population, generation, mutation probability, etc.).

Results

In this Section, the results of the two approaches are compared, evaluated and discussed, according to the indicators as defined in the previous Section.

Preliminary tests allowed to define some constraints to apply to both procedures, as shown in the Table 1. Hence each simulation has 100-individual popu-

Table 1: Limits and constraints applied to both procedures's parameters

Parameters	Value	Unit
Population	100	
Generations	25	
Mutation coefficient	0.1	
Repetition	4	
Construction thickness	35.6	cm
Construction th. transmittance	0.194	W/m^2K

lations (energy models), runs for 25 generations; 0.1 mutation coefficient was applied. To improve the results' precision, each procedure is repeated four times. The Phase 2, in the 2-Phase procedure, works with 1000-individual population (constructions), performs

for 50 generations, with 0.1 mutation coefficient. Before analysing the final results, the calculation time was been monitored; the first procedure, 1-Phase, complete every energy algorithm simulation in the average time of 1376 minutes, the second, 2-Phase, in 1305. It is visible the two approaches takes almost the same time (2-Phase 5% faster); though it should be recalled that the 2-Phase needs a second algorithm (second phase) that averagely takes 5 minutes and should be run twice: one for identify the wall construction and one for roof construction, therefore the final time to complete the procedure is estimated in 1315, 4.5% faster than 1-Phase procedure. Supposing the EnergyPlus simulations account the same time, independently of the procedure, the difference should be generated in the reproduction phase performed by Matlab. Further studies will investigate this guess.

Final Energy

The first evaluated parameter is the final energy achieved by the procedures. Specifically the most energy saving models, identified by the two procedure, are compared.

As previously said, the algorithms were run four times for each procedure. As visible in the Table 2, the results returned by the two performances, exhibit negligible differences (less than 20 kWh on the minimum, corresponding to 0.1%).

Table 2: The most performing models in terms of energy need performed by the two procedures

Most energy saving model			
	minimum kWh	average kWh	st. dev. kWh
1-Phase	16904	16935	43
2-Phase	16921	16967	44

Despite the similarity in the best model, differences can be found observing the last generations. The Figure 3 exhibits the cumulative distribution functions of the energies demands returned by the models belonging to the last generations of both procedures (repeated for four times). The graph shows that the 2-Phase procedure (red line) globally produced more performing solutions (numerical values are reported in the Table 3): as example, half of the models of 2-Phase procedure are under 17133 kWh of energy demand that is 1.3% higher than the minimum (see Table 2), on the other side, half of the energy demands of 1-Phase procedure are as high as 19839 kWh, the 117.4% of the most performing model.

Initial space of thermal characteristics

As explained in the previous Section, the initial population is randomly created, therefore a high number of non-performing solutions are expected in the first generation.

Even though the procedure creates walls and roof of

Figure 3: The cumulative distribution functions. Values in x-axis are expressed in kWh

Table 3: Last generation energy demand values (kWh)

Energy quantiles - last generation				
Quantiles	0.3	0.5	0.7	0.9
1-Phase	17429	19839	26153	41264
2-Phase	17027	17133	17742	22479

initial populations in different ways, their constructions can be compared using their global thermal properties. The Figures 4 and 5 locate in the space every construction according to 3 coordinates: thermal resistance (m^2K/W), superficial mass (kg/m^2) and thermal lag (h).

Figure 4: Distribution of thermal properties of constructions in 1-Phase procedure

For this specific analysis, 50 initial populations were generated allowing the location of 10.000 construction for each procedure. It is clear the 2-Phase procedure has a more uniform distribution, entailing that 2-Phase procedure is able to investigate the thermal-property-construction space in a deeper detail. This result can be explained considering the input phase.

Figure 5: Distribution of thermal properties of constructions in 2-Phase procedure

In 2-Phase procedure the three thermal characteristics are randomly and independently generated, on the contrary, in the 1-Phase procedure they derive from measured material characteristics that we can assume to be non-independent.

Material presence probability

As previously explained, both the procedures refer to the same database that contains 94 materials. For each procedure the 70 most performing solutions were analysed; considering that each of the 70 chosen model contains 2 constructions (walls and roof), and each construction contains 3 materials, this analysis considers 420 layer (materials) for each procedure.

The Figures 6 and 7 reports the graphs related to the material presence in the most energy performing solutions. In other words, they show the probability of each material to be present in the most performing constructions.

Figure 6: Appearance probability of a materials in 1-Phase constructions

The y -axis reports the probability, the x -axis the number of materials belonging to the database. These materials are sorted from the highest probability ma-

Figure 7: Appearance probability of materials in 2-Phase constructions

terial to the lowest (no code nor name of materials is described in the graphs for readability reasons). The red line represents the probability of each material to be in the constructions if randomly chosen.

The x -axes, reports that 54 materials (57% of the database) are present in the most performing solutions of 1-Phase procedure (see 6), versus 88 (94%) in the 2-Phase (see 7), highlighting the 2-Phase procedure better investigates the given database. The top five materials in terms of probability are shown in the Table 4 (1-Phase procedure) and Table 5 (2-Phase). From left to right, columns describe the rank, the database code, the presence probability, and finally material description.

Table 4: Rank of most used materials in the best energy models (1-Phase)

1-Phase material probability			
#	Code	Probability	Material
1	C02	0.0714	Polyurethan panels
2	B14	0.0595	Coconut fibre
3	E01	0.0595	Sheep wool
4	A30	0.0548	Stone masonry
5	A17	0.0478	Cement

Table 5: Rank of most used materials in the best energy models (2-Phase)

2-Phase material probability			
#	Code	Probability	Material
1	B18	0.0543	Cork
2	B14	0.0480	Coconut fibre
3	A05	0.0479	Glass wool
4	B15	0.0474	Hemp hurd
5	B01	0.0417	LD wood fiberboard

Possible applications

As example, we considered the best models achieved by the 2 procedures and we analyzed the returned wall constructions. The Table 6 shows the wall construction (3 layers and related thickness) for 1-Phase

procedure. Results of the 2-Phase procedure are summarized in the Table 7 that shows that the second-phase GA, returned 2 suitable solutions. Another remarkable outcome, in fact, is that the 2-Phase can return more than one construction for the same model, and considering the computational velocity, this phase can be repeated as long as the solution can be considered satisfactory.

Table 6: Wall construction in the best model of 1-Phase procedure

Best model wall (1-Phase)		
Code	Thickness (m)	Name
D07	0.150	Fibre reinforced mud brick
E01	0.150	Sheep wool
A30	0.035	Stone masonry

Table 7: Wall construction in the best model of 2-Phase procedure

Best model wall (2-Phase)		
Solution 1		
Code	Thickness (m)	Name
D07	0.070	Fibre reinforced mud brick
B06	0.060	Wood particleboard HD
C02	0.011	Polyurethane panels
Solution 2		
Code	Thickness (m)	Name
D07	0.100	Fibre reinforced mud brick
B36	0.140	Cellulose insulation
B37	0.050	Recycled paper panels

Conclusions

The present work compares two GA-based procedures designed to find the most energy saving solutions in a case-study building. The two procedures differs for walls and roof definition. The first (1-Phase) creates constructions directly picking materials from a database, the second (2-Phase) works with theoretical values and, in a second phase, associates materials to most performing solutions.

Results show 2-Phase procedure is slightly faster (4%), no remarkable differences are evident in the most most energy saving solution (16900 kWh), the 2-Phase last generation returns more energy efficient solutions (50% of the 2-Phase solutions are below the 102% of best-model energy need, while the 50% of the 1-Phase solutions are below the 117% of best-model energy need).

Other considerations can be made on the two procedures comparison. In their final result, both the procedure accuracies are affected by the material database reliability, but while the 1-Phase uses the database since the first step, the 2-Phase resort to the database only in the second phase, entailing the first phase is not affected by the database precision. Moreover, considering the speed of the second phase,

(10 minutes for each model), the outputs of the first phase can be used with different databases, increasing the variability of final constructions.

Summing up, the 2-Phase procedure proved to be as effective as the 1-Phase procedure to find the most energy saving solution, but exhibits better performance in terms of calculation velocity, number of low-consumption solutions and constructions' variability. Further developments will investigate different building parameters.

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