Parametric study and simulation-based exergy optimization for energy retrofits in buildings

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Abstract:

The undertaking of building energy retrofits is essential for the reduction of energy use and carbon emissions at a national level. Nowadays, a number of construction methods and energy technologies that are available to practitioners require that the appropriate retrofit solution is identified to ensure long-term project success. A significant limitation of conventional methods that may be used to examine this (e.g. scenario by scenario) is that only a limited number of design scenarios can be evaluated which limits the potential for identifying the "best" designs. Furthermore, while the building sector has a large thermodynamic potential where most of the buildings' energy demands (especially space conditioning) can be met by low-grade sources, the associated exergy analysis method is rarely used in architectural practice.

The following paper presents a simulation-based exergy optimization model, which aims to assess the impact of a diverse range of retrofit measures. Two non-domestic UK archetype case studies (a typical office and a primary school) are used to test the feasibility of the proposed framework. The objective optimization functions in this study are building energy use, exergy destructions throughout the building energy supply chain, and improvement of occupants' thermal comfort levels. Different measures combinations based on retrofitting the insulation levels of the envelope and the application of different HVAC systems configurations (VAV, VRF, ground-source heat pump, air-source heat pump, district heating/cooling systems) are assessed. A large range of optimal solutions were achieved highlighting the framework capabilities. This approach can be extended by using the outputs in cost-benefit analysis and in thermoeconomic optimization.

Keywords:

Exergy optimization; genetic algorithm; simulation; building retrofit; UK non-domestic buildings.

1. Introduction

To address the UK's national dependency on high quality energy sources such as, natural gas and coal, recent energy policies and regulatory shifts have aimed to improve cross-sectoral efficiency. At present, the UK non-domestic building sector (which is comprised of approximately 1.8 million premises) is responsible for 17% of the country's total energy use and is highly dependent on fossil fuels; where 60% is delivered in form of gas, 10% of oil respectively, and 25% is delivered in form of electricity [1], which is largely generated by the first two. Particularly, in the English and Welsh non-domestic building sector, the final energy utilisation in 2013 was estimated to be 840.9 PJ (equivalent to 20.085 Mtoe annually) with a primary energy input of 1576.9 PJ [2]. From an end-use perspective, about 50% of all energy demand in the sector was due to space heating, followed by lighting (17%), DHW (10%) and catering (10%). As the majority of non-domestic buildings were built before energy regulations were implemented, this resulted in poor fabric characteristics, inefficient HVAC equipment and automatic controls, and poor occupant energy awareness and comfort levels [3]. In addition, the building replacement rate is typically low (>2%) [4], and although is expected that by 2050 the footprint will increase by a third, 60% of existing buildings will still be in use. In this sense, energy retrofit measures (ERMs) represent a significant opportunity to reduce existing buildings energy use and carbon emissions.

With the current range of available technologies and measures, the identification of the most appropriate of these is a critical aspect of the early design phase. As any energy system, buildings are physically complex where interactions between the building, the occupants, the equipment, and the environment are poorly understood. In order to improve the selection of appropriate measures, practitioners require robust tools for effective design, where building simulation can play a major role in the early design of energy efficient buildings [5].

Regulations and modelling tools used in the built environment usually only follow the first law of thermodynamics. As Hammond and Stapleton [6] and Shukuya [7] showed, the majority of the buildings are thermodynamically inefficient, hence have a high potential for improvement. The efficiency values presented in the aforementioned studies are not based on the typical energy analysis, but based on exergy analysis; where unlike energy (which is conserved), exergy is exposed to destructions or irreversibilities. In the buildings' energy supply chain, these destructions are mainly caused from combustion and heat exchange processes derived from a poor match between the quality of the supply and the quality of the demand. In the UK, the non-domestic sector "true" overall efficiency is about 12%, with an efficiency of only 6.5% for heating processes [8]. In recent years, the amount of research and application of exergy analysis in buildings has been increasing, mainly supported by two IEA Energy in Buildings and Communities Programme Annexes [9, 10]; although with a higher interest in dwellings than non-domestic buildings. The application of exergy analysis has significant potential in the identification of what can be considered unconventional opportunities and the consequent reduction of dependency of high quality fuels [11, 12].

1.1. – Parametric studies and optimization for building exergy retrofit

Robust analysis of ERMs (as individual elements and combined strategies) in the early design phase is needed to determine the impact of each scenario, undertake comparative analysis of various options and, ultimately, make more "informed" design decisions. In practice, the most common approach to assess a wide range of retrofit strategies is the "scenario by scenario" approach, where the practitioner models several solutions based on experience. The main limitation associated with this approach is that the number of analysed scenarios is typically very low, which often leads to solutions that can be far from optimal. In recent years, parametric or full factorial tools have been developed. In this method a large number of simulations are carried out in order to assess all the possible combinations, usually having a search space of thousands of solutions with the certainty of reaching the theoretical optimal scenario. This method has the strength that can provide a large amount of data that, for example, can be used to train artificial neural networks (ANN) [13]. But in practice, the method presents the limitation that is computationally and time expensive, where depending on the number of parameters or retrofit measures to explore, in some cases several years or hundreds of years would be needed to simulate all the possible combinations (without considering the time required for data post-processing). Another user-experienced based approach is multi-criteria, where a set of pre-defined and pre-evaluated alternatives are assessed, with no assurance of finding the optimal solution because the alternatives search is constrained by the user [14]. Finally, an approach that has shown potential to explore large search spaces in an efficient manner is multi-objective optimization (MOO). Three basic types of algorithms are used in optimization problems applied to buildings: enumerative, deterministic, and stochastic [15]. As Nguyen et al. [16] claims, stochastic methods are widely used, being genetic algorithms the most popular method for building optimization. Attia et al. [15] found that MOO methods are normally used during early designs as researchers and practitioners that use optimization techniques applied 93% of the cases for new buildings. However, some studies have demonstrated the strength of MOO for retrofit projects. Improvement of the envelope characteristics, HVAC equipment, controls, etc., while optimising objectives such as energy savings, occupant comfort and total cost has been investigated [5, 17-18].

In the literature, no building optimization studies were found which uses exergy analysis. One aim of using exergy analysis for retrofits is to show the exergy interactions when different parts of the energy supply chain are retrofitted. This approach is very common for thermal plants or in the chemical industry [19, 20], where common optimization objectives are components cost, fuel cost, exergy destructions, exergy efficiency, and CO_2 emissions. The aim of this paper is to investigate the feasibility of an optimization framework applied to "building energy retrofit practice" by integrating exergy analysis and a MOO technique by considering three objectives: energy use, exergy destructions and occupant comfort.

2. Methodology

The proposed model is a combination of two main modules: a) An energy/exergy analysis tool for buildings and its systems, and b) a retrofit optimization module. The modelling engine is based on different existing tools and modules specifically developed for this research. This framework gives the possibility to study a wide range of retrofit measures under different objective functions such as energy savings, exergy destructions, user thermal comfort, return of investment, etc.

2.1. Simulation framework

2.1.1. Energy/Exergy Analysis

As energy demand calculations are an essential component of any exergy-related building models, EnergyPlus [21] was selected as the calculation tool for first law analysis. EnergyPlus calculates the energy required for heating and cooling using a variety of systems and energy sources through the simulation of the building and associated energy systems when exposed to different environmental and operating conditions. The tool was selected as heat balance based solution technique allows for simultaneous calculation of radiant and convective effects, transient heat conduction through building elements such as walls, roofs, floors, etc. In addition, EnergyPlus is able to deliver the detailed inputs needed for the dynamic exergy analysis such as the building's energy demand, indoor and outdoor temperatures, occupant's thermal comfort, working fluid temperatures of HVAC systems, primary energy use, etc. To determine the exergy use and destructions at different points of the building energy supply chain, the thermodynamic properties of the system should be specified. The selected exergy method, which has the potential to analyse the whole building energy supply chain is based on the model developed by [22] that was further improved in the ECB IEA Annex 49 [10]. This method follows an input-output approach based on seven different subsystems that are very strongly related to each other, and thus the performance of one subsystem is highly dependent on the other subsystems (Fig. 1).

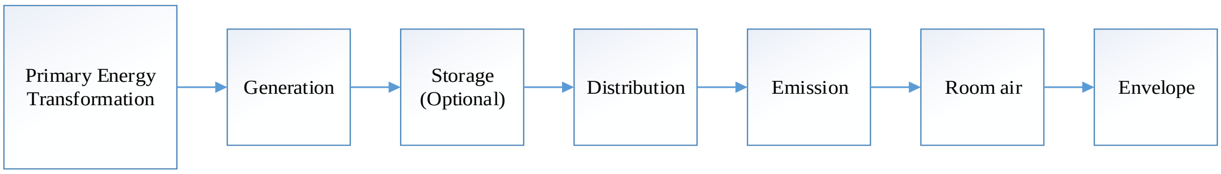

Fig. 1. HVAC Energy supply chain and subsystems for exergy calculations.

Exergy flows are very sensitive to the choice of the reference environment, since systems operate in a mode that is very close to the dead state. An essential characteristic of the reference environment is that it has to be irreversibilities-free, where all the major exergy destructions should occur on the system or process being analysed [23]. For this study, hourly external temperatures given by the TMY2 weather files were taken as the reference environment.

The calculation is performed in the opposite direction to the demand, starting from the envelope and concluding in the conversion of primary energy. The demand of each subsystem must be satisfied by the subsystem before. Unlike energy analysis, the exergy demand is not calculated using "exergy balance" equations; but is instead calculated by using the energy balance outputs (in this case given by EnergyPlus) multiplied by the quality factor given by the Carnot equation:

$$F_{q,building} = \left(1 - \frac{T_0\,(t_k)}{T_{i,avg}\,(t_k)}\right), \qquad (1)$$

where, T_0 is the outdoor temperature and $T_{i,avg}$ is the average inside temperature of the zones.

With this factor the exergy load of thermal zones can be calculated as follows:

$$Ex_{dem}(t_k) = F_{q,building} * \sum_i \,[Q_i\,(t_k)], \qquad (2)$$

where, Q_i is the heating or cooling load of each zone of the building.

When the energy supply passes through the energy supply chain, exergy destructions are expected throughout all the subsystems. These are dependant on factors such as the building's envelope or the systems components characteristics. Although the "primary energy transformation subsystem" is located outside the building boundary, the exergy method used in this study also considers the destructions at this stage. Within this framework it is possible to distinguished many sources (e.g. electricity, natural gas, and district energy), and external supplies (gas, oil, renewables), which gives a more robust understanding of the impact of different primary energy sources used for buildings and its systems. Hence, the exergy supplied to the system is calculated as follows:

$$Ex_{tot,input}(t_k) = \sum_i [\frac{En_{gen,i}(t_k)}{\eta_{gen,i}(t_k)} * F_{p,source,i} * F_{q,source,i}], \quad (3)$$

where, En_{gen} is the energy source used by the building HVAC generation system (chiller, boiler, CHP), η_{gen} is the system efficiency, $F_{p,source}$ and $F_{q,source}$ is the is the UK primary energy factor [24] and quality factor[1] of the fuel [10], respectively. These factors are shown in Table 1. Therefore, the annual exergy efficiency ψ_{total} of each case is calculated by dividing (2) over (3) and the total exergy destructions $\dot{Ex}_{dest}$ by subtracting (2) from (3). These outputs only account for space conditioning (heating and cooling end-uses). Exergy use and destructions at lighting, equipment, catering or DHW were not considered. Another limitation is that only thermal exergy is considered, neglecting the effect of chemical and mechanical exergy.

Table 1. Primary energy factors and quality factors of different energy sources.

Energy source	Primary energy factor (F_p) [kWh/kWh]	Quality factor (F_q) [kWh_ex/kWh_en]
Natural gas	1.112	0.94
Electricity (Grid supplied)	2.58	1
District Energy[2]	1.112	0.94

2.1.2. Multi objective optimization (Genetic algorithm)

Prior to conducting the optimization problem analysis, a retrofit module which considers all the variables that will be changed to our baseline models was developed. In this case, several EnergyPlus files (.idf) that account for each one of the retrofit measures were developed. These files are handled for simulation by the software jEPlus [25]. JEPlus is an open source tool that initially was created to manage complex parametric studies, having the possibility to run full-factorial studies in EnergyPlus.

To merge the energy/exergy analysis module with the multi-objective algorithm, a link to jEPlus + EA [26] was developed. The tool has the possibility to tackle multi-objective optimization by using a non-dominated Sorting Genetic Algorithm (NSGA-II). This is a stochastic method that imitates the evolution of species described by Charles Darwin. This algorithm works with a set of individuals, which can represent possible solutions of the problem. In this case the individuals are the different building models previously created. Each of these individuals (or chromosomes) are composed by a set of genes, in our case by the different building parameters or retrofit measures. The selection of individuals was undertaken through the application of the "survival of the fittest" principle [27], which selects the building models that are closer to our objective functions. These "genes" often go through the next generation, so similar models will be evaluated. For more variability among models, other recombination processes occur such as crossover and mutation. This is done to drive better solutions to the next generation by avoiding the algorithm to focus only on a limited number of parameters. A limitation of GA optimization can be the high computation time requirement where the proper design of the experiment is essential for the success. In this type

[1] The quality factor of a fuel is the relationship between the exergy content in one unit of energy

[2] The District system was assumed to be run by a single-effect indirect-fired absorption chiller with a coefficient of performance (COP) of 0.7.

of problems, due the competitive nature of different objectives is not possible to obtain only one solution but a wide range of non-dominated solutions given by the Pareto optimal results.

2.1.2.1. Decision variables (retrofit measures)

A module that encompasses a variety of retrofit measures applied to UK non-domestic buildings was created to build different scenarios that would be analysed at an individual and aggregated level. Based on this approach, different refurbishment measures were developed at each level of the energy supply system (Table 2.).

Table 2. Retrofit measures considered in the optimization project.

Retrofit Measure	Type/Technology Description	Values
Wall and roof insulation	•Cellular glass •Expanded polystyrene •Glass fibre (organic bonded) •Insulation board	Thickness: From 0.01m to 0.15m in 0.01m intervals *U-values range (W/m²K): 2.1 to 0.15*
Glazing	•Double Glazed (6mm glazing) •Triple Glazed (6mm glazing)	Air filled (6mm and 13mm) Argon filled (6mm and 13mm) Krypton filled (6mm and 13mm) *U-values range (W/m²K): 5.7 to 0.5*
Infiltration	•An hypothetically sealing of cracks, joints and holes	Air change rate (ach): *From 0.1ach to 1.1ach in 0.1ach intervals*
Lighting and Equipment	•Retrofit to a more efficient equipment e.g. From LF T8 to LF T5, or LF T8 to Led T8.	Lighting levels (W/m²): *17, 12, 10, 8, 5* Equipment levels (W/m²): **20, *15, 10,*8, 5,*4*
Heating/Cooling setpoint (classrooms/working areas)	•Heating setpoint •Cooling setpoint	Heating (°C): *22,21,20,19,18* Cooling (°C): *23,24,25,26*
Emission systems	•CAV* •VAV* •VRF* •MT Radiators (60/30)° •LT Radiators (35/25)°	
Generation system	•Condensing Boiler° •Air Source Heat Pump •Ground Source Heat Pump •District Heating/Cooling	

*Only considered for the office case
°Only considered for the school case

2.1.2.2. Objective functions

MOO was used to optimize the selection of retrofits and for this study to specifically minimize three objectives: the whole-building energy use intensity, discomfort hours, and the normalized exergy destructions for space conditioning:

$$F_1(x)\,min = \frac{Total\ annual\ building\ energy\ use}{Total\ building\ floor\ space}\ , \quad (4)$$

$$F_2(x)min = \ Occupants\ discomfort\ hours^3, \quad (5)$$

$$F_3(x)min = \ \{\textstyle\sum_i [\frac{En_{\,gen,i}(t_k)}{\eta_{gen,i}\,(t_k)} *\ F_{p,source,i} *\ F_{q,source,i}]\} - \{F_{q,building} * \textstyle\sum_i\ [Q_i\,(t_k)]\}, \quad (6)$$

No constraints in the building parameters or in the modelling outputs were considered.

[3] Given by the ASHRAE Standard 55-2004 [28]. It shows the amount of uncomfortable hours for each zone under the criteria of assuming both summer and winter clothes (0.5 Clo and 1.0 Clo respectively). These are based on whether the humidity ratio and the operative temperature are within region.

3. Case Study

3.1. Archetypes

The two building archetypes used included a primary school and an air-conditioned office building. These were based on data sources and a methodology developed as part of a pilot study [29]. For this study the multi-zone models were simplified. The primary school consist of 3 main thermal zones (common areas, ground floor classrooms and first floor classrooms). Space conditioning is provided by means of conventional gas boiler and high temperature radiators (80°C/60°C) with no heat recovery. The office case consists in an open-plan layout based on 6 thermal zones spread over three stories (common areas and working areas). Heating is provided by a gas boiler and cooling is provided by a chiller. The emission system is composed by Constant Air Volume (CAV) fan-coil units. Both physical models can be seen in Fig. 2. The most important baseline parameters, mainly based on CIBSE guides can be seen in Table 3. The calibration of the models was supported with the comparison against an analysis made on 73,160 Display Energy Certificates (DEC) of non-domestic buildings located in England and Wales based on a robust statistical exercise [30]. The weather data file, and thus the reference temperature for exergy analysis, is based on the London-Gatwick TMY2 file.

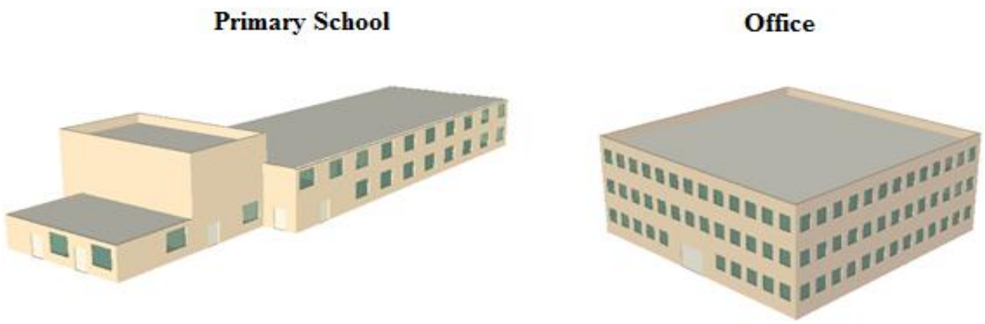

Fig. 2. A UK primary school and an office building archetype models.

3.1.1. Baseline results

Baseline outputs were obtained for both models. The results show different end-use patterns, especially because of the office cooling demand in summer months (Fig 3). The school's EUI (one of the optimization objectives) was found at 211.6 kWh/m²-year; with gas as the main energy source (76.5%). By end-use, heating represents 52.2% of the total demand, followed by lighting (15.9%) and DHW (15.5%). In the case of the office, the EUI was found at 272.8 kWh/m²-year with similar demands for gas and electricity (gas: 52.2%, electricity: 47.8%). The main end-use was heating (47.2%) followed by interior equipment (21.1%) and lighting (14.62%). A detailed energy use by month can be seen in Fig. 3.

Table 3. Baseline characteristics for the primary school and A/C office archetypes.

Building and system Characteristics	Primary School	A/C Office
Floor area (m²) - floors	2180 - 2	2700 - 3
External wall (W/m²K)	2.1	2.1
Roof (W/m²K)	1.99	1.99
Ground floor (W/m²K)	1.42	1.42
Glazing (W/m²K)	5.7	5.7
Infiltration (ach)	1.1	1.1
Glazing (%)	30%	30%
Lighting load avg. (W/m²)	12	12
Misc. Load avg.(W/m²)	5	15
HVAC System	*Gas Boiler*	*Gas Boiler and Chiller*
Main energy sources	Natural Gas	Natural Gas and Electricity
Heating Design Efficiency	0.8	0.8
Cooling Design Efficiency/ COP	n/a	2.5
Heating/Cooling Supply temperatures (°C)	80/no cooling	80/5
Emission System	Radiator HT	Fan Coil (CAV)
Heating/Cooling Return Temp (°C)	60/no cooling	60/13

The second objective, the non-comfortable hours, was found at 1,952 hours per year for the school building. This was considering all the analyzed zones (classrooms, offices and common areas). Evening activities, summer time activities and staff working hours were also considered. For the office was found at 2,861 hours. Finally, the normalized exergy destructions were found at 130.3 kWh/m2-year (ψ: 1.7%) and 213.6 kWh/m2-year (ψ: 1.4%) for the school and office, respectively.

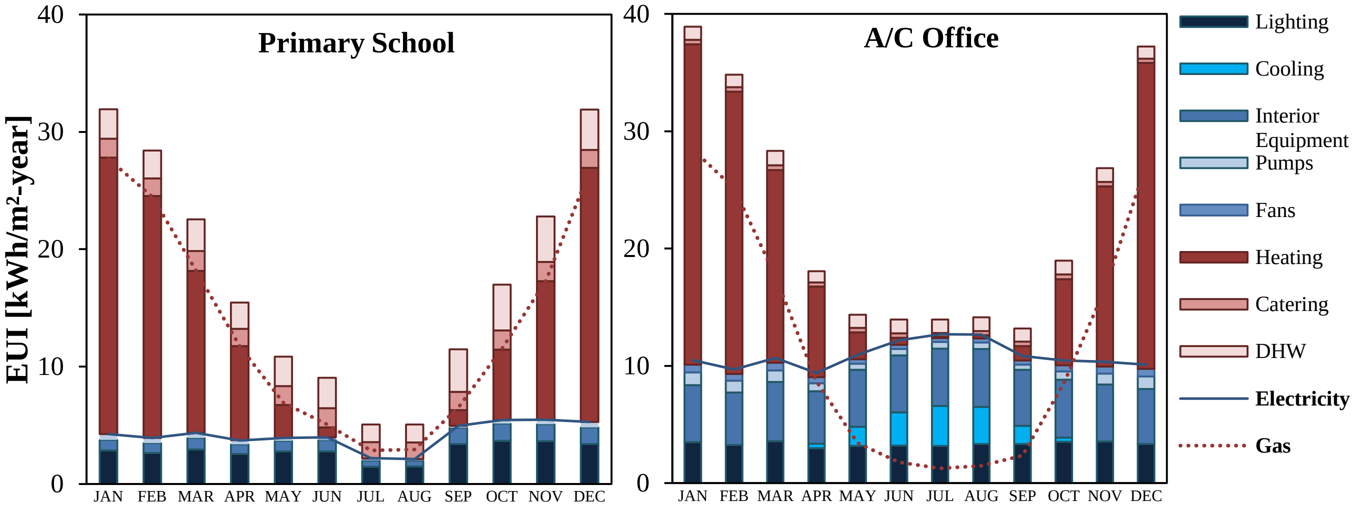

Fig. 3. Monthly Energy Use Indicators by end-uses for the baseline models. In red colors gas based end-uses. In blue colors electricity based end-uses.

4. Results and Analysis

4.1. Impact of different insulation materials

To study the full interaction, 60 simulations were performed for each building model. For the school case, with 0.15m of insulation board on walls and roofs, input energy reductions up to 34% (Fig.4) and an improvement of 25% (480 hours) in occupant comfort were achieved. For the office, the maximum reduction in energy use was given by the same measure, but only achieving 11% of savings and 15.3% of thermal comfort improvement. The lower energetic savings was due to an increasing demand on electricity to cover the higher cooling loads in summer time.

Finally, exergy destructions can be reduced up to 64.7% (Fig.4) and 15.7% for the school and office, respectively. In the school case the reduction was much higher thanks to a much lower input of fossil fuels, meanwhile in the office case higher reductions were not achieved due to increased consumption of electricity, a source with a high primary energy factor.

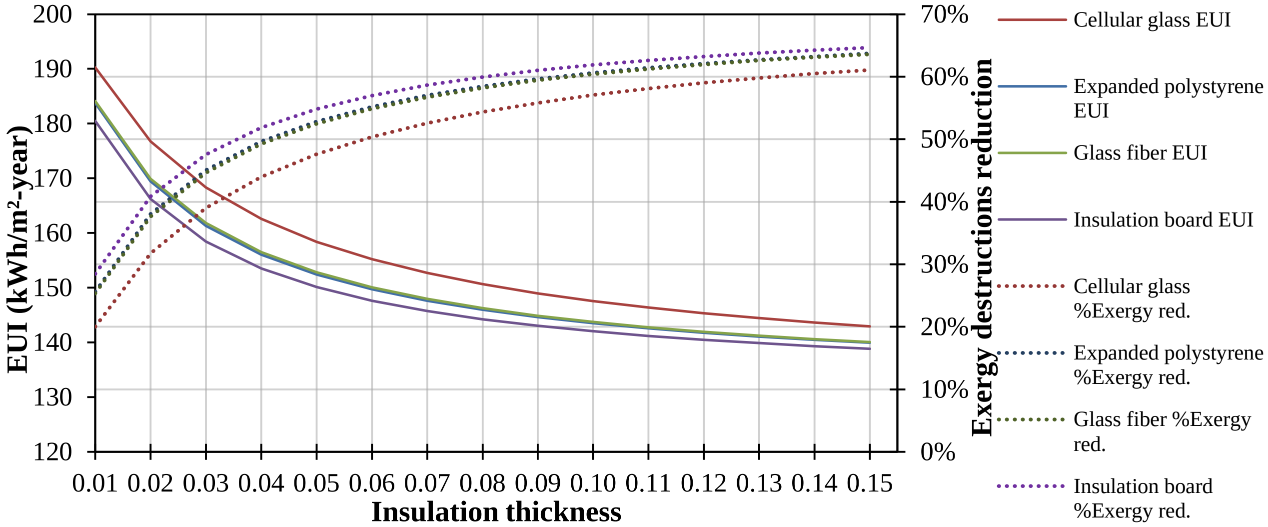

Fig. 4. Impact of different insulations types and different thickness on energy use and exergy destructions. Primary school case study.

4.2. Impact of different HVAC systems

A further parametric analysis was performed by combining the insulation material with the best performance (insulation board) and six different HVAC configurations. From the insulation analysis, two thicknesses were considered: 0.03m and 0.07m (since thicker values have no significant impacts on the analysed objectives).

For the school case, at an insulation level of 0.03m combined with a Ground Source Heat Pump (GSHP), it was possible to achieve a reduction of 38.5% in energy use, with a 16% improvement in occupant comfort. The highest exergy destruction minimization (60.4%) was obtained with the condensing boiler with a low-temperature emission system (35ºC supply/25ºC return) configuration. With an insulation of 0.07m, both the district heating system and the GSHP reached an energy reduction of 39%, but the latter achieved higher comfort improvements (22%). For exergy destructions the district system reached the maximum reduction of 68%.

For the office model at insulation level of 0.03m, the GSHP configuration achieved the maximum energy savings reductions (45.9%) and the highest exergy destructions reductions (62.3%); but only reducing discomfort hours by 8.1% of the baseline. The configuration that achieved better thermal comfort levels was the air source heat pump (ASHP), with an improvement of 38.0%. At an insulation level of 0.07m the results were similar, with the GSHP achieving the greatest reduction in energy use and exergy destructions (46.1% and 61.7%, respectively), and the ASHP configuration reducing discomfort by 43.4%. These results can be seen in Fig.5.

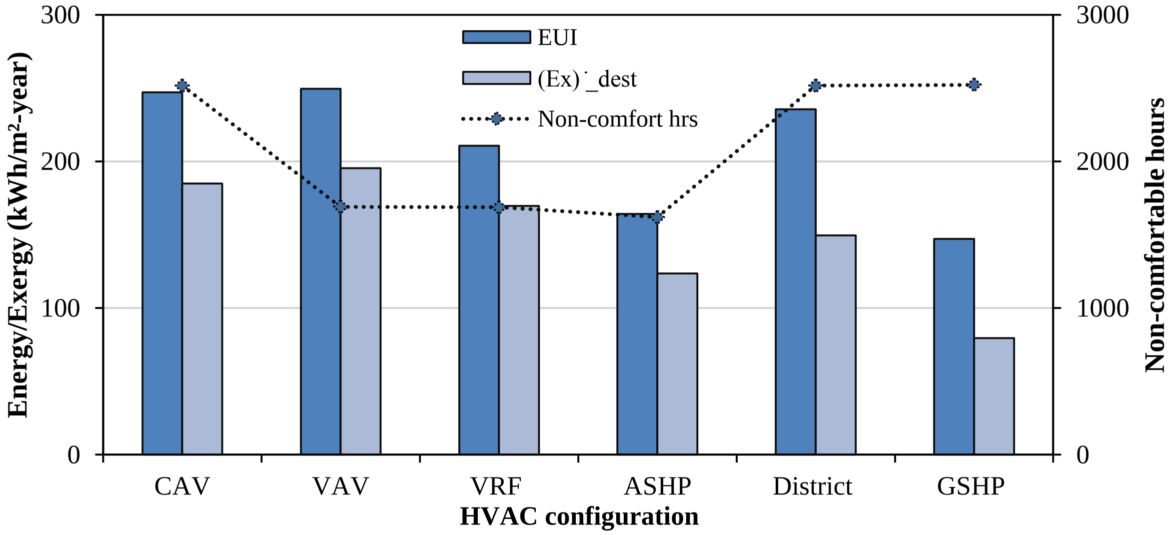

Fig. 5. Impact of different HVAC configurations on energy, exergy destructions, and comfort levels. Office case study with 0.07m of insulation board.

4.3. Combinational effect of retrofits on energy/exergy demand

It becomes impractical and time consuming to study the impact of more configurations and combination between retrofit measures. The application of the parametric approach often requires a large number of simulations, and the time is a critical factor in any real project. As expected, the search space (all possible retrofit combinations) for the school and the office building were at 6,435,000 and 32,175,000 models, respectively. In a 4-core laptop it will take 14 years to run the school project, and 428 years to run the office case study. The use of an optimization algorithm drastically reduces the number of energy simulations needed to at least achieve close to optimal results. After 80 hours of simulation, we were able to perform 3,574 and 3,105 simulations for the school and office, respectively. This is less than 1% of the entire search space. In a multi-objective analysis, several "optimal" solutions are obtained as a single solution that simultaneously optimizes each objective doesn't exist. In Fig. 6 and Fig. 7, for the school and the office respectively, a comparisson is shown between all the simulated solutions and the non-dominated Pareto optimal solutions found by the model. The Pareto solution is a series of solutions that depending on the weighting factor of each objective function, an optimal solution can be reached. The "Pareto space" is made by 111 possible solutions for the school, and by 65 solutions for the office case. Infiltration (ach) is taken as the colour range to illustrate the combined impact of this parameter on the three objectives. For both cases it can be seen the impact of a tighter building in a "temperate" climate as London (UK). Although as the office case suggests, overheating in summer months is a factor that needs further consideration.

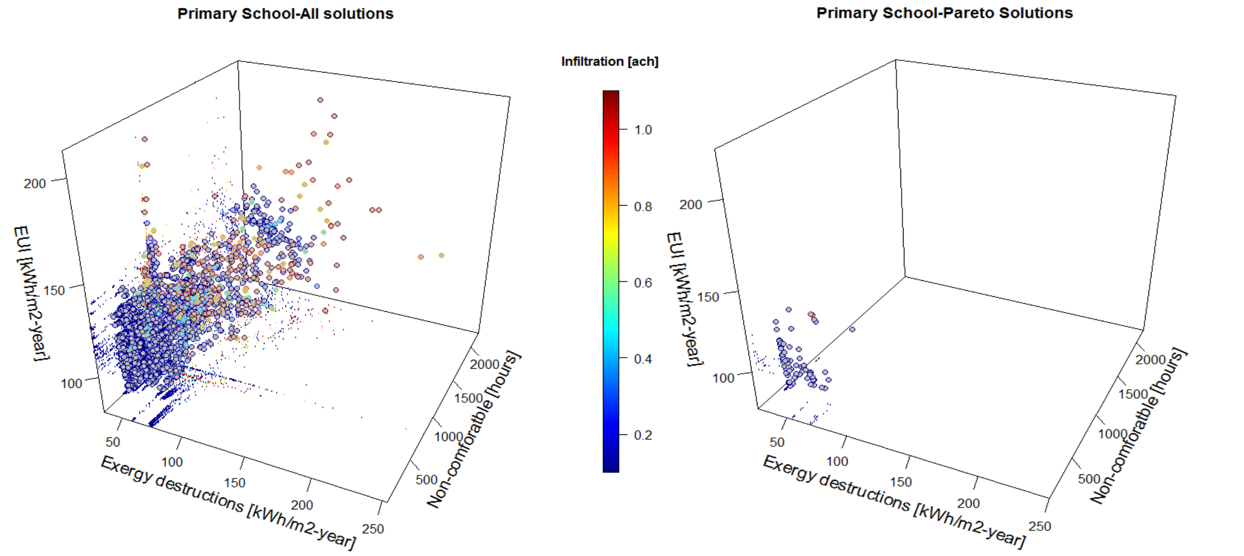

Fig. 6. Results of the multi-objective optimization and the Pareto optimal solutions. Primary school

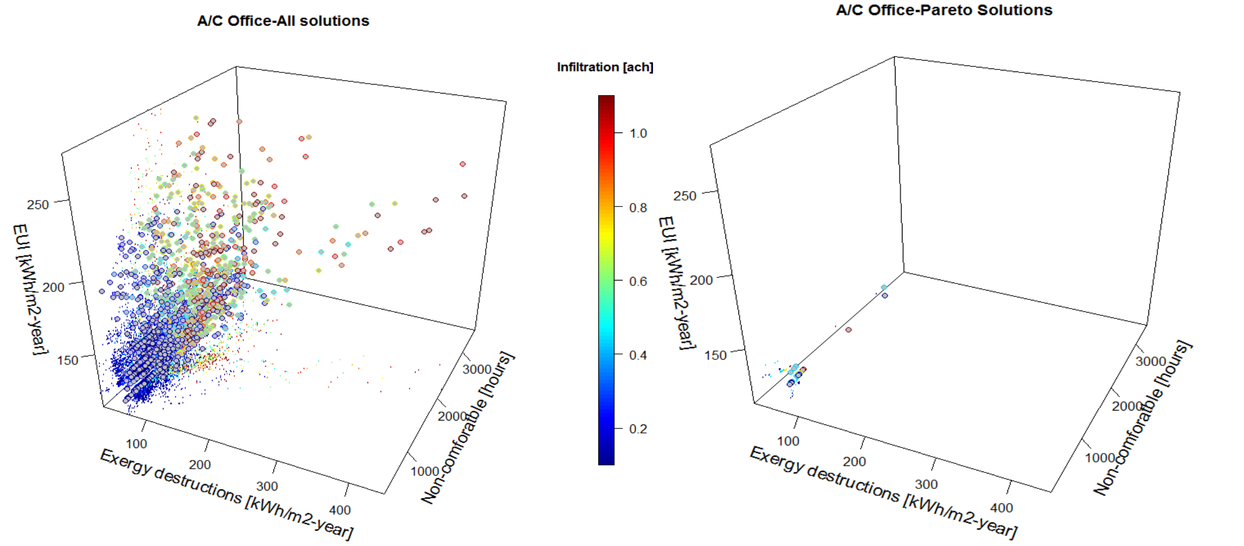

Fig. 7. Results of the multi-objective optimization and the Pareto optimal solutions. Office building

These "Pareto solutions" represent major improvements of the objectives with respect on the baseline and the insulation and HVAC parametric studies. All the Pareto solutions can be considered "equally good", where the decision maker can make a choice depending on the importance given to each one of the objectives. Table 4 (School) and Table 5 (Office) show the scenarios when an individual objective is considered to have all the weight with no attention to the other two. The reduction percentage of each objective with respect to the baseline can be seen inside parentheses. The results shows that measures such as triple glazed windows systems, high insulation thickness, low infiltration levels (0.1 and 0.2 ach) and heat pumps systems dominate the best solutions. Similarities in the outputs can be noted between energy use and exergy destructions; on the other hand the competitive nature of thermal comfort with the first two is noticeable in some parameters, especially the heating/cooling setpoint parameters. A big limitation of the study is that cost of equipment and energy/exergy saving cost was not considered. These objectives would change the solution space dramatically, as cost is one of the most competitive objectives in relationship with energy use and thermal comfort.

Table 4. Best solution by objective function discovered in the Pareto front. Primary school case.

Objective	**EUI [kWh/ m2-year]**	**Non-comfort [hrs]**	**Exergy dest. [kWh/ m2-year]**	Type of Insulation [-]	Insulation thickness [m]	Infiltration [ach]	Glazing [glass-gap-glass, in mm]	HVAC [-]	Light. Power [W]	Equip. power [W]	Heating Setpoint [°C]	Cooling Setpoint [°C]
[min] EUI	**79.2 (62.6%)**	1,185 (39.2%)	34.7 (73.4%)	Insulation board	0.15	0.1	Triple Glazed Krypton (6-6-6)	ASHP	5	4	18	-
[min] Non-comfort	114.3 (46.0%)	**60 (96.9%)**	74.9 (42.5%)	Insulation board	0.15	0.1	Triple Glazed Argon (6-13-6)	ASHP	12	5	22	-
[min] Exergy destructions	99.3 (53.0%)	698 (64.2%)	**34.5 (73.5%)**	Cellular glass	0.06	0.1	Triple Glazed Air (6-13-6)	ASHP	5	10	19	-

Table 5. Best solution by objective function discovered in the Pareto front. A/C Office.

Objective	**EUI [kWh/ m2-year]**	**Non-comfort [hrs]**	**Exergy dest. [kWh/ m2-year]**	Type of Insulation [-]	Insulation thickness [m]	Infiltration [ach]	Glazing [-]	HVAC [-]	Light. Power [W]	Equip. power [W]	Heating Setpoint [°C]	Cooling Setpoint [°C]
[min] EUI	**110.0 (59.7%)**	2,784 (2.7%)	43.6 (79.6%)	Cellular glass	0.14	0.1	Triple Glazed Air (6-6-6)	GSHP	5	15	18	26
[min] Non-comfort	121.3 (55.5%)	**333 (88.4%)**	70.0 (67.2%)	Insulation board	0.13	0.1	Triple Glazed Krypton (6-6-6)	ASHP	5	10	21	23
[min] Exergy destructions	111.1 (59.3%)	2,960 (-3.4%)	**29.2 (86.3%)**	Expanded polystyrene	0.14	0.2	Triple Glazed Argon (6-13-6)	GSHP	5	5	19	26

5. Conclusions

At first, we showed a typical parametric process by exploring the impact of different types of insulation and HVAC configurations, showing that although this process leads to improvements it is time consuming. By following the proposed exergy-based multi-objective optimization method, major improvements (close to optimal) were achieved regarding the big space search. This method can provide more information than the typical optimization methods based solely on energy analysis. The aim of implementing this model was to find the optimal retrofit measures by minimising energy use, exergy destructions and thermal discomfort. Also, two case studies were considered that showed the complexity and variability of building types in the UK non-domestic sector. As expected, optimal results for the London climate without considering any economic constraints are dominated by measures such as triple glazing, heat pumps systems while having a very tight envelope. One of the Pareto solutions for the school model exhibited energy use reduction of 53% and exergy destructions minimization of 73.5% while improving 64.2% occupant thermal comfort. For the office it was possible to reduce 55.5% of energy input, 67.2% of exergy destructions, and 88.4% of discomfort.

High uncertainties on the outputs exist because of the nature of building simulation tools, exergy analysis (e.g. reference environment) and the lack of empirical data. The model application in real project will determine its robustness and limitations. More model runs of the same projects are required to avoid results that can be obtained due to a hypothetical early convergence of the algorithm. Also, as mentioned before, the biggest limitation of the study is that the cost objective function was not considered, an objective that would radically change the optimal solutions obtained in this research. Further work contemplates the development of a thermoeconomic module by considering the exergy cost, cost of retrofits (information on capital investment and operating cost of technologies*)* and cost of fuels. Also, it is recommended to consider a Life Cycle Analysis (LCA) of exergy destructions at the production stage of equipment and materials; especially for thermal insulations, which typically requires large amounts of exergy for manufacturing.

Acknowledgments

The first author acknowledges support from The Mexican National Council for Science and Technology (CONACyT) through a scholarship to pursue graduate studies.

Nomenclature

En_{gen} energy demanded by the generation system
Ex_{dem} hourly exergy demand, kW
$\dot{Ex}_{dest}$ exergy destructions, kW
$\dot{Ex}_{total,in}$ average exergy input, kW
F_p primary energy factor
F_q quality factor
Q energy demand, kW
T_0 reference temperature, K
T_i room temperature, K

Greek symbols

η_{gen} energy efficiency
ψ_{tot} exergy efficiency factor

Subscripts and superscripts

i ith zone, equipment or energy source

References

[1] DECC, *The Future of Heating: Meeting the challenge*, DECC., Editor 2013: United Kingdom.
[2] DECC, *Energy Consumption in the UK*, DECC, Editor 2014: United Kingdom.
[3] Clarke, J.A., et al., *The role of built environment energy efficiency in a sustainable UK energy economy.* Energy Policy, 2008. 36(12): p. 4605-4609.

[4] CarbonTrust, *Technology Innovation Needs Assessment (TINA). Non-Domestic Buildings*, 2012, Low Carbon Innovation Coordination Group: United Kingdom.

[5] Siddharth, V., et al., *Automatic generation of energy conservation measures in buildings using genetic algorithms.* Energy and Buildings, 2011. 43(10): p. 2718-2726.

[6] Hammond, G.P. and A.J. Stapleton, *Exergy analysis of the United Kingdom energy system.* Proc. of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2001. 215(2): p. 141-162.

[7] Shukuya, M., *Exergy concept and its application to the built environment.* Building and Environment, 2009. 44(7): p. 1545-1550.

[8] Gasparatos, A., M. El-Haram, and M. Horner, *Assessing the sustainability of the UK society using thermodynamic concepts: Part 2.* Renewable and Sustainable Energy Reviews, 2009. 13(5): p. 956-970.

[9] ECB-Annex37, *Technical Synthesis Report: Low Exergy Systems for Heating and Cooling of Buildings, IEA ECBCS*, R. Jagpal, Editor 2007: UK.

[10] ECB-Annex49, *Detailed Exergy Assessment Guidebook for the Built Environment, IEA ECBCS*, H. Torio and D. Schmidt, Editors. 2011, Fraunhofer IBP.

[11] Jansen, S.C., J. Terés-Zubiaga, and P.G. Luscuere, *The exergy approach for evaluating and developing an energy system for a social dwelling.* Energy and Buildings, 2012. 55(0): p. 693-703.

[12] Favrat, D., F. Marechal, and O. Epelly, *The challenge of introducing an exergy indicator in a local law on energy*. Energy, 2008. 33(2): p. 130-136.

[13] Asadi, E., et al., *Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application.* Energy and Buildings, 2014. 81(0): p. 444-456.

[14] Diakaki, C., E. Grigoroudis, and D. Kolokotsa, *Towards a multi-objective optimization approach for improving energy efficiency in buildings.* Energy and Buildings, 2008. 40(9): p. 1747-1754.

[15] Attia, S., et al., *Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design.* Energy and Buildings, 2013. 60(0): p. 110-124.

[16] Nguyen, A.-T., S. Reiter, and P. Rigo, *A review on simulation-based optimization methods applied to building performance analysis.* Applied Energy, 2014. 113(0): p. 1043-1058.

[17] Asadi, E., et al., *Multi-objective optimization for building retrofit strategies: A model and an application.* Energy and Buildings, 2012. 44(0): p. 81-87.

[18] Malatji, E.M., J. Zhang, and X. Xia, *A multiple objective optimisation model for building energy efficiency investment decision.* Energy and Buildings, 2013. 61(0): p. 81-87.

[19] Ahmadi, P., I. Dincer, and M.A. Rosen, *Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants.* Energy, 2011. 36(10): p. 5886-5898.

[20] Kaviri, A.G., M.N.M. Jaafar, and T.M. Lazim, *Modeling and multi-objective exergy based optimization of a combined cycle power plant using a genetic algorithm.* Energy Conversion and Management, 2012. 58(0): p. 94-103.

[21] EnergyPlus, *Getting Started with EnergyPlus. BasicConcepts Manual*. The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory., 2012: p. 73.

[22] Schmidt, D., *Methodology for the Modelling of Thermally Activated Building Components in Low Exergy Design*, in *Civil and Architectural Engineering*, 2004, Kungliga Tekniska Högskolan: Sweden.

[23] Angelotti, A., P. Caputo, and G. Solani, *Dynamic exergy analysis of an air source heat pump.* 1st International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium, 2009: p. 8.

[24] Pout, C.H., *Proposed Carbon Emission Factors and Primary Energy Factors for SAP 2012*, in *Techical papers supporting SAP 2012*, BRE, Editor 2011: UK.

[25] Zhang, Y. and I. Korolija, *Performing complex parametric simulations with jEPlus*, *9th International Conference on Sustainable Energy Technologies*, 2010: Shanghai, China.

[26] Zhang, Y., *Use jEPlus as an efficient building optimisation tool*, in *CIBSE ASHRAE Technical Symposium*2012: Imperial College, London UK.

[27] Spencer, H., *Principles of Biology*, 1864, vol. 1, p. 444

[28] ASHRAE, *ANSI/ASHRAE Standard 55-2004. Thermal Environmental Conditions for Human Occupancy*, R.a.A.-c.E. American Society of Heating, INC, Editor 2004.

[29] Garcia Kerdan, I., R. Raslan, and P. Ruyssevelt, *Dynamic exergy simulation coupled with thermoeconomic analysis to support retrofit decisions in non-domestic buildings*, in *9th International Conference on System Simulation in Buildings* 2014: Liege, Belgium.

[30] Hong, S. and P. Steadman, *An analysis of Dispaly Energy Certificates for Public Buildings, 2008 to 2012*, CIBSE, Editor 2013, UCL Energy Institute.