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# An exergy-based multi-objective optimisation model for energy retrofit strategies in non-domestic buildings

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While the building sector has a significant thermodynamic improvement potential, exergy analysis has been shown to provide new insight for the optimisation of building energy systems. This paper presents an exergy-based multi-objective optimisation tool that aims to assess the impact of a diverse range of retrofit measures with a focus on non-domestic buildings. EnergyPlus was used as a dynamic calculation engine for first law analysis, while a Python add-on was developed to link dynamic exergy analysis and a Genetic Algorithm optimisation process with the aforementioned software. Two UK archetype case studies (an office and a primary school) were used to test the feasibility of the proposed framework. Different measures combinations based on retrofitting the envelope insulation levels and the application of different HVAC configurations were assessed. The objective functions in this study are annual energy use, occupants' thermal comfort, and total building exergy destructions. A large range of optimal solutions was achieved highlighting the framework capabilities. The model achieved improvements of 53% in annual energy use, 51% of exergy destructions and 66% of thermal comfort for the school building, and 50%, 33%, and 80% for the office building. This approach can be extended by using exergoeconomic optimisation.



## 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 is responsible for 17% of the country's total energy use and is highly dependent on fossil fuels (60% gas, 10% oil, and 25% non-renewable electricity) [1]. 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 controls, and poor occupant energy awareness and comfort levels [3]. Also, the expansion of HVAC systems in new and existing buildings represent higher energy usage rates every year, mainly driven by the constant increasing of cooling demands. 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, 80% 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.

Currently in the UK, there are a wide range of building energy codes and programmes that encourage the implementation of ERMs on existing buildings by setting minimum values for energy efficiency. For example, Part L2B [5] sets minimal envelope insulation levels when retrofits actions are implemented in existing non-domestic buildings. Moreover, a number of financial mechanisms have been introduced in an aim to drive down demand and improve efficiency (e.g. Climate Change Levy, CRC Energy Efficiency Scheme, ESOS). In addition, policies to support the implementation of low carbon HVAC systems have been developed (Energy Labelling Directive, Renewable Heat Incentive), where technologies such as biomass boilers, heat pumps, and solar thermal equipment are widely supported. Other example at a European level is the recast of

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the Energy Performance of Buildings Regulations [6]. The directive took effect in 2013 and among the articles; it sets minimum energy performance requirements on all renovated buildings (Article 7) as well as minimum energy performance on energy systems retrofits (Article 8). The directive seeks that ERMs projects should aim to achieve a trade-off between energy saving and cost-effectiveness.

## 2. Background

### 2.1. Simulation-based tools and optimisation of ERMs

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 with any energy system, buildings are physically complex systems 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 play a major role in the design of energy efficient buildings [7]. The use of simulation tools for ERMs represents a quick and cost-effective method to estimate pre and post retrofit energy use of a building. Although building simulation tools lack direct orientation to retrofit analysis, the outputs can be used in life cycle cost analysis tools to calculate energy and cost savings in the future. Too overcome this, several retrofit oriented tools have been developed in the last decade. Hong [8] provided a review of 18 retrofit toolkits categorized in three kinds of methods: a) empirical data driven, b) normative calculations, and c) physics-based modelling. The latest provide the highest fidelity but with the drawback of being more complex because of the need of more input data and longer simulation times. These tools commonly use as the main energy calculation engine open source tools such as DOE 2.2 [9] and EnergyPlus [10]. Among the most recent developments are ROBESim [11], CBES [12] and SLABE [13]. On the other hand, Rysanek and Choudhary [14] developed an exhaustive retrofit simulation tool using TRNSYS [15] and MatLab [16]; the tool is capable to simulate a large set of building retrofit strategies under economic uncertainty.

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) [17]. However, in practice the method presents the limitation that is computationally and time expensive. 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 [18]. Finally, an approach that has shown potential to explore large search spaces in an efficient manner is multi-objective optimisation (MOO). Three basic types of algorithms are used in optimisation problems applied to buildings: enumerative, deterministic, and stochastic [19]. As Nguyen et al. [20] claims, stochastic methods are widely used, being genetic algorithms the most popular method for building optimisation. Other popular methods are Direct Search, Simulated Annealing, and Particle Swarm optimisation [21]. Attia et al. [19] found that MOO methods are normally used during early designs as researchers and practitioners that use optimisation techniques applied 93% of the cases for new buildings. However, some studies have demonstrated the strength of MOO for retrofit projects [7,22,23]. Improvement of the envelope, HVAC equipment, renewable generation, controls, etc., while optimising objectives such as energy savings, occupant comfort, total investment, and life cycle cost has been investigated.

### 2.2. The use of exergy analysis for buildings

However, the aforementioned building energy regulations, modelling tools and optimisation procedures usually only follow the first law of thermodynamics. Energy analysis typically shows similar efficiencies between different systems configurations, so it has significant limitations when it comes to assess the characteristics of energy conversion systems. It also struggles to pinpoint exact locations where inefficiencies are taking place through the whole energy supply chain. As Hammond and Stapleton [24] and Shukuya [25] showed, the majority of the buildings are thermodynamically inefficient, hence have a significant potential for improvement. These inefficiencies are related to the concept of exergy (energy quality or potential to do work), and where unlike energy which is conserved, exergy is exposed to destructions. In the buildings' energy supply chains, these destructions are mainly caused from combustion and heat exchange processes derived from a poor quality match between the supply and the demand. By destroying exergy, useful work that could be useful for other higher quality processes (e.g. industrial, transport, and chemical) is wasted. Inefficient and unwise use of resources can significantly impact national energy security [26]. Among all economic sectors in the UK, the building sector has the highest potential to improve its thermodynamic efficiency (Fig. 1), and among end-uses, space conditioning processes present the lowest efficiencies (>6.5%) [27].

In recent years, the extent of research and application of exergy analysis in buildings has significantly increased, mainly supported by two IEA Energy in Buildings and Communities Programme Annexes [28,29]. 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. Some research has demonstrated how primary energy input into buildings can be reduced by the application of different principles based on exergy, such as

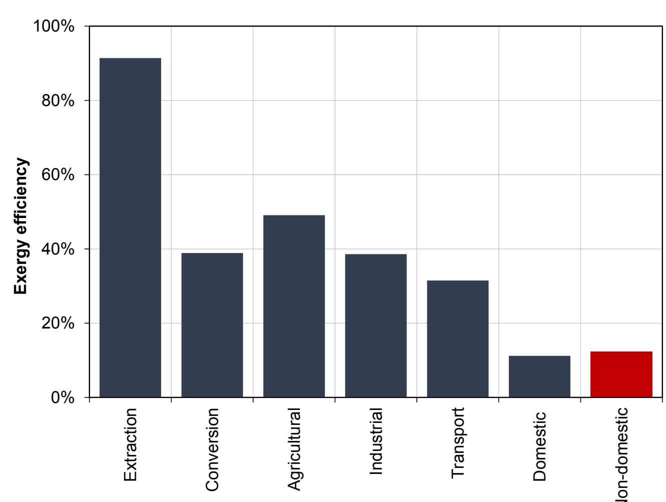


**Fig. 1.** Exergy Efficiency in different UK sectors.
Source: [27]

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