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A review of computational optimisation methods applied to sustainable building design

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ABSTRACT

This paper presents a comprehensive review of all significant research applying computational optimisation to sustainable building design problems. A summary of common heuristic optimisation algorithms is given, covering direct search, evolutionary methods and other bio-inspired algorithms. The main summary table covers 74 works that focus on the application of these methods to different fields of sustainable building design. Key fields are reviewed in detail: envelope design, including constructions and form; configuration and control of building systems; renewable energy generation; and holistic optimisations of several areas simultaneously, with particular focus on residential and retrofit. Improvements to the way optimisation is applied are also covered, including platforms and frameworks, algorithmic comparisons and developments, use of meta-models and incorporation of uncertainty. Trends, including the rise of multi-objective optimisation, are analysed graphically. Likely future developments are discussed.

Contents

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1. Introduction

1.1. Sustainable building optimisation

Energy used in buildings for heating, cooling and lighting comprises up to 40% of the carbon emissions of developed countries [1]. Buildings are the sector with the greatest potential and lowest cost for carbon reductions [2]. There are many regulatory and certification incentives to make buildings more sustainable, including national building regulations, the EU Energy Performance of Buildings Directive (EPBD), BREEAM and LEED assessments and local planning policies. Computational simulation allows the energy used by proposed building designs to be quantified. This involves thermal, solar and air flow modelling and concerns the geometry, materials, control and systems of the building [3].

However, the design of sustainable buildings is not straightforward. All buildings are unique, and there are no prototypes. Designs must achieve high levels of performance for the lowest possible cost. There are many physical processes that lead to conflicting objectives. The design space of possible solutions is very large. These challenges have made it advantageous to apply computational methods of design optimisation.

1.2. This review

An initial search for relevant works was conducted using Google Scholar with search terms including 'sustainable', 'energy', 'carbon', 'building' and 'optimisation'. Further searches were then conducted in the archives of the journals and conference proceedings identified. (Conference papers are included unless a similar journal paper exists, in which case it is given in preference). Papers cited by works found were also checked for relevance. From this broad search, articles were selected for inclusion in the main summary, Fig. 1, on the following basis:

- All areas of sustainable building design (e.g. water use) have been included in the search, although the works found are almost exclusively concerned with energy and carbon emissions.
- For technologies used in buildings, works have been included where there is significant information concerning building-level performance. For example, the design of an air conditioning system for a building is included, whereas the design of the coil within an air conditioning unit is not.
- Works must make significant use of computational optimisation. Works which use the term optimisation but perform only algebraic or manual processes (e.g. identifying the minimum via the low point on a graph) are not included, even if computational simulation is used to generate data.
- Works that focus on the optimisation process are not included in the summary (these are addressed separately in a later section).
- Works entirely concerned with dynamic control (including model-based control) are excluded, since this area is distinct from design optimisation, often having more in common with artificial intelligence.
- Only works since 1990 have been included. The final cut-off for inclusion was 1 October 2012.

In the first section of this paper, a brief overview is given for different methods of computational optimisation, including common algorithms. Next, works addressing major areas of sustainable building design are reviewed and discussed, covering: building envelope (including constructions and form); HVAC systems; renewable energy generation; and holistic appraisals that cover several areas. Each section discusses (for the single- and multi-objective cases) common formulations, novel approaches, and other works of interest not included in the main table. The final review section covers improvements to the optimisation process as applied to sustainable building design. The concluding section suggests possible future areas of profitable investigation based on current trends and omissions.

1.3. Previous reviews

Previous reviews have overlapped with elements of this field, though none have brought together all material related to optimisation and sustainable building design. An interesting early appraisal of optimisation and architecture is given in [4]. Gosselin et al. [5] reviewed the application of Genetic Algorithms (and briefly other methods) to heat transfer problems. Regarding energy generation, Baos et al. [6] covered the optimisation of renewable and sustainable energy and Pezzini et al. [7] reviewed optimisation techniques applied to power systems. The related field of multi-criteria decision analysis as an aid to sustainable decision-making was reviewed by Wang et al. [8]. There are numerous reviews of specific fields of building design including control [9], energy efficient design [10], passive design [11], and double-skin facades [12]. Reviews of urban-scale Combined Heat and Power (CHP) systems (i.e. not accounting for building-scale processes) have covered analytical optimisation [13] and economic dispatch optimisation [14]. In the wider area of engineering design optimisation, Roy et al. [15] reviewed methods and Marler and Arora [16] reviewed multi-objective methods.

2. Computational optimisation

2.1. Generic optimisation process

"Optimisation theory encompasses the quantitative study of optima and methods for finding them" - Beightler et al. in [17]. The following is a general mathematical description of the optimisation problem [18]:

Minimise $F(x_1, x_2, \ldots, x_n)$