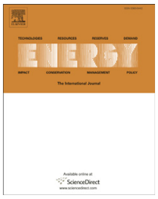
Energy xxx (2015) 1–15

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Multi-level optimization of building design, energy system sizing and operation

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form
24 June 2015
Accepted 2 July 2015
Available online xxx

Keywords:
Multi-level
Multi-objective
Optimisation
Energy hub
Building
Operation

ABSTRACT

Multi-level optimisation divides a problem into sections such that each can be addressed using the most appropriate evaluation and optimisation processes. A methodology is proposed to address the design and operation of a building and its energy system, split into three levels: building design, system design and system operation. The optimisation techniques used are a multi-objective genetic algorithm (design) and mixed-integer linear programming (operation); the evaluation methods used are the building energy simulation program EnergyPlus (building level) and the 'energy hub' model (system level). The objective functions used here were annual carbon emissions and initial capital cost (for the multi-objective design problem) and annual running costs (for the single objective operational problem).

The methods used are described in detail, and the proposed methodology is applied to a case study concerning an office building. The detailed results presented include the trade-off front of optimal design-level solutions, the convergence of the optimisation, trends in the associated design variable values, derived properties of each solution, the operational variable values, and the run-times of the operational optimisation. Conclusions are drawn regarding the case study and the overall approach, and future directions are suggested.

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1. Introduction

1.1. Background

Preventing disastrous levels of man-made climate change, ensuring energy security, providing a sustainable built environment and coping with depletion of fossil fuels are serious issues that must be tackled promptly. Buildings make up one of the largest contributors to this problem, but also offer great potential for improvements. Future sustainable energy systems will help to accomplish this by balancing demand and supply as effectively as possible, either within a building or between many buildings. This will be increasingly important as higher levels of renewable energy generation give fluctuating supplies as well as demands, necessitating storage or conversion to other energy streams. It is also important to account for limitations in the ability of the electricity grid to absorb such fluctuations; achieving net reductions by exporting energy when plentiful and importing when scarce is not practical for lots of buildings.

As such networks get more complicated, it becomes more important to account for details of their operation at the design stage. Conversions between multiple energy streams as well as large storage capacities will give many possible operating modes, so it is no longer possible to state in advance how such a system would be optimally operated. One of the key factors in the '4th generation' of district heating systems is that they will require that planning and design account for detailed operational characteristics [15]. The 'energy hub' concept employed here addresses this by conducting an operational optimisation that determines how energy should best be dispatched to meet demand at each timestep.

Optimisation processes have been applied at the design stage to many aspects of buildings related to energy use [6]. However, they are often limited in scope to building form, fabric, system or other single issues. This means that they cannot identify holistic solutions that exploit synergies between all areas of design. To overcome this a multi-level optimisation process has been used, since different design areas require different simulations to verify their performance. In this work, diverse design variables related to the building

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http://dx.doi.org/10.1016/j.energy.2015.07.007
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Please cite this article in press as: Evins R, Multi-level optimization of building design, energy system sizing and operation, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.07.007

Nomenclature

Θ	energy conversion matrix (dimensions m by k)
A_n^*	storage loss per timestep for store n
A_n^{ch}	charge efficiency of store n
A_n^{dis}	discharge efficiency of store n
$b_m(t)$	binary variable governing activation of plant m
$d_n(t)$	binary variable governing operation mode of store n
$E_n(t)$	contents of store n at time t
E_n^{max}	capacity of storage n
F_j	carbon factor for energy stream j
G_j	coefficients of input stream j in objective function
$I_j(t)$	input of energy on stream j
$I_j^{max}(t)$	available energy on input stream j
I_j^{cap}	capacity multiplier for stream j
I_{wind}^{index}	index of wind turbine model
$L_k(t)$	output energy required for stream k
M	large constant used in ‘Big M’ constraint formulation
$P_m(t)$	operational variables giving the energy through converter m at time t
P_m^{max}	capacity of plant m
P_m^{min}	minimum output of plant m
$Q_n^{ch}(t)$	operational variables giving the energy charged to store n at time t
$Q_n^{dis}(t)$	operational variables giving the energy discharged from store n at time t
t	current timestep
V_b	design variables related to the building
V_p	design variables related to the plant

(fabric insulation, glazing areas, shading thresholds) and systems (capacities for renewable generation, plant and storage) are optimised all together, along with the operation of each proposed system.

1.2. Previous research

An extensive review of multi-objective optimisation applied to a wide variety of problems related to building energy is given in Ref. [6]. Various previous works relating to energy hub design and operation are discussed in Ref. [8], almost all of which either assume a fixed control strategy while optimising design, or assume a fixed design while optimising control. When heuristic methods (e.g. genetic algorithms) are used to optimise building or system design parameters, either the control is fixed (though it may be a complicated control logic [10]) or is optimised over a limited time period (e.g. one design day [17]) due to the poor performance of such methods with many variables. There are many examples of system-level problems being solved using programmatic methods, of which MILP (mixed-integer linear programming) is the most common, either for the dispatch problem alone or for sizing and dispatch together (see Ref. [6]). While this allows many variables (e.g. annual hourly operational values) to be solved, such methods are incompatible with black-box problems, precluding simulation-based building design optimisation.

System selection and sizing optimisation has been combined with building control by Ashouri et al. [1], who developed a framework consisting of many detailed models of storage and converter units linked to a lumped parameter building model. This allowed the building control problem (fluxes supplied to keep temperatures within bounds, based on the building heat balance) to be solved jointly with the energy supply side of the problem. Fux et al. [12] added MPC (model-predictive control) to the problem. They formulated a detailed model of the energy system of a single building, including PV (photovoltaics), battery, CHP (Combined Heat and Power), storage and waste-water treatment, and solved the resulting MILP problem over 1 year. The MPC problem was solved once per day over a 5 day horizon. No building demand simulation or optimisation was included, since measured demand data was used.

Deb and Sinha [4] used the term bi-level optimisation to refer to problems that “require every feasible upper-level solution to satisfy optimality of a lower-level optimization problem”. They have since [18] developed further techniques in this area, including a hybrid evolutionary/local-search method that includes multiple objectives at both levels. Other applications of bi-level methods have used different meta-heuristic algorithms, such as Differential Evolution [14]. Bi-level techniques have been applied to various problems concerning power systems, largely ‘attacker-defender’ formulations that attempt to provide solutions that are robust to disruptive threats [16].

There are few examples of previous research applying bi-level optimisation processes to building-related problems. Weber et al. [20] used a bi-level approach to optimise the design (upper level) and operation (lower level) of a fuel cell system for an office building using a multi-objective evolutionary algorithm and linear programming. Building energy demand was fixed using 24 h profiles of demand for January and August. Fazlollahi and Marechal [11] used a similar approach (but termed master-slave) that combined a multi-objective evolutionary algorithm with local mass and energy balance equations solved using MILP. Building energy demand was fixed using twelve monthly values for heat flux.

1.3. This work

Optimisation in its various forms is a powerful process to aid in the exploration of the design space of a given problem. The aim of the approach taken here is to combine the design-level issues related to the building and plant specifications with the operational-level performance of these systems into one holistic optimisation. The design-level therefore addresses the twin objectives of capital costs (always a key metric for any engineer) and carbon emissions, since these are often subject to regulations or may be needed for environmental certification. At the operational level the objective was running costs, since these are of concern to the tenants or occupants.

This work builds upon the concept of bi-level optimisation of building design and operation presented in previous works [8,7]. This paper extends the previous work by including design variables related to the building fabric as well as the energy system, giving a third level. This also requires the building energy simulation to be integrated as part of the optimisation process rather than pre-calculated. Additionally, simulation and operational optimisation were performed for a whole year (rather than typical weeks, as previously). Wind power is also included as an additional source of renewable energy that exhibits a complex temporal distribution.

It is acknowledged that the operational optimisation conducted in this work is a very detailed way of determining the sequence of plant operations that describe the performance of the energy system in question. In a real building there is insufficient future

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