HVAC-Aware Occupancy Scheduling
(Extended Abstract)

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1 Introduction

Energy consumption in commercial and educational buildings is impacted by group activities such as meetings, workshops, classes and exams, and can be reduced by scheduling these activities to take place at times and locations that are favorable from an energy standpoint. Recent studies show that heating, ventilation and air-conditioning (HVAC) expenditure, which constitutes to 20% of the US total energy consumption, can be significantly reduced by adopting occupancy-based control strategies (PSU 2012). For instance, model *predictive* control strategies determine supply air flow rate and temperature over longer time horizons so as to optimise energy consumption, whilst remaining within air flow and temperature bounds that reflect the predicted occupancy of various building zones (Goyal, Ingley, and Barooah 2013). Another recent research line investigates the *proactive* control of *occupancy* in order to minimise HVAC consumption (Kwak et al. 2013; Majumdar, Albonesi, and Bose 2012; Pan et al. 2012). Unfortunately, existing occupancy scheduling approaches assume conventional HVAC control strategies (Kwak et al. 2013). Moreover, since reasoning using explicit models of the HVAC and the building is computationally expensive, they typically adopt suboptimal scheduling strategies guided by proxies for the optimisation criterion. One such proxy is the minimisation of the number of rooms used and of the time gap between successive meetings; it is used to guide the search towards solutions that take advantage of thermal inertia and schedule meetings to take place back-to-back in as few rooms as possible (Pan et al. 2012; Majumdar, Albonesi, and Bose 2012).

In my thesis, I am designing an integrated approach to HVAC control and occupancy scheduling, which aims at combining the strengths of the above research directions. We improve on the effectiveness of energy-aware room-booking and occupancy scheduling approaches, by allowing the scheduling decisions to rely on an explicit model of the building's occupancy-based HVAC control. A naïve combination would be to schedule occupancy in a first phase using existing methods, and then control HVAC based on this occupancy schedule. In contrast, we model and solve the *joint* HVAC control and occupancy scheduling problem. This re-

sults in an integrated approach whose benefits exceed the naïve superposition of both of its parts, as the scheduling fully exploits the capabilities of the underlying occupancy-based HVAC control across available times and locations. We focus on meeting scheduling, but our model is more broadly applicable to scheduling occupant activities within specified time windows, and ultimately, can be integrated into a range of room booking and scheduling systems, including large-scale university timetabling applications.

2 Progress to Date

My progress to date relates to two aspects of the problem. The first aspect is concerned with the formulation of a mixed integer linear programming (MILP) model for integrated HVAC control and occupancy scheduling. The second aspect tames the problem complexity and scales to large problems by combining MILP model with large neighbourhood search (LNS)(Lim et al. 2015).

Integrating HVAC control and occupancy scheduling. The core component of our approach is a MILP model which optimally solves the joint occupancy scheduling and occupancy-based HVAC control problem. In more detail, the joint problem we consider is that of deciding the respective times and locations (rooms) of a set of meetings or similar activities, as well as the HVAC supply air temperature and air flow rate for each zone and time, in such a way as to optimise the overall HVAC consumption over a long time horizon. The occupancy schedule complies with the HVAC and building dynamics models, and with comfort and air-flow rate bounds that depend on the scheduled zone occupancy. It also satisfies typical meeting scheduling constraints, including constraints on meetings times, on meeting locations (e.g. room capacity, equipment availability), and on participant attendance conflicts. To tame the challenges caused by the presence of non-linear HVAC control constraints, we relax them using McCormick relaxation to obtain a MILP model guaranteed to provide a lower bound on the objective function. Results show that the HVAC-aware scheduling model leads to significant consumption reduction (50% to 70% in our experiments) when compared to occupancy-based HVAC control using arbitrary schedules or energy-aware schedules generated by heuristic methods.

MILP-based LNS. MILP enables us to easily manage the tightly constrained interactions between meeting scheduling

and its direct impact on energy consumption. However, it only allows us to solve small problem instances in reasonable time. To scale up to realistic problem sizes that universities face when scheduling courses, we developed a hybrid solution that embeds the MILP model into a LNS. LNS destroys parts of the schedule and MILP repairs them. The main idea behind LNS is that a large neighborhood allows the heuristic to easily navigate through the solution space and escape local minima even when the problem is highly-constrained. One important decision when implementing the destroy step is determining the amount of destruction. If too little is destroyed the effect of a large neighborhood is lost and if too much is destroyed then the approach turns into repeated re-optimisation. Another important decision is whether the repair step should be optimal or not. An optimal repair will be slower than a heuristic, but may potentially lead to high quality solutions in a few iterations. As a result, some parameter tuning will be essential in achieving good performance overall. In our destroy step, we remove all meetings in two, three, or four randomly selected zones. This forms a subproblem that the repair step can effectively solve using MILP. We do, however, limit the MILP runtime to avoid excessive search during repair. That means we do not necessarily solve the subproblem to optimality, but given that MILP solvers are anytime algorithms, we do improve solution quality in many of the LNS iterations. Results show that LNS is capable of returning significantly better solutions on large problems. The performance gap increases as the problem scales, and is higher for problems that are neither too weakly not too tightly constrained.

3 Proposed Plan for Research

Until my graduation in March 2016, I will continue to investigate (i) the practical aspects of integrating HVAC control and occupancy scheduling in smart buildings, and (ii) the theoretical properties of optimal control and scheduling using MILP in complex systems. In particular, I will focus on:

Online scheduling and stochastic control. Currently our method assumes that all meeting requests are known in advance. However, impromptu meeting requests and cancellations greatly impact the efficiency of the occupancy-based HVAC control mechanism, which is optimised some time in advance of the meetings taking place. In (Kwak et al. 2013), statistics show that 56% of the meeting requests arrive with at most 24hrs in advance, and amongst all requests, 10% are canceled. As the HVAC regulates the zone temperature based on a pre-constructed schedule, energy is wasted in cooling a zone which is scheduled for a canceled meeting. Moreover the temperature at a zone which hosts an ad-hoc meeting may fail to achieve the occupied zone temperature. Therefore, we intend to adopt an online stochastic approach to our control and scheduling mechanism. Apart from the existing schedule, our mechanism will also take into consideration future requests and cancellations while regulating the HVAC. This mechanism can also be further enhanced to incorporate dynamic temperature bounds to adjust thermal comfort based on outdoor temperature. It is expected to greatly reduce the energy consumption while improving the solution feasibility.

Symmetry breaking. Symmetries exist when the control and scheduling problems consist of a large number of (i) meetings with similar properties (eg. number of attendee, meeting time windows, rooms etc), (ii) rooms with similar temperature and temperature fluctuation rates, and (iii) scheduling periods with low diurnal temperature variation. It is possible to exploit symmetries in (i) and reformulating the model so that meetings with similar properties are grouped. However, for (ii) and (iii), as the room temperatures fluctuate according to occupancy, two rooms with similar properties may have different temperatures depending on the scheduled meeting allocations, hence resulting in an asymmetrical state. Therefore it is impossible to group them into one room type. This leads to multiple symmetric optima with very small differences that causes branch-and-bound to be ineffective. In ongoing work, we strive to identify branching strategies that cope better with symmetries in a mixed discrete-continuous system.

Other directions for future work include: (1) investigating the application of multi-objective optimisation to over-constrained problems where, additionally, violation of scheduling constraints needs to be minimised, (2) learning the correlation between temperature dynamics and actual building temperature sensors to formulate a more accurate HVAC model, (3) investigating the optimality gap between the nonlinear model vs. the linearized model, and the feasibility of relaxing non-linear constraints in HVAC control.

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