An Integrated Approach to Optimal Energy Operations in Buildings

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ABSTRACT: We address the short-term energy management of a building. To this end, we propose an optimisation model that dynamically determines the operation of the building's existing technologies and the procurement of energy. Our model is composed of upper- and lower-level operational modules. Assuming that the occupants' comfort preferences are expressed by a range for the temperature, the lower-level operational module returns the flow rates of air and water in the cooling and heating systems that maintain the zone temperature in the desired range. The upper-level operational module determines how the energy consumption from adjusting the zone temperature and other end-use energy requirements are satisfied so as to minimise energy costs, e.g., through on-site generation, and/or energy purchases. We assess the performance of our model in the context of two EU buildings. Our results indicate that energy consumption, CO_2 emissions, and energy costs can be reduced by implementing dynamic-as opposed to fixed-temperature set points.

1. INTRODUCTION

The transition towards more sustainable energy systems is of paramount importance in many industrialised countries and has been subject to recent regulation. For example, passage of Directive 2009/28/EC of the European Parliament and the Commission, which outlines the "20-20-20" targets of the European Union (EU), means that consumers as well as producers will have to improve energy efficiency. While power companies and industrial concerns may have the expertise to adapt to such a changing landscape, many small-scale energy consumers may lack the decision support to make cost-effective requisite reductions in consumption. Indeed, even at the building level, the trade-offs involved in deploying various energy resources and shifting loads are too complex to be analysed without recourse to an optimisation approach. Given this need, we develop an integrated short-term model to provide decision support to a building manager.

Because of the complexity of building-level operations, our decision-making approach consists of upper- and lower-level operational modules; see Fig. 1. Specifically, given the strategic variables, i.e., installed technologies and long-term contracts, which are determined in a complementary strategic model, the operational model determines not only how to run installed equipment such as conventional heating and heating, ventilation, and cooling (HVAC) systems to keep the zone temperature within specified limits but also how to source the energy needed for these technologies, e.g., via on-site production or off-site purchases. The latter are upper-level decisions and are the centrepiece of distributed generation models that assume fixed energy loads (King, & Morgan, 2007; Marnay et al., 2008; Stadler et al., 2012; Pruitt et al., 2013). By contrast, the former are lower-level decisions in which energy loads are endogenous and are the result of equipment operations that adhere to the temperature limits. Such a lower-level module is enriched by its incorporation of equipment thermodynamics and building physics, which renders the resulting optimisation problem highly nonlinear. While such an approach has been taken by (Liang et al., 2012) and (Groissböck et al.,

2013) to illustrate the benefits of setting zone temperature set points dynamically, an integrated operational model comprising both upper- and lower-level decisions would provide further insights about the effects of new policy measures or equipment installations on building operations. Hence, in order to gain a better understanding of short-term building level energy operations, we develop such a model in this paper and find that it is able to reflect load-shifting behaviour that is not detected by a lower-level optimisation.

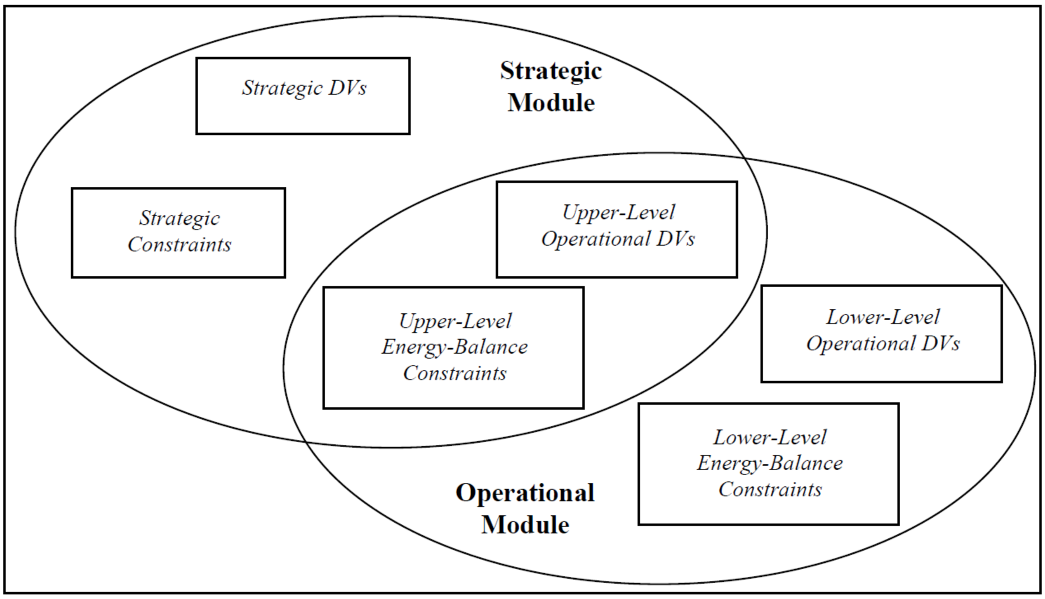

Fig. 1: Decision support system schema.

The structure of this paper is as follows. Section 2 provides an overview of the problem formulation. Section 3 describes the test sites and reports on the results of numerical examples with various operating scenarios. Conclusions are drawn in Section 4, and acknowledgements in Section 5 conclude this paper.

2. INTEGRATED OPERATIONAL OPTIMISATION MODEL

2.1 MODEL FORMULATION

We propose a short-term optimisation model that dynamically determines the dispatch and operation of the building's existing technologies and the sourcing of energy. The aim is to minimise the total energy trading costs and the technology operation and maintenance costs, while satisfying the comfort needs of the building's occupants and the building's end-use energy requirements. Due to the short-term nature of the problem, we assume that the building shell, the installed equipment, and the financial positions are fixed and that the model parameters are deterministic. For the sake of tractability, we further assume that the interior of the building consists of a single zone. The proposed model comprises upper- and lower-level operational constraints and decision variables. While the upper-level operational module is concerned with the optimal dispatch of the installed equipment and the short-term procurement of energy, the lower-level module focuses on the operation of the heating, ventilation, and cooling systems. Our integrated operational optimisation model is a non-linear deterministic optimisation problem, which can be described in pseudo-code as follows:

MINIMISE

Energy trading costs + technology operation costs

SUBJECT TO

Upper-level constraints:

- Energy balance,
- Technology capacity limits,
- Energy trading limits,
- Storage constraints,

Lower-level constraints:

- Zone temperature update and bounds,
- Energy flows and operational constraints for radiators and HVAC systems.

2.2 LOWER-LEVEL CONSTRAINTS

The lower-level constraints reflect the thermodynamics of the heating, ventilation, and cooling systems as well as the building's physics. Instead of considering exogenous end-use demands for space heat and cooling, we assume that the occupants' preferences are expressed in terms of a range for the internal zone temperature. Given the external temperature, the solar gains, the building's shell, and the internal loads, the lower-level operational module returns the flow rates of air and water in the cooling and heating systems that maintain the zone temperature in the desired range. Thus, the end-use energy requirements for certain types of space heat, venting, and cooling are decided endogenously. The modelling of the lower-level energy flows relies upon the literature on buildings physics presented in (Engdahl, & Johansson, 2004; Platt et al., 2010; Xu et al., 2008). For a complete specification of the lower-level constraints, we refer to (Groissböck et al., 2013).

2.3 UPPER-LEVEL CONSTRAINTS

The upper-level operational module determines how the endogenous and other end-use energy requirements are satisfied in a cost-effective manner, e.g., through on-site generation, storage, and/or energy purchases. At the heart of the upper-level module is the energy-balance constraint, which guarantees that the net supply of energy meets the end-use energy demand. The net energy supply is composed of the net energy purchased in energy markets, the energy produced with energy-generating technologies, the net energy removed from storage, less the primary energy used in production. The remaining upper-level constraints ensure that: the technologies operate within the installed capacity limits and according to their availability (e.g., photovoltaic systems cannot produce electric energy during the night); the energy purchases and sales do not exceed the volumes stipulated in the signed energy contracts; and the energy charged, discharged, and stored into energy-storage technology remains within certain limits dictated by the infrastructure and chemistry of those technologies. The mathematical formulation of these upper-level constraints can be found in (UCL et al., 2012).

3. NUMERICAL EXAMPLES

To validate the proposed operational optimisation model comprising both upper- and lower-level modules, we apply it to two public buildings in the EU. The first site is Centro de Adultos La Arboleya (Siero, Spain), which belongs to the Fundación Asturiana de Atención y Protección a Personas con Discapacidades y/o Dependencias (FASAD). The second site is Fachhochschule Burgenland's Pinkafeld campus, which is located in Pinkafeld, Austria.

For our numerical experiments, we consider a typical winter day with hourly decision intervals. For each site, we investigate two cases: fixed-mean temperature (i.e., the average of the lower and upper zone temperature limits) requirements (FMT), and a fixed temperature range over which an optimal operation of the heating and natural ventilation or HVAC systems can be sought (OPT). Moreover, we consider the current configuration and three likely future operating scenarios for each building. For FASAD, the operating scenarios under consideration are the following:

- Scenario 1 (baseline): conventional heating and natural ventilation; one 1293.3 kW and one 232.6 kW natural gas-fired boiler, one 5.5 kW_e combined heat and power (CHP) unit; exogenous end-use electricity load of 691 kWh_e and domestic hot water demand of 1592 kWh; flat energy tariff rates (0.14 €/kWh_e for electricity purchases, and 0.05 €/kWh for natural gas purchases); electricity feed-in tariff (FiT) of 0.18 €/kWh_e.
- Scenario 2: revocation of the FiT.
- Scenario 3: a new regulatory requirement, which imposes that the zone temperature cannot exceed 21ºC if a conventional heating system is in place.
- Scenario 4: installation of a 7.58 kW solar thermal system.

For Pinkafeld, we examine the following operating scenarios:

- Scenario 1 (baseline): heating and HVAC system; one 1.28 kW_e photovoltaic (PV) system; exogenous end-use electricity demand of 543 kWh_e; flat energy tariff rates (0.15 €/kWh_e for electricity purchases, 0.08 €/kWh_e for electricity sales, and 0.08 €/kWh for district heat purchases).
- Scenario 2: installation of a 100 kW_e PV system and availability of a FiT (with a rate of 0.18 €/kWh_e).
- Scenario 3: change from a flat to a time-of-use (TOU) electricity purchasing tariff (whose rate is 0.16 €/kWh_e between 7:00 and 14:00 and between 17:00 and 20:00, 0.15 €/kWh_e between 14:00 and 17:00, and 0.14 €/kWh_e otherwise).
- Scenario 4: installation of a 75 kW solar thermal system.

All optimisation problems are solved in MATLAB R2012a using the FMINCON solver for the OPT case and the LINPROG solver for the upper-level module of the FMT case. The computations are carried out on a Linux workstation with a 3.40 GHz Intel quad-core processor with 8 GB RAM. The longest OPT solution time amounts to 25 min for Pinkafeld (scenario 4) and 160 min for FASAD (scenario 4).

3.1 FASAD

Tab. 1 presents the primary energy consumption, the energy costs, and the CO_2 emissions of the cost-minimising solution for FASAD, while Fig. 2 depicts how the zone and external temperatures change during the day. We begin by comparing scenarios 2-4 against the baseline scenario. If the FiT is revoked (scenario 2), then there is no incentive to sell the electric energy produced by the CHP unit. Instead, this energy is used to meet the building's electricity load. Consequently, the CO_2 emissions and the primary energy consumption decrease as less natural gas is burned. On the downside, the net energy sales profit decreases. By installing a new solar thermal system, part of the hot water production shifts from the natural gas-fired boilers to a carbon-free and costless energy-generating technology. Therefore, all of the performance indicators improve in scenario 4. The energy-efficiency requirement in scenario 3 translates into a lower required temperature range and, thus, less heating. As expected, the energy costs, the CO_2 emissions, and the primary energy consumption decrease in this setting.

In most operating scenarios, we observe that the OPT case reduces the primary energy consumption, the costs, and the carbon emissions by 5-6% compared to the FMT one; see Tab. 1. Due to the high solar gains in the middle of the day, the FMT case requires venting in order to comply with the rigid temperature requirements. Conversely, the OPT case allows the zone temperature to fluctuate within the acceptable temperature range (see Fig. 2, right), thereby taking advantage of the solar gains. The OPT solution requires much less heating during the evening and no ventilation during the entire day. Its space heat load amounts to 493 kWh, which is a 30% reduction from the level of 700 kWh obtained in the FMT case. We remark that the outperformance of the OPT case over the FMT one is lower in scenario 3 due to the narrower desired temperature band, which leaves less room for profiting from solar gains.

Tab. 1: Summary of operational results for FASAD

Case / Scenario	FMT			OPT		
	Primary Energy (kWh)	Costs (€)	CO_2 Emissions (kg)	Primary Energy (kWh)	Costs (€)	CO_2 Emissions (kg)
1	4,071.0	213.7	809.9	3,847.9	202.0	764.9
2	3,798.8	218.0	757.3	3,576.1	206.4	712.3
3	3,917.3	205.6	778.9	3,827.2	200.9	760.7
4	4,019.6	211.0	799.5	3,796.6	199.3	754.5

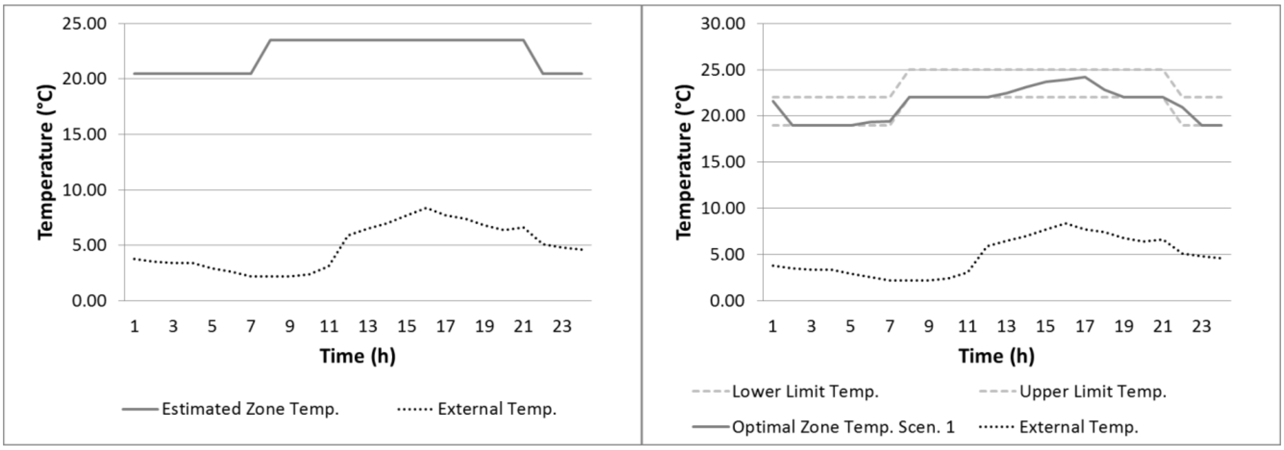

Fig. 2: Internal and external temperatures for FASAD in scenario 1 (left: FMT, right: OPT).

3.2 PINKAFELD

A summary of the operational results for Pinkafeld is presented in Tab. 2, whereas Fig. 3 shows the evolution of the zone temperature during the day relative to the external temperature. Fig. 4 depicts Pinkafeld's patterns of the space heat demand (left chart) and the ventilation (right chart) throughout the day. We start by comparing scenarios 2-4 against the baseline scenario. If a larger PV system is installed (scenario 2), then Pinkafeld's building manager can sign up to a FiT. In that case, all of the electric energy generated by the PV system is sold since the FiT rate is higher than the electricity purchasing tariff rate. This leads to a cost reduction as well as a slight increase in the primary energy consumption and CO_2 emissions as the entire building's electricity load is met solely via electricity purchases. Changing from a flat tariff to a TOU tariff (scenario 3) has a minor impact on the optimal solution due to the relatively low electricity requirement of the HVAC system and the absence of batteries for storing electricity. By contrast, installing a solar thermal system (scenario 4) improves the economic, energy-efficiency, and pollution indicators. Solar thermal energy is cost- and carbon-free and does not contribute towards the primary energy consumption of the building.

Similar to our findings for FASAD, we observe that the ability of the building's conventional heating and HVAC systems to adapt to environment and market conditions is valuable at Pinkafeld. In fact, migrating from a FMT to a OPT approach reduces the primary energy consumption and the carbon emissions by approximately 7% and the energy costs by 4-5%; see Tab. 2. Since the OPT case allows the zone temperature to drift within the desired range (see Fig. 3, right), it can make use of the high solar gains that occur in the middle of the day and reduce the need for the HVAC system. In scenarios 1-3, the OPT operation of the heating and HVAC systems consumes 3.64 kWh_e of electricity for ventilation and 629 kWh of heat—a reduction of 37% and 10%, respectively, vis-à-vis the FMT case; see Fig. 4. In scenario 4, the OPT space heat demand amounts to 644 kWh, yet the building's primary energy consumption is lower; see Tab. 2. Since the solar thermal system produces heat for free, the OPT solution pre-heats the building at noon and uses the building's capacity to retain heat in order to reduce the daily heating costs; see Fig. 3 (right) and Fig. 4. This cost reduction offsets the slightly higher ventilation costs incurred in scenario 4 to maintain the zone temperature within the desired temperature range.

Tab. 2: Summary of operational results for Pinkafeld

Case / Scenario	FMT			OPT		
	Primary Energy (kWh)	Costs (€)	CO_2 Emissions (kg)	Primary Energy (kWh)	Costs (€)	CO_2 Emissions (kg)
1	1,987.5	137.9	29.5	1,851.2	132.2	27.5
2	1,989.4	113.0	29.6	1,853.1	107.3	27.5
3	1,987.5	139.4	29.5	1,851.2	133.7	27.5
4	1,933.3	135.7	28.7	1,808.8	130.5	26.9

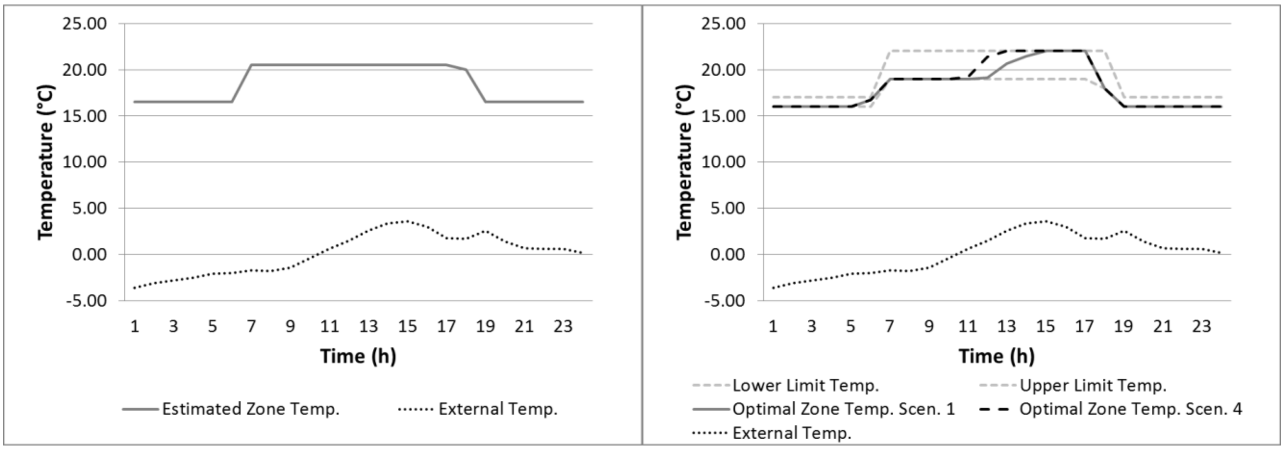

Fig. 3: Internal and external temperatures for Pinkafeld in scenarios 1 and 4 (left: FMT, right: OPT).

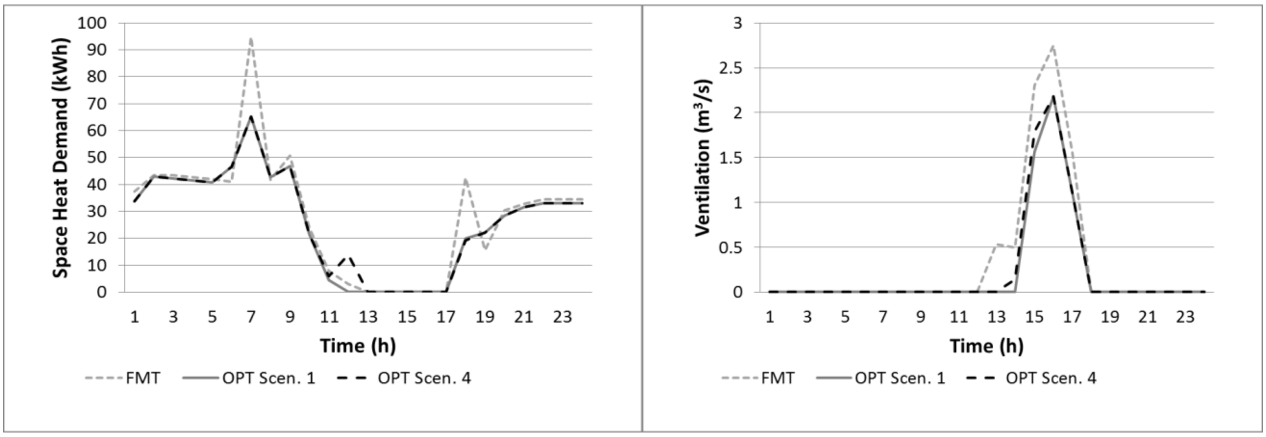

Fig. 4: Space heat demand (left) and ventilation (right) for Pinkafeld in scenarios 1 and 4.

4. CONCLUSIONS

In recent years, many industrialised countries are taking steps towards a more sustainable energy framework, e.g., via the promotion of the production of energy from renewable sources, the reduction of greenhouse gas emissions, and the improvement of energy efficiency. Under this new setting, building managers are faced with the challenge of satisfying certain sustainability requirements in a cost-effective manner. Consequently, a need arises for improved approaches that aid building managers in operating installed equipment and sourcing of energy while meeting certain economic and/or environmental criteria as well as satisfying the comfort needs of the building's occupants. To address this need, we propose an integrated short-term optimisation model for the energy management of a building. Our model is composed of upper- and lower-level operational modules. While the latter focuses on the operation of the heating, venting and cooling systems so as to maintain the internal temperature within specified limits, the former determines how the energy consumption from adjusting the temperature and the remaining building's energy needs are satisfied in a cost-effective manner. We have numerically evaluated our integrated operational model in the context of two buildings located in the EU. Our numerical results show that the flexibility of the building's conventional heating and HVAC systems to adjust to environment and market conditions is valuable from the economic, energy-efficiency and environmental point of view. Furthermore, the integrated model reflects load-shifting behaviour that is not detected by a lower-level optimisation model. In the future, we plan to replace the cost-minimising with a multi-criteria objective function, thereby allowing for a trade-off between minimising the energy costs and the pollution emissions.

5. ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 260041 for Collaborative Project "Energy Efficiency and Risk Management in Public Buildings" (EnRiMa). The Center for Energy and Innovative Technologies (CET) is supported by the Austrian Federal Ministry for Transport, Innovation, and Technology through the "Building of Tomorrow" program and by the Theodor Kery Foundation of the province of Burgenland. Cooperation of Centro de Adultos La Arboleya of Fundación Asturiana de Atención y Protección a Personas con Discapacidades y/o Dependencias (Siero, Asturias, Spain), Fachhochschule Burgenland's Pinkafeld campus (Burgenland, Austria), and Fachhochschule Technikum Wien's ENERGYbase facility (Vienna, Austria) has greatly enhanced our understanding of energy management at the building level. We are grateful to our EnRiMa partners Universidad Rey Juan Carlos, Hidrocantábrico Energía, Tecnalia, and SINTEF Group for their valuable input. All remaining errors are the authors' own.

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