Waste heat from mobile groups of people in energy system optimisation

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1 Abstract

The heat emitted by people indoors ranges from 70 W to 150 W [1], depending on the activity. This waste heat is taken into account in the design of cooling systems, but can also be used for heating. This article considers the control of mobile groups of people in an office building without fixed desks and in an airport in order with several waiting rooms, to optimise the use of their waste heat. A linear optimisation model based on oemof.solph [2] is used for the calculation, which takes into account both the thermal inertia of the building and the ability to influence the movement of groups of people in the building within a given framework. This work presents the formulation of the model, explains the assumptions made and compares optimisation results with standard operation.

2 Introduction

The consideration of internal gains in the design of buildings is a common practice, however, they are often incompletely considered in the operational optimisation of the energy system [3], [4]. Pallikere et. al [5] and Pisello et. al [6] examine existing occupancy plans for buildings to optimise the operation of the energy system. The control of mobile groups of people within airports though the tracking of their mobile devices to prevent queues or mitigate potential security risks has become increasingly prevalent [7]. However, the adaptation of occupancy plans to optimise the whole energy system has not been considered in previous work. This creates the potential to use the waste heat from people directly to heat spaces, or to distribute people across multiple spaces to reduce the cooling loads. Buildings with planned flows of people are particularly suitable for this. In addition to railway stations and airports, these also include cinemas, theatres, offices, universities and schools. This is already done manually in control systems, so heating is often reduced in anticipation of an event, reducing the need cooling during the event. Lowering the temperature in unoccupied rooms has also long been a practised strategy of energy management. On the other hand, this study examines the short-term adjustment of occupancy schedules and flows of people as well as system control, as part of a more comprehensive energy-efficient operational optimisation.

In this study, we consider two of the aforementioned building types, namely and airport and an office building.

3 Methodology

3.1 Energy System Model

The room air temperature T_n is of central interest in this work. It is assumed that it can be directly controlled by a ventilation system. When people are present in the room n, the room temperature must be permanently maintained between 20 °C and 23 °C. No corresponding specification is made in empty rooms. The heat stored in the room n is

$$Q_n = (T_n - T_{\mathrm{ref}}) \times V_n \times \rho c_{\mathrm{p}}, \tag{1}$$

where V_n is the volume of the room, ρ is the density of the air and c_{p} is the specific heat capacity of the air. Here we neglect the fact that the volume of the air changes with the occupancy of the room and assume that the density of the air is constant.

The energy balance of the room n is depictes in Figure 1. The shown heat flows are explained and defined in the following.

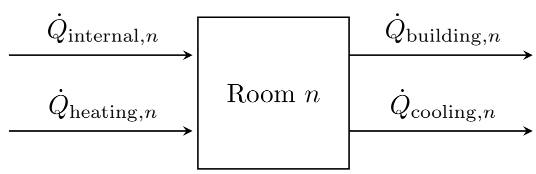

Figure 1: Energy balance of a room with energy flows

From the temperature difference between the current room air T_n and at the outlet temperature of the conditioner T_{c} the power of the air conditioner can be calculated as

$$\dot{Q}_{\mathrm{conditioning},n} = (T_n - T_{\mathrm{c}}) \times \dot{V} \rho c_{\mathrm{p}} = \begin{cases} \dot{Q}_{\mathrm{heating},n}, & \text{when } T_n \leq T_{\mathrm{c}} \\ -\dot{Q}_{\mathrm{cooling},n}, & \text{when } T_n > T_{\mathrm{c}}, \end{cases} \tag{2}$$

where $\dot{V}_n$ is the volume flow of the ventilation. Note that we define $\dot{Q}_{\text{cooling}}$ to be positive when there is cooling.

There is also heat loss through the walls of the room. Due to the short time horizon of our optimisation and because this study focuses on the integration of the flow of people, a constant value for the walls T_{w} is assumed as 18 °C and 17 °C, for the airport and offices respectively. Without limiting generality, for both cases the same temperature is chosen as the reference temperature.

According to [8], the heat transfer coefficient is $h_{\text{w}} = 7.14\,\text{W/m}^2\text{K}$ between the room air and the wall, $h_{\text{c}} = 10.14\,\text{W/m}^2\text{K}$ between the room air and the ceiling, and $h_{\text{f}} = 5.84\,\text{W/m}^2\text{K}$ between the room air and the floor. This results in a heat transfer between the room air and the respective surface of

$$\dot{Q}_{\text{building},n} = (T_{\text{n}} - T_{\text{w}}) \times (h_{\text{w}} A_{\text{w}} + h_{\text{f}} A_{\text{f}} + h_{\text{c}} A_{\text{c}}), \tag{3}$$

where the area of the walls A_{w}, the area of the ceiling A_{c}, and the floor area A_{f}.

For this purpose, the temperature of the air in the room is assumed to be fully mixed. In this study, it is always greater than T_{w}. For the airport analysis, three square waiting rooms are assumed with an area of $180\,\text{m}^2$ and a height of 15 m [9]. The offices have an area of $30\,\text{m}^2$ and a height of 2.5 m. For a detailed analysis, the thermal inertia of the building material could be modelled more precisely, e.g. using a 5R2C model [10].

For the internal gains of the room, the waste heat of the N_n people in the room

$$\dot{Q}_{\text{internal},n} = N_n \times \dot{Q}_{\text{person}} \tag{4}$$

is taken into account. In this sense, $\dot{Q}_{\text{person}} = 100\,\text{W}$ has been assumed. This choice is not meant to be the most realistic one but to facilitate the analysis of the results.

In total, in the energy in room n at time t can be expressed as

$$\begin{aligned} Q_n(t) &= Q_n(t - \Delta T) \\ &\quad + \int_{t-\Delta T}^{t} \mathrm{d}t' \left(\dot{Q}_{\text{internal},n}(t') + \dot{Q}_{\text{conditioning}}(t') - \dot{Q}_{\text{building},n}(t') \right), \end{aligned} \tag{5}$$

where $t - \Delta T$ is an earlier point in time. When working with discrete time steps, the integral becomes the product by the time resolution Δt.

For the optimisation, $Q_{\text{conditioning}}$ for the airport, and Q_{heating} for the offices, are minimised. The latter choice reflects the option to open windows for cooling. Note that Eq. (4) makes the number of persons an optimisation variable.

3.2 Movement Model

We use a simple model to express the movement of people, as it is shown in Figure 2. For the sake of simplicity, the movement of each individual person is not tracked, but analysed considering the time series of arrivals and departures, the number of persons N_n in the rooms and the rooms (binary) occupancy status $y_n \in \{0, 1\}$. The latter is calculated using

$$y_n(t) > N_n(t)/\mathrm{N}_{n,\max}, \tag{6}$$

where $\mathrm{N}_{n,\max}$ is the capacity of the room.

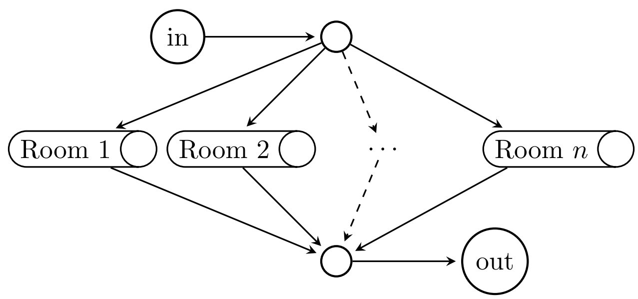

Figure 2: Simple model for the movement of people. People move into a room after arrival (in) and stay there until the end (out).

Note that in this model, a constant number of people present at the same time allows different levels of flexibility: in the office, most people will arrive in the morning and leave in the evening, so the occupancy of the desks cannot be changed during the day. At the airport, on the other hand, people are constantly arriving and departing.

Airport terminals are complex hubs where passenger arrival times must be predicted and managed to avoid delays and bottlenecks. This arrival time can be understood as the time it takes for passengers to arrive at the check-in counters before boarding. The arrival time of the passengers can be calculated as a Weibull distribution

$$f(x) = \frac{\beta}{\alpha^{\beta}} x^{\beta-1} \times \exp\left[-(\frac{x}{\alpha})^{\beta}\right] \tag{7}$$

described by [11], [12]. Here, x is the parameter for the arrival time or arrival location of the passenger, α is the scale parameter and β is the shape parameter. For a general domestic flight, $\alpha = 4.5$ and $\beta = 1.3$ are selected, for an (international) EU Schengen flight $\alpha = 4.0$ and $\beta = 1.9$. Four waiting rooms are modelled as described above, each with a maximum capacity of 300 people. This leaves the option of using only two of the rooms. Figure 3 shows the cumulative number of people present at the airport over the course of a day, based on their flight schedules.

For the occupancy of the office building, historic data from the DLR-VE office building is used. The original time series contains the total number of people present at any minute in the year of 2016. The data is anonymised by disregarding a random number of people per day by setting an offset. Despite these changes, the resolution of the data is considered to be sufficient to reliably

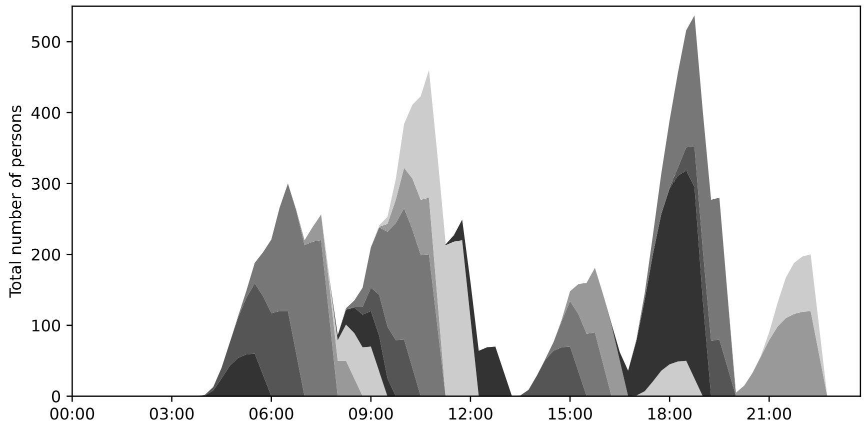

Figure 3: Total number of persons at the airport. Each flow is shown in a different shade of grey to distinguish between flights.

identify the arrival and departure times of people. Five offices are modelled as described above, each with a maximum capacity of five people. As for the airport model, this leaves the option to let one of the rooms completely unused.

4 Results

The optimisation results for both scenarios are quite similar. It is particularly noteworthy that the differences between the cases are mostly due to the costs of cooling. If the goal of optimisation is changed from minimising air conditioning to minimising heating or vice versa, the resulting strategies match for office and airport.

For both, the heating is turned on only just before the first people arrive in a room between 7 and 8 am. At around 6 pm, the temperature is brought to the maximum allowed using waste heat from persons to the reduce the demand for heating in the morning.

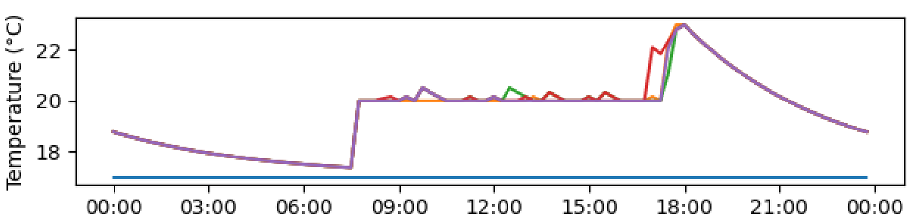

Figure 4: Optimised temperatures in the office scenario. Different colours signify the individual rooms.

In the office scenario (see Fig. 4), that avoids heating but allows free cooling, one room is left unoccupied. In fact, this only prevents the initial heat-up: If at least one person is present, its waste heat will be sufficient to keep the room warm. In the other rooms, the temperature occasionally deviates from 20 °C. As there is no optimal temperature, these deviations are mostly random and can be seen as people letting the room heat up and then opening the windows a bit further just until 20 °C are met again. As mentioned before, by the end of the day, there is a good reason to increase the temperature using the internal gains. Thus, the optimiser does so.

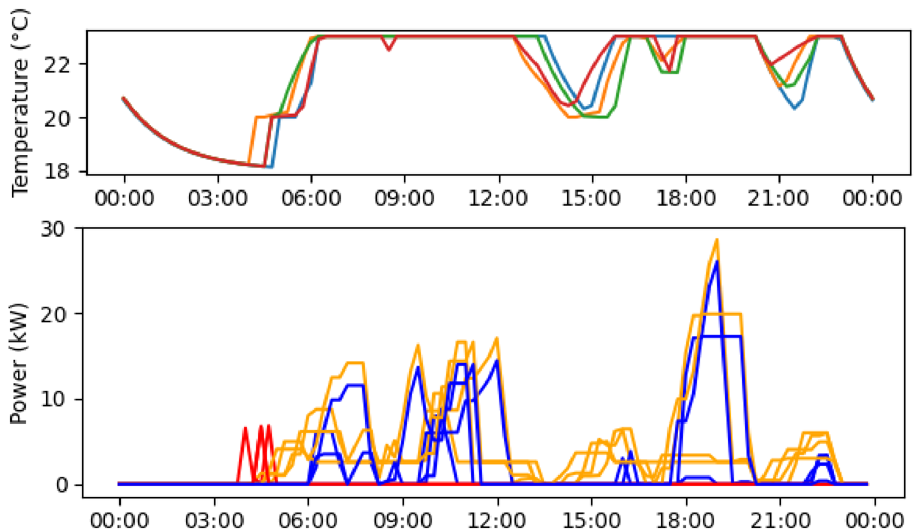

Figure 5: Top: Optimised temperatures for each waiting room, shown in different colours. Bottom: Heat flows by type for the airport scenario; red: heating, orange: heat from persons, blue: cooling

In the airport scenario, that also minimises cooling demands, all of the rooms are used (see Fig. 5). This can be explained by the increased surface that can absorb more heat. To intensify this effect, the room temperature is left at the upper limit. It is noteworthy, that in the morning the first people arriving at the airport are distributed almost evenly, so that neither heating nor cooling is needed. The same is true in the early afternoon, where fewer people are around. Still, the heat of the people is sufficiently high to keep the temperature from falling below 20 °C; only initially, each of the rooms is heated actively so that the first guests may enter. Most of the time, the internal gains have to be compensated mostly by the ventilation system.

In comparison to standard use, the optimisation results in a reduction of the office heating demands of about 20 % by leaving one room (out of five) unoccupied. This number is probably bigger than it would be in the real world: Setting the walls to constant temperatures is a valid approximation just if it is constantly heated. Not heating a room in the end will increase the heat demands of other rooms that loose more heat through walls touching the cold one, reducing the overall benefit. The demand for heating is further reduced by 10 % (offices) and 5 % (airport) by increasing the temperature using the heat of the people at the end of the day. The difference in the values is mainly due to the higher loss rate we assumed for the airport room. Letting the temperature reach 23 °C instead of constantly conditioning to 20 °C reduces the demand for cooling in the airport example by about 100 kWh (from 255 kWh to 146 kWh). Note that this is due to the added degree of freedom and not due to the optimisation per se.

5 Summary and outlook

We introduced a way to implement waste heat from mobile groups of persons in a mixed integer linear model. This way, we are able to optimise the flow of people under energetic aspects. The results in our examples reproduce standard strategies, e.g. grouping persons in less rooms to save heating costs or spreading people to save cooling costs. On the one hand, this underlines the feasibility of the method, on the other hand, the simplicity of the optimal strategies means that they can also be applied without an optimisation model. To fully quantify the potential, future studies should include more complex models for exchange of air through the doors of the waiting rooms and for the thermal inertia of the wall.

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References

[1] “Calculation of thermal loads and room temperatures (design cooling load and annual simulation),” VDI, Berlin, Germany, VDI 2078, Jun. 2015.

[2] U. Krien, P. Schönfeldt, J. Launer, S. Hilpert, C. Kaldemeyer, and G. Pleßmann, “Oemof.solph—a model generator for linear and mixed-integer linear optimisation of energy systems,” *Software Impacts*, vol. 6, p. 100 028, 2020, ISSN: 2665-9638. DOI: `10.1016/j.simpa.2020.100028`.

[3] D. H. Dorrah and M. Marzouk, “Integrated multi-objective optimization and agent-based building occupancy modeling for space layout planning,” *Journal of Building Engineering*, vol. 34, p. 101 902, 2021, ISSN: 2352-7102. DOI: `https://doi.org/10.1016/j.jobe.2020.101902`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S235271022033535X`.

[4] R. Evins, "Multi-level optimization of building design, energy system sizing and operation," *Energy*, vol. 90, pp. 1775–1789, 2015, ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2015.07.007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544215009019.

[5] A. Pallikere, R. Qiu, P. Delgoshaei, and A. Negahban, "Incorporating occupancy data in scheduling building equipment: A simulation optimization framework," *Energy and Buildings*, vol. 209, p. 109 655, 2020, ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2019.109655. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778819320432.

[6] A. L. Pisello, M. Bobker, and F. Cotana, "A building energy efficiency optimization method by evaluating the effective thermal zones occupancy," *Energies*, vol. 5, no. 12, pp. 5257–5278, 2012. DOI: 10.3390/en5125257.

[7] *Data processing and crowd management*, Accessed: February 12, 2024, Schiphol Airport. [Online]. Available: https://www.schiphol.nl/en/page/data-processing-crowd-management/.

[8] International Organization for Standardization, "Building components and building elements thermal resistance and thermal transmittance," ISO, Draft International Standard ISO/DIS 6946, 2015.

[9] Lin Lin, Xiaochen Liu, Xiaohua Liu, Tao Zhang, and Yang Cao, "A prediction model to forecast passenger flow based on flight arrangement in airport terminals," *Energy and Built Environment*, vol. 4, no. 6, pp. 680–688, 2023, ISSN: 2666-1233. DOI: 10.1016/j.enbenv.2022.06.006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666123322000423.

[10] J. H. Kämpf and D. Robinson, "A simplified thermal model to support analysis of urban resource flows," *Energy and Buildings*, vol. 39, no. 4, pp. 445–453, 2007, ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2006.09.002.

[11] M. Schultz and H. Fricke, "Managing passenger handling at airport terminals," 2011. [Online]. Available: https://api.semanticscholar.org/CorpusID:18631264.

[12] M. N. Postorino, L. Mantecchini, C. Malandri, and F. Paganelli, "Airport passenger arrival process: Estimation of earliness arrival functions," *Transportation Research Procedia*, vol. 37, pp. 338–345, 2019, ISSN: 23521465. DOI: 10.1016/j.trpro.2018.12.201.