UNIVERSITÀ DEGLI STUDI
DI GENOVA

Energy saving room scheduling system for smart hotels

Ernesto Denicia, Emanuele Sansebastiano, Rocco Caravelli

1. Abstract

The energy consumption is probably the most important aspects engineers have to take into account when they project a robot case or plan the action sequence to make it do. Generally, this problem is handle by optimal path research and optimal decision analysis. There are infinitive application in robotics regarding optimal storage strategy, for instance, manipulators managing storehouse have to decide where they have to store the packs according to shortest time spend, force and velocity they can apply on the pack (fragile or not), and best storage location according to the specifics of the object: the robot do have to put milk in a fridge, not in a hoover. Our analysis deals with this last case: where I do have to put something which must stay in specific temperature bounds. In particular, we analysed how the customers are placed in hotel room according to their needs, at first, the maximal revenue the hotel owner can get and the minimal energy usage to keep the temperature feasible to live by law. In this paper we are going to analyse the Winter period, but the identical approach can be used to find the optimal distribution during Summer.

2. Introduction and proposal

This paper deals with the necessity of reducing the energy loss in hotels related to the usage of heat sources (radiators, heat pumps, etc..). Since a hotel has to provide a fixed minimum in every room used to host of 20 $\pm$ 2 °C by the norm DPR n° 412/1993, during Winter, at least in Europe, hotel managers need to turn on heaters. Assuming the buildings we are observing have the possibility to turn on and off the heat sources of each room independently from the other ones we wonder if the usage of the heat source is just dependent on the dimension of the specific room or if the other rooms will contributes to reduce the energy required to heat up the considered room. Moreover, we assume that if none booked a room on a day, that heater is not active in that room on that specific day. In order to see check it we made a lumped parameter model of the hotel using a on/off controller, having heat pumps as heating (and cooling) system source. These heat pumps directly blow wormed air in the room (forced convection), so they are very fast, and easy to control by an on/off control. The figure 1 shows that, thanks to the fact the room located on the first floor (blue line) is occupied on the days 2, 4, 5 and the room located on the third floor (blue line) is occupied on the days 2, 4, 6, the room located on the second floor (red line), which is in the middle, receives a consistent heat flux from the other two. That room is never booked on the mentioned period, but its temperature is almost always above to minimum temperature required to keep the heat pump off (18.5 °C). Finally, we have the proof the temperature of a room influences the one of the other and vice verse. Thus, we want to formulate and optimal decision algorithm, which takes in consideration all the rooms in their complexity, to accept, at first, the best requests combination among the ones we have, and then, optimize the distribution of the accepted costumers in the rooms available.

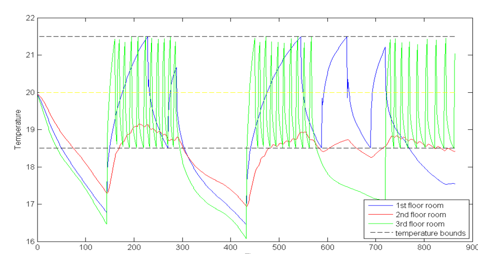

Figure 1: *Temperature of three rooms located one over the other having various customers along 6 days.*

3. State of the art

In order to understand the algorithms already used we decided to perform a market analysis asking to specific hotels, located in Genoa, chosen according to they class of quality (number of stars) to explore every kind of quality service provided: the quality service is a valid index to check the possible price of

a room, and so the possible revenue coming from each room. In particular we asked if they make forecasts on the demand according to their own customers and/or the Genoa statistics, and if they use software to manage the demand. Surprisingly, we found out the just the 20% of the hotel manager interviewed use to check the demand statistics and they take more into consideration the agencies' forecasts more than looking at their past customers.
On the other hand the usage of computer to manage the whole hotel is a common layer. It bursts all the paper work and the customer distribution could not wait for a different fate. However, none uses a software which optimizes the room booking, most of the software just uses a first list/first choice or a random choice. The internet sources reveal some software which are sponsored as optimization software, but they do not have the algorithm available because of industry secret. The hotel manager must pass to the software the parameters of the rooms like price and grade of priority. These kind of software, instead, tend to optimize the revenue management (schedule an offer campaign and the optimal room price) more than optimize the room booking.
Thanks to researches we are confident that the algorithm (based of the energy consumption) we want to propose is not already present on the market. Since it is strictly related to topology of the hotel (room adjacencies), we strongly think companies doing building energy analysis could be interested in offering this kind of service to their clients.

Anyway, the algorithm we are proposing for this specific problem is largely versatile to solve every placing and/or storage optimization.

4. Previous heat and control analysis

In order to analyse the heat fluxes governing the heat transmission of a building there are two ways to proceed: taking blueprints of the building and, knowing all the material properties, making a heat analysis of every room, or taking the temperature of every room and identify the parameters to know the behave of heat fluxes. Because both approaches lead to the solution, we decided to make two independent previous analysis.
Each procedure is based on the equivalence having on the left side the summation of heat fluxes at a specific time instant and on the right side the variation of the internal energy from an instant to the following one:

$$\begin{aligned} q_{tot_t} &= \Sigma q_{k_t} + \Sigma q_{h_t} + \Sigma q_{vent_t} + \Sigma q_{sun_t} + q_{pump_t} \\ q_{tot_t} &= \rho V c_p \frac{dT}{dt} \end{aligned} \quad (1)$$

Where:

q_k is the thermal convection;
q_h is the thermal conduction;
q_{vent} is the ventilation flux according to the norm UNI/TS 11300;
q_{sun} is the sun radiation took from weather forecast;
q_{pump} is the heat flux coming from the heat pump (if activated);
$\rho V c_p \frac{dT}{dt}$ is the time derivative of the internal energy.

4.1. Blueprint analysis strategy

Since the used scenarios must be realistic we planned three kind of room according with their price and structure (25 m^2, 50 m^2, 75 m^2) and the same amount of customer kinds. Every wall is made by common bricks (density: 2000 $\frac{kg}{m^3}$; heat capacity: 0.9 $\frac{kJ}{kgK}$; thermal conduction: $8e^{-4}$ $\frac{kJ}{smK}$); the exterior wall thickness is 0.4 m, while the interior one is 0.1 m. Every room have at least a window and one door on the corridor. The windows are made by common glass (density: 2400 $\frac{kg}{m^3}$; heat capacity: 0.84 $\frac{kJ}{kgK}$; thermal conduction: $9.6e^{-4}$ $\frac{kJ}{smK}$), and its thickness is 0.04 m, while the doors are assumed to be like the interior wall for their heat behaviour. To run these initial set of experiments we decided to use real heat pumps (any other kind of heat source do not change the result) taken by the commercial catalogue Daikin Industries, in particular we used the heat pump called 'FTXZ35N'.

Due to the fact computer cannot handle continuous domain, the heat transfer equation must be discrete:

$$q_{tot_t} = \rho V c_p \frac{dT}{dt} \qquad --> \qquad \frac{q_{tot_t}}{\rho V c_p} = \frac{T_{t+1} - T_t}{timegap}$$

Then, we can rewrite the equation:

$$K_{i,j}(T_{i,t} - T_{j,t}) = \frac{C_i}{timegap}(T_{i,t+1} - T_{i,t})$$

Where:

$K_{i,j}$ is the heat transfer coefficient from the room j to i;
$C_{i,j}$ is the capacitance of the room i;

4.2. System identification strategy

The practise requires the temperature of the air of each room at each instant of the analysis

E-plus

bla bla

4.3. P control vs. ON/OFF control

map of the hotel

different curves for the temperature depending on floors

gap-time

Assumptions on the hotel (temperature in - out, sun)

4.4. Parameter identification

At the first phase, the scheduling system must be robust enough to be put into operation with possibly little a priori information available. A fast revision of the construction conditions of the hotel motivates thence to the use of an initial model estimate of the linear time invariant form 1. This assumption is not inadequate at all given that the fundamental frequencies of the transference relationships are expected to be low.

However, it is required that the system acquires a good estimate on the real thermal performance of the building with time. An intelligent layer capable of learning the parameters characterizing its thermal isolating quality is then proposed. Consider an extended continuous abstraction of the form:

$$\begin{aligned} & c_i \dot{T}_i = -K_{i,e}(T_i - T_e) + \sum_{i\sim j}(T_i - T_j) + K_u u_i + q_i^S \\ & \forall i \mid 0 = 1 \ldots n_r \end{aligned} \tag{2}$$

with parameters c_i (conservation of energy) and transmittance (principle of continuity) parameters for inner adjacencies $K_{i,j}$ as well as those with the exterior (exogenous in nature) state T_e. Strictly adjacent rooms i and j are considered by emphasizing the coherence of their flux equality relations, described strictly by $q_{i,j} = K_{i,j}(T_i - T_j)$. Room control inputs u_i are also taken into account as well as the predictable solar flux q_i^S radiated into windows of each room. The characteristic discretisation is therefore given by the predictive form S_p:

$$\begin{aligned} & \hat{T}_{i,t+1} = \frac{1}{c_i}\left[\sum_{i\sim j\bigcup e}(\hat{T}_{i,t} - \hat{T}_{j,t}) + K_u u_{i,t} + q_{i,t}^S + \hat{T}_{i,t}\right] \\ & u_{i,t} = u_{i,t-1} + K_{u,i}(e_{i,t} - e_{i,t-1}) \\ & e_{i,t} = T_{sp,t} - T_{i,t} \\ & \forall i \mid 0 = 1 \ldots n_r \\ & \forall t \mid t = 1 \ldots P \end{aligned} \tag{3}$$

where already the exterior node is considered inside the whole set of adjacencies per room and a deliberate proportional control structure of the form $q_{u,i} = K_{u,i}(T_{sp,t} - T_i)$ is proposed for $T_s p$ desired temperature at the time a room is to be heated. A pure algebraic error state $e_{i,t}$ is also expanded determining the whole discretisation strategy. With initial parameter estimates $K_{i,j}^o$ and c_i^o from mechanical abstraction in Eq. 1, it is possible to solve a Nonlinear Least Squares optimisation problem with the aim of minimising predicting errors by means of the formulation

$$\begin{aligned} \theta^* = \arg\min_{\theta\in\mathbb{R}} \quad & (T_{i,t} - \hat{T}_{i,t})^2 \\ \text{s.t.} \quad & \theta \geq 0 \\ & S_p = 0 \end{aligned} \tag{4}$$

returning the optimal parameter vector θ^* and performed over timespan P. Notice that one can warm up the optimisation routine with an initial first Linear Least Squares approach applied to an ARX-Model attempt. Nevertheless, in the scope of this work, it was demonstrated that the default trust-region-reflective algorithm implemented by **MATLAB** `lsqnonlin` solver could deal very well with this task.

For changes in the sampling rate at which the system can learn the parameters of the building, one could also start with a rough approximation and iteratively decrease the time differential in order to refine the solution. The analysis proposed here uses a sampling period of one hour and involves the use of more accurate simulations from the toolbox **`E-plus`**, providing the exogenous inputs of the optimisation problem and thence bounding the performance of the system up to the degree of mismatch of the toolbox itself.

In the real scenario, after put in operation, the scheduling system can be interfaced with the (probably) existing thermostats of the building and program itself e.g. once a week to improve the parametric estimation of the real structure and ensure more accurate results with time. Fig. 2 shows the obtained estimation.

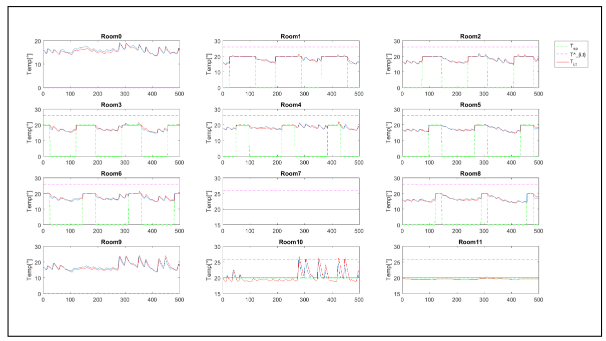

Figure 2: Forward simulation of the system after parameter identification.

4.5. Decision and control layers

For this work, two layers of intelligence are provided. One dealing with the revenue maximisation problem, which returns the assignment of clients to the rooms according to the booking characteristics and the commercial description of the rooms involved in the building. The second layer represents a lower level optimal control problem that ensures minimal energy consumption for an imposed maximum revenue and which depends on the topology and adjacency relationships within the rooms, exterior and ground.

With consideration of the sets:

$$\begin{aligned} & d \in D = \{0, 1, \ldots n_d\} \\ & r \in R = \{0, 1 \ldots n_c, n_c + 1 \ldots n_s \ldots n_r\} = \bigcup\{R_c, R_s\} \\ & R_d \subseteq R \\ & R_{dn} = R_d \bigcup \gamma \\ & d \in D_d \subseteq Dnd \\ & t \in T_1 = \{1 \ldots N\} \\ & t \in T_2 = \{1 \ldots N+1\} \end{aligned} \tag{5}$$

described by booking requests set D, R available n_r rooms in building, out of which there are n_c client rooms and n_s service rooms or common areas (corridors and lounges), R_d compatible rooms to request d (in the case of considering the dummy node γ, one considers R_{dn}), the time sets T_1 and T_2 for revenue and energy consumption optimisation problems respectively and D_d competing requests of request d.

The corresponding constants defined for this step of development are:

$$\begin{aligned} & T_{sp} = 20 \\ & \hat{T}_{i,1} \\ & q^S_{i,t},\, T_{e,t} \\ & K_{i,j} \text{ and } c_i \forall i,j \mid i,j \in R,\, i \sim j \end{aligned} \tag{6}$$

where T_{sp} determines the temperature setpoint to be reached when a room is selected. The initial temperature states of each room are imposed to be $\hat{T}_{i,1}$. The exogenous inputs $q^S_{i,t}$ and $T_{e,t}$ correspond to the solar radiation through the windows of each room differentiated according to its position on the Earth and the external temperatures measured at every sample. Finally, the transmittance and capacitance parameters $K_{i,j}$ and c_i obtained either through initial theoretical estimate or parameter identification routines.

With this information, the decision variables used for the solution of both optimisation problems are:

$$\begin{aligned} & x_{d,r} \in \mathbb{B}\ \forall d \in D \text{ and } r \in Rd \bigcup \{\gamma\} \\ & z_{i,t} \in \mathbb{B}\ \forall i \in Rd \text{ and } t \in T \\ & T_{i,t} \in \mathbb{C}\ \forall i \in Rd \text{ and } t \in T \\ & u_{i,t} \in \mathbb{C}\ \forall i \in Rd \text{ and } t \in T \end{aligned} \tag{7}$$

The complete optimisation problem with emphasis on its linear multi objective nature is shown in Eq. 8.

$$\begin{aligned} Y^* = \max_{x_{d,r}} \quad & \textstyle\sum_{d\in D}\sum_{r\in R_d} Y_{d,r} x_{d,r} \\ \text{s.t.} \quad & \textstyle\sum_{r\in R_{dn}} x_{d,r} = 1\ \forall d \in D \\ & x_{d,r} + x_{k,r} \leq 1\ \forall d \in D, \forall k \in D_d \\ & \text{and } \forall r \in R_d \cap R_k \\ E^* = \min_{x_{d,r}} \quad & \textstyle\sum_{t\in T}\sum_{i\in R} u_{i,t} \\ \text{s.t.} \quad & \textstyle\sum_{r\in R_{dn}} x_{d,r} = 1\ \forall d \in D \\ & x_{d,r} + x_{k,r} \leq 1\ \forall d \in D, \forall k \in D_d \\ & \text{and } \forall r \in R_d \cap R_k \\ & z_{i,t} = \textstyle\sum_{\substack{d\in D \\ t^{in}_d \leq t \leq t^{out}_d}} x_{d,r}\ \forall r \in R, \\ & \forall t \in T_1 \\ & \hat{T}_{i,t+1} = \tfrac{1}{c_i}(\textstyle\sum_{i\sim j \bigcup e}(\hat{T}_{i,t} - \hat{T}_{j,t}) + \\ & K_u u_{i,t} + q^S_{i,t} + \hat{T}_{i,t}) \\ & T_{i,1} = \hat{T}_{i,1} \\ & u_{i,t} \geq 0 \\ & u_{i,t} \geq z_{i,t}(T_{sp} - T_{i,t}) \\ & z_{j,t} \geq \wedge z_{k,t}\ \forall j \in R_s \text{ and } k \sim j \\ & Y_t \geq Y^* \end{aligned} \tag{8}$$

The aim of this multiobjective problem is that of generating optimal energetically performing assignments once the revenue was maximised. With this a clear differentiation between actual solvers in the market and this scheduling system can be highlighted. For the development of this task, the work is divided into the next steps:

1. Solution of the revenue maximisation assignment problem (upper bound on revenue).
2. Generation of additional revenue-wise optimal solutions
3. Determination of the energy consumption of each of the obtained solutions. (Energy efficiency estimation).
4. Solution of the energy consumption minimisation problem (energetical lower bound on maximal revenue solution).

Notice than the profit is redefined to be depending on the kind of assignments $x_{d,r}$ performed instead of on attempting only to maximize income, which is also something that many easy solvers do. For this, six levels of profit were proposed, each for the compatible assignment of three levels of clients to three levels of rooms and accordingly to Table 1.

Table 1: Levels of profits used as a marketing strategy for this work

Request	Room type		
	Low	Medium	High
Low	9	7	2
Medium	0	22	17
High	0	0	72

The profit was proposed in representative costs, not related to the real world and chosen with the proposal of a desired probability distribution to allow for approachability into a more real scenario. Notice that this profit definition does not suppress the possibility of assignment of high level rooms to low level requests, for which it is also possible to include an intelligent offer for the clients to ensure their pleasure as much as these profit values are tuned. As an example, one could consider the hotel in Fig. 3 with rooms 5 and 6 categorised as a high level rooms and rooms 9 and 10 with the biggest amount of solar irradiation (therefore energetically less demanding, at least in a direct sense).

After running the framework, one can find, among the several solutions, that by ensuring the optimum revenue value, it is possible to get energetically less demanding solutions preferring to start assigning rooms near rooms 9 and 10 than farther away. Notice that for this case, the fact that one room is occupied implies that the temperature of the central corridor (11) is also set to T_{sp} so that it might become more difficult to give a direct interpretation of the solutions. Nevertheless, the optimisation framework approach corresponds to a software robot capable of deciding for the owner of the building which rooms to assign by protecting the revenue, ensuring least energy consumption and learning the real parameters of the system for further proposals.

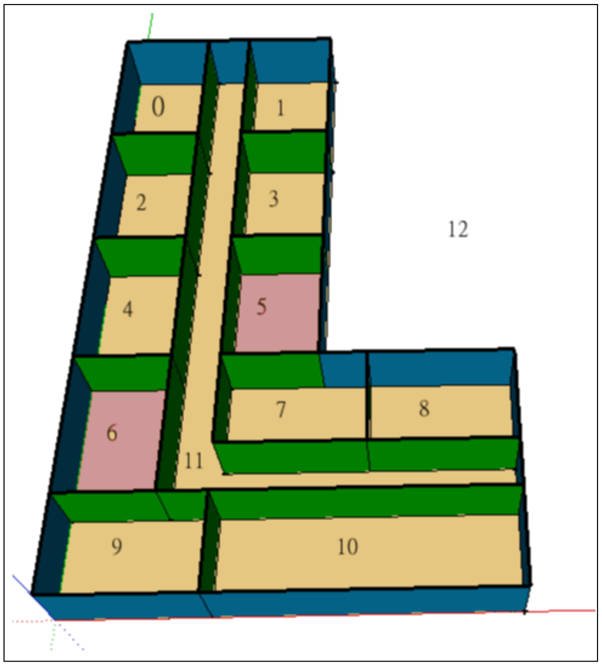

Figure 3: Forward simulation of the system after parameter identification.

5. analysis of the problem

maximize revenue

minimize costs

reject request

Optimized software used is Gurobi

?formulas?

6. Results

6.1. Revenue

6.2. Random assigning vs. optimized assigning

7. Conclusion