Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 6 (2020) 87–92
www.elsevier.com/locate/egyr

7th International Conference on Energy and Environment Research, ICEER 2020, 14–18 September, ISEP, Porto, Portugal

Key performance indicators regarding user comfort for building energy consumption management

Mahsa Khorram[a,b], Pedro Faria[a,b,*], Omid Abrishambaf[a,b], Zita Vale[b]

[a] *GECAD – Research Group on Intelligent Engineering and Computing for Advanced Innovation and Development, Porto, Portugal*
[b] *Polytechnic of Porto, Porto, Portugal*

Received 4 December 2020; accepted 9 December 2020

Abstract

This paper proposes an optimization approach to minimize the power consumption of an office building considering user comfort and key performance indicators. The present approach implements the power reduction by reducing power consumption of lights and air conditioners as reducible loads, and implements load shifting by considering dishwasher as shift able load. Two key performance indicators and several comfort parameters are defined to limit the power reduction of lights and air conditioners to consider the user comfort. In the context of load shifting, the complete operation cycle of dishwasher should be shifted without interruption based on the priority weight of the periods and available power. In the present optimization approach, sufficient number of periods have been considered for running the optimization, considering operational constraints and multiple levels for key performance indicators to evaluate their effectiveness. The case study of the work contains six different scenarios to validate different characteristics of the approach. Real consumption data of 20 lights, 10 air conditioners and 1 dishwasher in 20 working days have been applied to implement six different scenarios to propose a real comparable view of present approach.

Peer-review under responsibility of the scientific committee of the 7th International Conference on Energy and Environment Research, ICEER, 2020.

Keywords: Air conditioner; Multi-period optimization; Office building; SCADA system; User comfort

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1. Introduction

The work in the present paper has been done in the sequence of the work presented in [1] in the context of energy optimization in buildings. The increasing energy consumption in last decades is a big concern for many countries [2] and this growth is expected to increase by 30% by 2035 [3]. The process of controlling energy consumption takes a high level of attention from the generation to consumption. Nowadays, the world is moving towards comprehensive automation and smart infrastructures in order to prevent the loss of energy as much as possible [4]. Also, consumers

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[*] Corresponding author at: Polytechnic of Porto, Porto, Portugal.
E-mail address: pnf@isep.ipp.pt (P. Faria).

https://doi.org/10.1016/j.egyr.2020.12.018

Peer-review under responsibility of the scientific committee of the 7th International Conference on Energy and Environment Research, ICEER, 2020.

are not only consuming the energy. They can offer their flexibility to change the consumption pattern to take action to the Demand Response (DR) programs [5]. In this case, DR programs modifies the user's consumption pattern based on the electricity price variations or technical issues with considering benefits for the both sides [6]. All kinds of buildings can be considered as good targets for implementing DR programs and energy optimization methods, since they are responsible for a large part of energy consumption [7]. According to [8], consumption of building in all types is 40% of the world's energy consumption and between 40% to 70% is belonged to Heating, Ventilation, and Air conditioning (HVAC) systems. The main challenge of energy optimizers in these days, is to maintain balance between goals of optimization and user comfort [1].

Another important assessment of the sustainability of building energy managements is key performance indicators (KPIs) which is categorized to several aspects such as energy consumption and resources saving, energy policy and audit, energy return ratio, Peak Energy Demand Reduction for building operations, thermal performance, use of daylight in the primary areas [9]. Many studies have been done in the context of power consumption optimization with considering user comfort. [7] and [10] propose the optimization algorithms to optimize the power consumption of the building with considering visual comfort and thermal comfort respectively. Those papers are based on linear approach optimization. Authors in [11] have proposed a home energy management system to optimize the power consumption of Air conditioning (AC) system of the building with considering user comfort by determining power consumption of each hour to satisfy the thermal comfort demand. The main objectives of authors [12] was to propose a comfort-based and efficient environment. For this purpose, a multi-objective optimization method was proposed based on the genetic algorithm to propose the capability of HVAC for energy saving considering user comfort.

The present paper proposes a multi-period optimization algorithm for minimizing the power consumption of an office building. The algorithm focuses on the minimization of the power consumption of the lights and ACs with respect to user comfort in several aspects. Additionally, a dishwasher (DW) has been considered for shifting the consumption load from some periods to other periods to optimize power consumption. Comparing with the work in [1], this paper focuses on the comfort parameters by detail to establish conclusions relied on user preferences and user decisions. After this introductory section, the optimization algorithm and related mathematical formulation are shown in Section 2. The case study and its results are proposed in Section 3 and Section 4 respectively, and finally, the main conclusions of the work are presented in Section 5.

2. KPI optimization approach

This section presents an optimization approach for minimizing the power consumption of lights, ACs, and Dishwasher (DW) in an office building. In the present approach, lights and ACs are considered as reducible loads for reducing their consumption based on the required power reduction. However, the consumption of DW cannot be reduced or be interrupted in the middle of operation, therefore, DW is considered as a shiftable load to implement the load shifting.

The present optimization approach is a linear problem which has been solved by Rstudio software using OMPR package (www.rstudio.com). There is a required power reduction in each period, which defines the amount of power reduction from lights and ACs. This power reduction affects on the performance of the lights, ACs, and present method. In this context, two KPIs as Lights Performance Indicator (LPI), and AC Performance Indicator (ACPI) have been defined to have effects on the power reduction of lights and ACs respectively. LPI and ACPI are measurable values in different levels to validate the performance of the approach. In addition to LPI and ACPI, there are comfort parameters to restrict the amount of power reduction based on various aspects. These parameters can be updated in each period by users and the algorithm runs with the recent defined values.

In some appliances such as DW, there is an operation cycle that should be completed to achieve a certain task. It means that their power consumption is not reducible and interruptible as they need a certain number of periods to finish their operation cycle. In order to implement load shifting of DW, the complete operation cycle should be shifted from some periods to other periods. It means that an appropriate starting point should be selected to shift the power consumption of DW. After adjusting the defined parameters such as comfort parameters, LPI and ACPI, the optimization approach minimizes the power consumption of the building based on the required power reduction in each period. Eq. (1) presents the objective function.

$$Minimize\ OF = \sum_{t=1}^{T} \left[\sum_{l=1}^{L} W\_L_{(l,t)} \times P\_L_{(l,t)} + \sum_{a=1}^{A} W\_AC_{(a,t)} \times P\_AC_{(a,t)} + \sum_{d=1}^{D} W\_DW_{(d,t)} \times DW\_Bin_{(d,t)} \right]$$

$$+\sum_{st=1}^{ST} W\_DW\_sh_{(st)} \times P\_DW\_sh_{(st)} \quad (1)$$

As it can be seen in (1), W_L shows the importance weight of lights in each period, and P_L means the power of lights in each period which is one of the decision variables of the method. W_AC and P_AC are related to importance weight of ACs and power of ACs in each period respectively. W_DW is the importance weigh of DW, and DW_Bin is a binary variable to present the operation status of DW. It is clear that 1 means ON and 0 means OFF. W_DW_sh is the importance weight of each period for starting point of shifted power, and P_DW_sh is the shifted power of the dishwasher. In this context, L, A, and D show the maximum number of lights, ACs, and DW respectively. ST is the final period for starting time of DW. T indicates the maximum number of periods.

This objective function is subjected to several constraints as:

- Required power reduction in each period which is equal to the reduced power of lights and ACs.
- Number of operations of DW to guarantee that power consumption of DW should be shifted once among the focused periods.
- The amount of shifted power is equal to the initial power consumption of DW.
- Reducing power from lights and ACs may reduce their visual comfort and thermal comfort, respectively.

Therefore, it is important to consider constraint to restrict the power reduction of devices to prevent the excessive power reduction:

- Max_L_h, and Max_AC_h have been defined to limit the power reduction of lights and ACs in special times. It means that some lights and some ACs can reduce their participation in power reduction based on the time and periods.
- Max_L_R limits the power reduction of each light based on the place of light.
- Max_Red_L, and Max_Red_AC are considered to prevent the excessive power reduction of devices in consecutive periods. It means that all devices should participate in power reduction instead of reducing the power from certain devices.
- Eqs. (2) and (3) present the defined LPI and ACPI respectively. It can be seen that LPI and ACPI can specify the maximum allowed power reduction of each devices in all day. It is clear that when LPI and ACPI are equal to 1, it means that devices can share all their capability.

$$\sum_{t=1}^{T} P\_L_{(l,t)} \le \sum_{t=1}^{T} LPI_{(l,t)} \times P\_L\_Nom_{(l,t)};\, \forall 1 \le l \le L \quad (2)$$

$$\sum_{t=1}^{T} P\_AC_{(a,t)} \le \sum_{t=1}^{T} ACPI_{(a,t)} \times P\_AC\_Nom_{(a,t)};\, \forall 1 \le a \le A \quad (3)$$

P_L_Nom and P_AC_Nom are the nominal power consumption of lights and ACs respectively.

3. Case study

In order to validate the proposed optimization approach, six different scenarios have been defined considering 20 lights, 10 ACs, and 1 DW in an office building. The present case study focuses on working hours of 20 days. Working hours of this office building have been considered as 12 h from 8 am to 8 pm with 15 min time intervals (48 periods). It should be noted that lights of present building are reducible by Digital Addressable Lighting Interface (DALI) system. Each scenario focuses on a specific aspect of the optimization approach but initial power consumption of devices, priority of devices, and required power reduction are the same in all scenarios. Table 1 shows the participating devices in each scenario and their comfort level, which is classified as three categories of first (I), second (II), and third (III). Comfort level (I) considers constraints (2), and (3) for restricting the power reduction of lights and ACs respectively based on LPI and ACPI. Comfort level (II) focuses on constraints related to power reduction bounds based on specific time and place. In the last stage, comfort level (III) is dedicated to consideration of constraints for avoiding power reduction from a certain device in two consecutive periods.

As it can be seen in Table 1, in scenario A, the power consumption of lights and ACs should be reduced based on the RR. Scenario B is similar to the scenario A in the case of power reduction, however, in this scenario, DW is

Table 1. Introduction of 6 scenarios based on their features.

Scenarios	AC	Light	DW	Comfort level I	Comfort level II	Comfort level III
A	✓	✓	–	–	–	–
B	✓	✓	✓	–	–	–
C	✓	✓	–	✓	–	–
D	✓	✓	–	✓	✓	–
E	✓	✓	–	✓	✓	✓
F	✓	✓	✓	✓	✓	✓

considered to implement the load shifting. In scenario B priority of each period is important as it can specify the starting point of load shifting.

Scenario C tests and validates the functionality of LPI and ACPI on power reduction of lights and ACs. The required power reduction in scenario C is equal to the scenarios A and B, but the participation of devices in power reduction of each device may change due to LPI and ACPI.

Scenario D presents the impacts of comfort levels (I) and (II) in power reduction of devices. In addition to LPI and ACPI, this scenario limits the power reduction of devices in special times and places based on the user preference by comfort level (II). Scenario E presents the impacts of maximum level of comfort on power reduction of devices. The comparison of this scenario with previous ones shows the impact of each distinct constraint on user comfort. Scenario F can be mentioned as the complete version of optimization approach considering all controllable devices and all comfort levels. Table 2 and Fig. 1 indicate the level of each parameter in all scenarios.

Table 2. The parameter's value in each scenario.

	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
RR	Fig. 1	Fig. 1	Fig. 1	Fig. 1	Fig. 1	Fig. 1
LPI	–	–	0.4	0.4	0.4	0.4
ACPI	–	–	0.6	0.6	0.6	0.6
Max_AC_h	–	–	–	0.7	0.7	0.7
Max_Red_L	–	–	–	–	0.6	0.6
Max_Red_AC	–	–	–	–	0.46	0.46

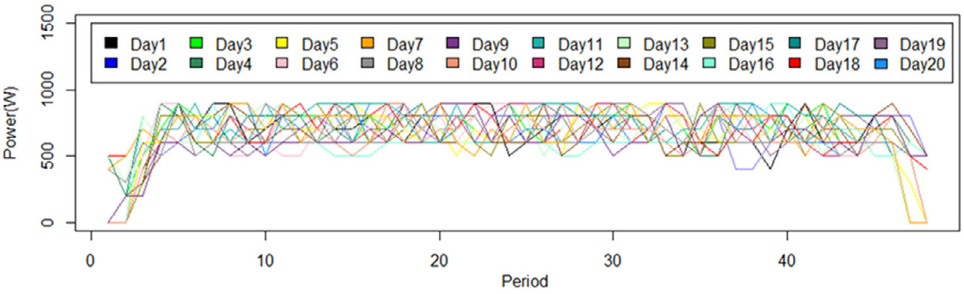

Fig. 1. The demand for power reduction in each period for 20 days.

According to Table 2, comfort parameters maintain their initial value in all scenarios to verify the impacts of added constraints, however they can be changed in each scenario based on the user preference. As it can be seen in Fig. 1, there are different amount of required power reduction in each periods of different days. These values are the minimum power reduction in each period; however, they can be changed to compensate the power consumption due to shifted power.

4. Results

Table 3 shows the percentage of power reduction of lights and ACs in one-day #20 in all scenarios compared to base case. The base power consumption presents the total consumption of the devices in 48 periods of the day.

Table 3. Variation of power reduction of devices in one day in different scenarios.

	Base Power [W]	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
Light #1	900	-8.3%	-11.1%	-16.6%	-16.6%	-8.3%	-8.3%
Light #2	725	-10.3%	-10.3%	-10.3%	-10.3%	-6.2%	-6.2%
Light #3	525	-4.7%	-4.7%	-9.5%	-9.5%	-7.6%	-8.5%
Light #4	825	0	0	-6%	-4.2%	-1.8%	-1.8%
Light #5	750	-6.6%	-6.6%	-6.6%	-6.6%	-4%	-4
Light #6	525	-4.7%	-9.5%	-9.5%	-9.5%	-7.6%	-9.5%
Light #7	700	-7%	-7%	-10.7%	-9.6%	-10.7%	-12.8%
Light #8	525	-9.5%	-9.5%	-9.5%	-14.2%	-11.4%	-11.4%
Light #9	825	-12%	-9%	-12%	-9.3%	-7.2%	-7.2%
Light #10	725	-6.8%	-6.8%	-3.4%	-3.4%	-4.1%	-2%
Light #11	675	-14.8%	-14.8%	-11%	-11.1%	-4.4%	-5.9%
Light #12	675	-18.5%	-18.5%	-22.2%	-18.8%	-17.7%	-17%
Light #13	850	-2.9%	-2.9%	-2.9%	-1.1%	-3.5%	-3.5%
Light #14	1000	-2.5%	-2.5%	-2.5%	-2.5%	-2.5%	-3%
Light #15	800	-15.6%	-15.6%	-21.8%	-17%	-11.2%	-11.8%
Light #16	725	-6.9%	-6.9%	-13.7%	-9.6%	-10.3%	-12.4%
Light #17	900	-8.3%	-8.3%	-8.3%	-8.9%	-6.6%	-6.6%
Light #18	625	-12%	-12%	-16%	-13.6%	-9.6%	-12%
Light #19	775	-6.4%	-6.4%	-12.9%	-12.9%	-9.6%	-9.6%
Light #20	675	-3.7%	-3.7%	-11.1%	-6.6%	-8.1%	-7.4%
AC #1	10400	-4.5%	-4.8%	-5.5%	-5.5%	-4.8%	-5.3%
AC #2	9675	0%	0	-2.5%	-2.7%	-3.35%	-3.6%
AC #3	6000	-14.1%	-14.5%	-13.3%	-13.3%	-13.9%	-14.2%
AC #4	10025	-13.9%	-13.7%	-15.2%	-15.5%	-12.6%	-14.8%
AC #5	7625	-12.7%	-12.4%	-11.8%	-11.8%	-10.2%	-10.6%
AC #6	8800	-8.5%	-9.6%	-3.6%	-3.7%	-4.1%	-3.7%
AC #7	7175	-2.4%	-2%	-0.7%	-0.8%	-1.4%	-2.1%
AC #8	8725	-7.4%	-6.3%	-8.8%	-9.3%	-9.5%	-10.3%
AC #9	7375	-8.1%	-8.4%	-12.2%	-13%	-12.4%	-13.6%
AC #10	9750	-6.9%	-6.9%	-5.6%	-5.7%	-7.2%	-6.4%

It can be seen in Table 3, the base power of each device is equal in all scenarios, however the variation in power reduction is different. For instance, many devices have ascending power reduction from scenarios A to F that some of them is highlighted with blue as an example. These ascending variations mean those devices were reducing more than their allowance based on LPI and ACPI and comfort constraints. Adding constraints by scenarios that are considering user comfort, might be limited the power reduction more than previous scenarios, therefore the devices can consume more and increase the comfort. However, the demand for power reduction is constant. In order to compensate the increment of power consumption, some devices that have capacity to compensate required reduction, are highlighted with green have descending power reduction based on the LPI, ACPI and comfort constraints. It can be seen that there is significant different in scenario B and C that shows the impact of LPI and ACPI. Load shifting of DW is also affecting on power reduction in scenarios B and F. As it can be seen in yellow rows, the reduction has been increased in order to compensate the power consumption related to shifted DW. Regarding electricity cost, the average electricity cost in base scenario is 272 euros. Since the required power reduction in all scenarios are equal, electricity cost in scenarios A, C, D, and E are equal to 251.7 euros.

5. Conclusions

The obtained results of comfort scenarios show comfort restrictions decrease the excessive power reduction in many devices. Load shifting and comfort constraints, presented the most optimal results, which is the lowest electricity cost among all scenarios with 23 euros reduction in 20 days. Future work should consider different building sizes regarding cost reduction. The algorithm plays an important role in the demand response programs since the consumption reduction and load shifting are performed according to key performance indicators defined by the users.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work has received funding from Portugal 2020 under SPEAR project, Portugal (NORTE-01-0247-FEDER-040224) and from FEDER Funds through COMPETE program and from National Funds through (FCT, Portugal) under the project UIDB/00760/2020, and CEECIND/02887/2017.

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