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Day Ahead Scheduling to Optimize Industrial HVAC Energy Cost Based ON Peak/OFF-Peak Tariff and Weather Forecasting

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ABSTRACT The cost consumption of industrial buildings is increasing, with heating, ventilation and air conditioning (HVAC) functions typically comprising half of all cost requirements. These cost requirements are heavily influenced by weather conditions based on the season and time of day, which may require different amounts or types of HVAC to provide habitable working conditions. Similarly, different activities that take place in an industrial building during a 24-h period also have different HVAC requirements. In this paper, we propose an optimal scheduling strategy based on activity type and weather forecasting to conserve HVAC costs. We have formulated the activity scheduling problem as a binary integer linear programming problem (BILP), and solved it using a CPLEX solver. Experimental results show that by scheduling activities, using 8-h time slots, we can achieve a reduction in costs of up to 27%. In addition, with 1-h time slots, optimal activity scheduling can yield up to a 38% reduction in costs.

INDEX TERMS HVAC, scheduling, weather forecasting, smart grid, IoT.

I. INTRODUCTION

Energy is essential to daily life, promoting growth and development by powering industry and home life. Due to new consumer demands, though, it has been forecast that worldwide energy consumption will increase by 33% in the next 15 years [1]. However, the sheer scale of such growth will have an adverse effect on sustainable human development, and the competing challenges of demand and sustainability leave energy management as one of the major challenges of the 21st century [2]. In order to combat this large-scale problem while preventing shortages or outages, energy must be used more efficiently,– especially in the highly-consumptive commercial, industrial, and residential sectors.

The industrial sector, which comprises laborers, machines, and processes needed to produce goods, accounts for 35% of global energy consumption [3], as opposed to the commercial sector, which focuses on providing services to consumers. Because of these different requirements, the demand for energy is much higher in the industrial sector, particularly in industrial-use buildings such as offices, warehouses, and manufacturing plants [4]. For instance, office buildings are required to provide a significant number of amenities (heating, cooling, health, safety) in order to protect both human and non-human assets, with these many amenities requiring intense energy usage [5]. Thus, industrial buildings offer an excellent prospect for reducing both energy requirements and negative environmental impact. Moreover, the cost savings generated by reducing energy usage could also play a pivotal role in driving commercial viability and success by freeing considerable financial resources for use in other parts of the business model [6].

The end goal of any such industrial undertaking is thus to reduce energy costs while ensuring that production and efficiency are not adversely affected – which can potentially be achieved by changing activities and processes. An energy-efficient industry provides a productive research area in which to focus on improvements that will reduce energy consumption while leaving the environment for daily activities untouched. Since conventional Heating, Ventilation, and Air Conditioning (HVAC) systems consume approximately 50% of an industrial building's total energy requirements [7], these systems are a good initial focus.

Industrial use of HVAC systems is highly regulated. Detailed guidelines and frameworks related to indoor air quality, productivity, and energy sustainability have been provided by major engineering bodies such as the

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [8]–[11], since energy sources such as lighting constitute around 20% of total energy consumption [12]. While the heating and ventilation systems of residential buildings are meant to provide comfortable living environments adjustable to individual tastes, HVAC systems in the industrial and commercial sectors must also account for various machinery (office equipment, production units and self-operating machineries) that are also set up inside the buildings.

These machines must be considered just as much as the building' human workers, but the two demands are not always compatible. Machines' operating temperatures vary from −40 to 85°C [13]. According to various studies on human optimum comfort, the ideal ambient temperature varies from 19°C to 23°C during the winter and from 21°C to 26°C during the summer [14], [15]. As a result, industrial buildings must accommodate a range of different and sometimes competing ambient temperatures in order to suit efficient work from both the machines and the human workers. In a further complication, machines and equipment have a wide range of possible operating temperatures while people's range of operating temperatures is much narrower. Consequently, appropriate measures should be taken to ensure that industrial buildings' internal temperatures allow for the productive operation of both machineries and human beings.

Another factor that must be taken into consideration is the heat generated by the human body, which produces around 100 watts/hr.; this amount of heat affects the environment greatly, especially when considering multiple human workers. Normally, the amount of heat that the human body produces depends not only on individual metabolic rate, but also on the activities that a person undertakes. The ASHRAE standard 55 provides clarification on Metabolic Equivalent of Task (MET) output for various types of activity [15]. For instance, on average an office worker produces 1.0 MET (100 watt of energy per hour) units while being engaged in such activities as reading, typing, writing, and sitting. On industrial premises or within industrial settings, workers are normally undertaking multiple different physical activities, such as loading, packing, machine work, and office work – resulting in increased MET output and fluctuating exposure to work environments that further affect the buildings' heating and cooling systems. Apart from these considerations, weather is also a significant factor that has a significant influence on the heating and cooling of an industrial building's environment. An efficient daily scheduling of different activities within the building can potentially address these issues, allowing for significant savings of both costs and energy.

II. SCHEDULING

In the literature, scheduling problems are widely discussed in the fields of computer sciences and engineering. Depending on the nature of the operations, scheduling can be used to minimize energy requirements, improve resource management, etc. In an industrial set-up, scheduling activities around worker exposure can be compared to process scheduling in real-time operating systems, since both methods are often limited by production deadlines and finite resources [16]. Workers' activities within industrial buildings are intended to accomplish the goals and tasks that the business requires, and thus these activities can be scheduled within deadlines and resource constrains. Today, the most commonly-used scheduling strategies include First Come First Serve (FCFS), Earliest Deadline First (EDF), etc. In all cases, though, the use of scheduling strategies will depend on the nature of the task as well as the availability of resources and workers. In addition, activity scheduling is often influenced by weather conditions, given that such conditions affect and change the buildings' internal environments alongside the heat generated by both machines and human workers. All these variables must be considered when scheduling for optimal HVAC use.

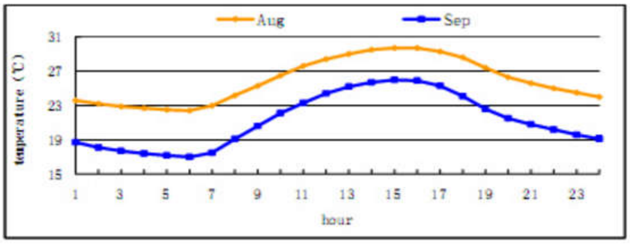

FIGURE 1. Temperature Changes of Beijing [30].

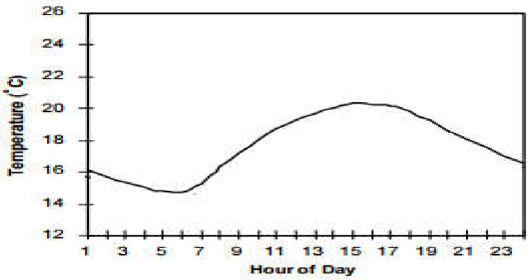

FIGURE 2. Temperature Changes for Toronto [31].

In recent years researchers are attracted to energy efficiency for HVAC scheduling [17], [18], such that indoor air quality standards and the comfort level of the occupants are not compromised [19]–[21]. There are two main HVAC scheduling strategies in buildings. The first strategy uses MPC to handle complexity and multi-variability of the environment while following pre-specified temperature trajectories inside the building [22]–[25]. The second strategy follow conventional scheduling techniques. In this case, the whole day is divided into set point temperature according to requirements [26], using line-up and set-up techniques [27], [28], which adjust inside temperature on a linear and set-point pattern. The focus of MPC is HVAC design and control strategies. In this study we are focusing on activity scheduling based on projected savings of energy cost, while acknowledging that the energy requirements required for ambient internal temperature will change according to external temperature, building occupancy, and scheduled activities. Because the 24-hour cycle will be divided up based on those three requirements, our study will use the conventional HVAC EnergyPlus model in its simulations.

Weather can influence scheduling of activities in an industrial set-up, since the buildin's internal temperature must be adjusted for comfort against external weather. Hence weather forecasting is an important factor in activity scheduling. Even though the average daily temperature varies in different industrial cities depending on location, observing the temperature patterns for Beijing [29] and Toronto [30], provided in figure 1 and 2, shows that the daily temperature curves are relatively smooth. In Beijing, September's minimum temperature was approximately 17 degrees, while the peak temperature in the same month was around 26 degrees. By contrast, Toronto's temperature ranged from 13 to 20 degrees. Given that the temperature curve is quite smooth for both cities, this means that weather forecasting could promote cost-effective energy management simply by allocating different tasks in the appropriate manner based on the da's weather conditions. With this possibility in mind, we have examined temperature curves over the course of a month for some of the world's most significant industrial cities, specifically Karachi, Seoul, Mumbai, San Paulo, Jakarta, Moscow, Mexico City, New York City, Istanbul, Tokyo, and Shanghai. Of these eleven cities, Seoul, San Paulo, Mumbai, Jakarta, Karachi, and Mexico City all exhibit relatively smooth curves in temperature change over the others. In all cases, though, weather forecasting and HVAC energy characteristics can help schedulers rearrange assigned tasks in industrial buildings to ensure a more efficient use of energy. For example, when the weather is extremely hot employees can work night shifts, while the machines being unaffected by weather can work during the daytime no matter how high the temperature is. Therefore, the weather forecast can be used to efficiently find the best suitable tasks for a particular time of day on any given day.

In this paper, we extend our previous work [31] by adding parallel activities and using peak, off-peak tariffs when calculating electrical energy utilization. Our previous work focused on optimum scheduling of different activities (Office work (OW), Loading work (LW), Packing work (PW) and Machine work (MW)) in the industrial sector to conserve energy. In this paper, we are focusing on the scheduling of activities for cost optimization rather than energy conservation, and we have also extended the machine group to include three more groups, which are the Light Machine (LM) group, Moderate Machine Group (MM*) and Heavy Machine Group (HM). The LM requires human interaction, whereas the MM* has two sub groups: Moderate Machine (MM1) work with human involvement and Moderate Machine (MM2) work without human involvement. Finally, the Heavy Machine group (HM works entirely without human participation. These work groups have to be scheduled over a 24-hour timeframe with the previous groups. To this end, we compare different combinations of scheduling in order to propose options that fulfill the energy requirements of required HVAC systems at the lowest possible cost, thereby maximizing cost savings. The following assumptions were made:

1. Peak and Off-Peak tariffs are used to focus on scheduling for cost savings rather than energy savings. Electricity companies commonly divide their tariff into peak and off-peak, with higher costs during peak hours as compared to off-peak slots.
2. We have consecutive 8-hour time slots and 1-hour time slots. Normally in industrial or corporate sectors the maximum work time is eight hours for a particular process. For the one-hour time slot, we believe more flexible exchanging/swapping of tasks can conserve energy.
3. Office work is given an 8-hour consecutive time slot because we believe that such work requires more intellectual effort than physical, and thus these workers are not distracted by other physical activities.
4. The maximum continual time allowed for any working activity is limited to 8 hours.
5. Only two parallel activities are performed at a time. We are focusing on finding the minimum cost for activities, and thus a high-cost activity can be swapped with a lower-cost activity.
6. It is possible for any activity to be performed at any time, since we are trying to find the optimal scheduling that will minimize costs.
7. Moderate Machine group contains two sub-groups (Moderate Machine Group 1 with human interaction and Moderate Machine Group 2 without human interaction), and 4 hours are allocated to each sub group. The purpose of having two separate sub-groups is that in extreme weather situations the machines in MM2 can work autonomously where the machines in MM1 cannot.

III. EXPERIMENTAL SETUP

Workers are placed into one of seven groups. Variables of interest within each group include power consumed by the machines, lighting required, and wattage produced per worker, values taken from these sources [15], [32]. The main factor in these calculations is the amount of heat being produced by various workers and equipment. Table 1 below highlights these factors in seven groups

In order to test our variables and manage the complexity of the study, we created three groups related to machines. The heavy machine group (HM) has 10000 watt-hours of energy consumption because human workers are not involved. While the light machine group (LM) consumes significantly less energy compared to HM, HM will automatically require less heating and cooling when humans are not involved; therefore, we add human operations into the total for LM. The moderate machine (MM) group lies between the extreme cases of HM and LM, with different requirements and values for each

TABLE 1. Activity power consumption.

Group	Watts/person (Watt-hour)	Lighting required (Watt-hour)	Electric Machine Consumption (Watt-hour)	Total
Heavy Machine (HM)	-	684	10000	10684
Moderate Machine (MM1)	432	684	5000	6116
Moderate Machine (MM2)	-	684	5000	5684
Light Machine (LM)	432	684	2500	3616
Office work (OW)	110	684	250	1044
Loading work (LW)	234	684	1000	1918
Packing (PW)	216	684	2000	2900

of the two sub-groups based on whether or not the machines' operation required human workers.

For the purpose of this study's simulation, these values of work are fixed constants, and will serve as the basis of our search for the energy requirements of various HVAC systems. To determine the HVAC energy requirements outlined in Table 1 we used EnergyPlus version 8.0.4 with a range of temperatures simulating three different types of days: a cold winter day, a moderate summer day, and a hot summer day. The temperature curves for these three different days are shown Figure 5. On the hot summer day, the outside temperature varied from 30 °C to 50 °C while on the moderate day, the outside temperature remained between 20 °C to 30 °C. This simulation is based upon a single-floor building measuring 61 m (200 ft) × 30.4 m (100 ft) × 3m (10 ft). The outside temperature of the cold day varied from 5 °C to 15 °C. The building's ambient temperature of 22 °C was based upon a mean temperature balancing the extremes of summer and winter [14], [15], which also falls approximately in the middle of the documented range for human comfort. As mentioned earlier, machines are able to continue operating despite higher temperatures, so we turned off HVAC functions during the HM and MM2 shifts in order to save unnecessary energy consumption. Finally, we use the electricity tariff of Shanghai, China, which is one of the biggest industrial cities in the world. The peak timings for electrical tariff are from 0700 to 1800 while the rest are off-peak hours [33].

To find the optimum strategy among all possible combinations of activities in Table 1, we formalize this problem into a linear equation and use CPLEX to solve it.

Mathematical Model:

We formulated the scheduling of different activities into a Binary (0,1) Integer Linear Programming problem, with the objective being to minimize the cost of energy necessary to drive a 24-hour cycle of work that includes various shifts of machine and worker output.

A. OBJECTIVE FUNCTIONS FOR 8-HOURS TIMESLOTS

$$(HVAC_d) = \min \sum_{d \in D} \sum_{h \in H} \sum_{r \in R} e_{dhr} x_{dhr} r_{dh}$$

Parameters:

D $= \{1, 2, 3 - Days\}$
H $= \{1..24 - hours\}$
R $= \{1 \ldots 7 - activitiestypes\}$
T $= \{1 \ldots 3 - timeslots$:(1-8, 9-16, 17-24)
T_s $= \{1 \ldots 6 - timeslots\}$: (1-4, 5-8, ….21-24)
d $= indexofday,\ d \in D$
h $= indexofhour,\ h \in H$
r $= indexofactivityrequirments,\ r \in R$
t $= indexoftimeslots,\ t \in T$
t_s $= indexoftimeslots,\ t_s \in T_s$
e_{dhr} $-hourlyenergyrequirementsbasedon$ *activities*
d_{dr} $-$ *demand for energy r*
p_{th} $-$ *timeslot hours. Equals 1 if hour h is in timeslot* $t \in T$, 0-otherwise
$q_{t_s i}$ $-$ *timeslot hours. Equals 1 if hour h is in timeslot* $t_s \in T_s$, 0-otherwise
r_{dh} $-rateperkilowatthourforhour\ h \in H$

Variables:

x_{dhr} =1 *if energy type r is assigned to time h on day d, 0-otherwise*
y_{dtr} =1 *if energy type r is assigned to timeslot t on day d, 0-otherwise*
$z_{dt_s r}$ =1 *if energy type r is assigned to timeslot* t_s *on day d, 0-otherwise*

Constraints:

$$\sum_{h=1}^{24} x_{dhr} = d_{dr} \quad \forall r \in R, d \in D \tag{1}$$

$$\sum_{r=1}^{7} x_{dhr} = 2 \quad \forall h \in H, d \in D \tag{2}$$

$$\sum_{t=1}^{3} y_{dtr} = 1 \quad \forall r \in R, d \in D \tag{3}$$

$$x_{dhr} = \sum_{t=1}^{3} y_{dtr} p_{th} \quad \forall d \in D, h \in H, r \in \tag{4}$$

$$x_{dh6} = 1 - x_{dh7} \quad \forall h \in H, d \in D \tag{5}$$

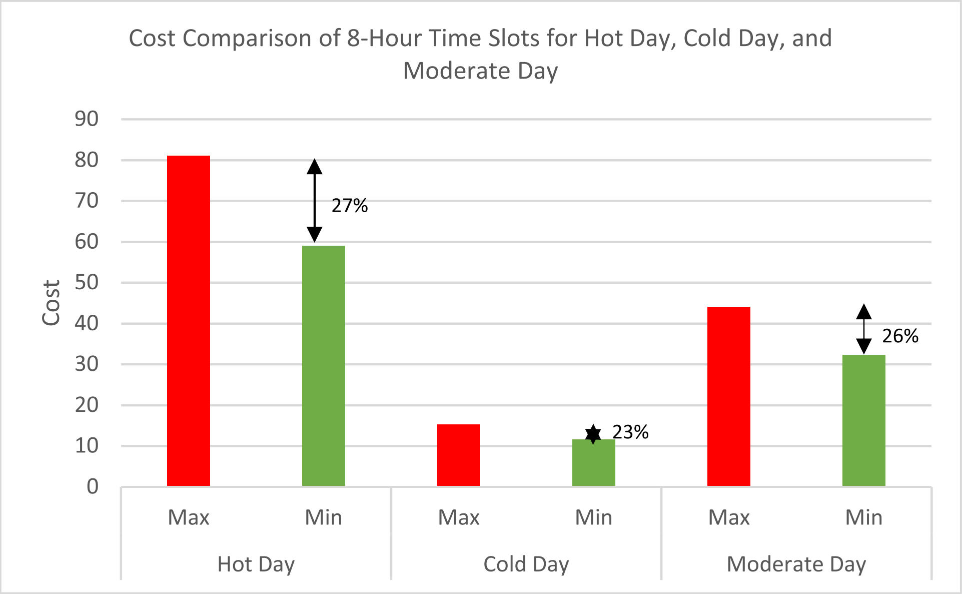

FIGURE 3. Cost comparison of 8-hour time slots for hot day, cold day and moderate day.

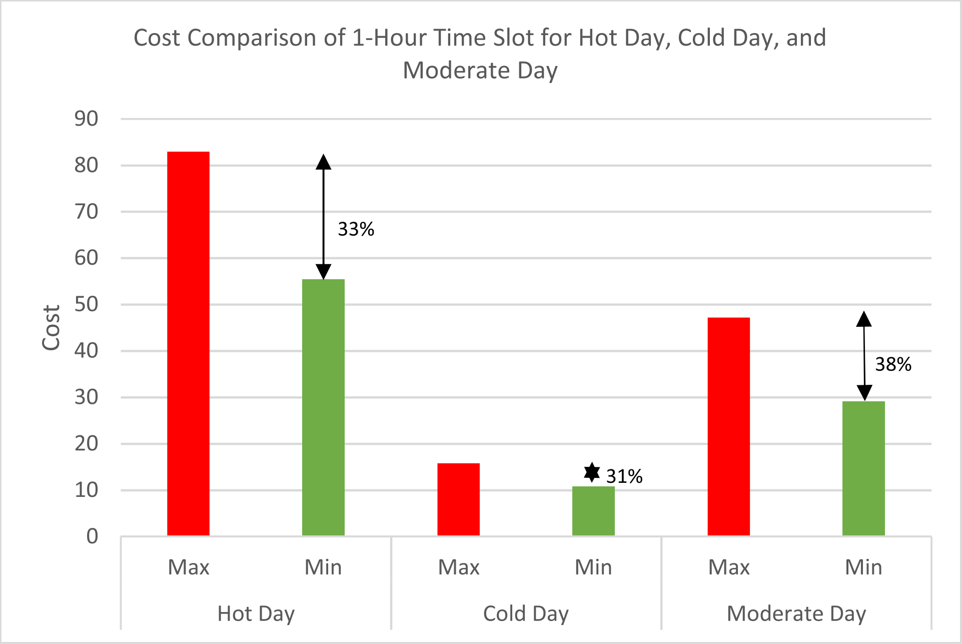

FIGURE 4. Cost comparison of 1-hour time slots for hot day, cold day and moderate day.

$$y_{dt6} = y_{dt7} \quad \forall d \in D, t \in T \tag{6}$$

$$\sum_{t_s=1}^{6} z_{dt_s r} = 1 \quad \forall r = \{6, 7\}, d \in D \tag{7}$$

$$x_{dhr} = \sum_{t=1}^{6} z_{dt_s r} q_{t_s h} \quad \forall d \in D, h \in H, r = \{6, 7\} \tag{8}$$

B. OBJECTIVE FUNCTIONS FOR 1-HOURS TIMESLOTS

$$(HVAC_d) = \min \sum_{d\in D} \sum_{h\in H} \sum_{r\in R} e_{dhr} x_{dhr} r_{dh}$$

Parameters:

$D \quad = \{1, 2, 3 - Days\}$
$H \quad = \{1..24 - hours\}$
$R \quad = \{1 \ldots 7 - activitiestypes\}$
$T \quad = \{1 \ldots 3 - timeslots$:(1-8, 9-16, 17-24)$\}$
$d \quad = indexofday, \ d \in D$
$h \quad = indexofhour, \ h \in H$
$r \quad = indexofactivityrequirments, \ r \in R$
$t \quad = indexoftimeslot, t \in T$
e_{dhr} $-$*hourly energy requirements based on activities*

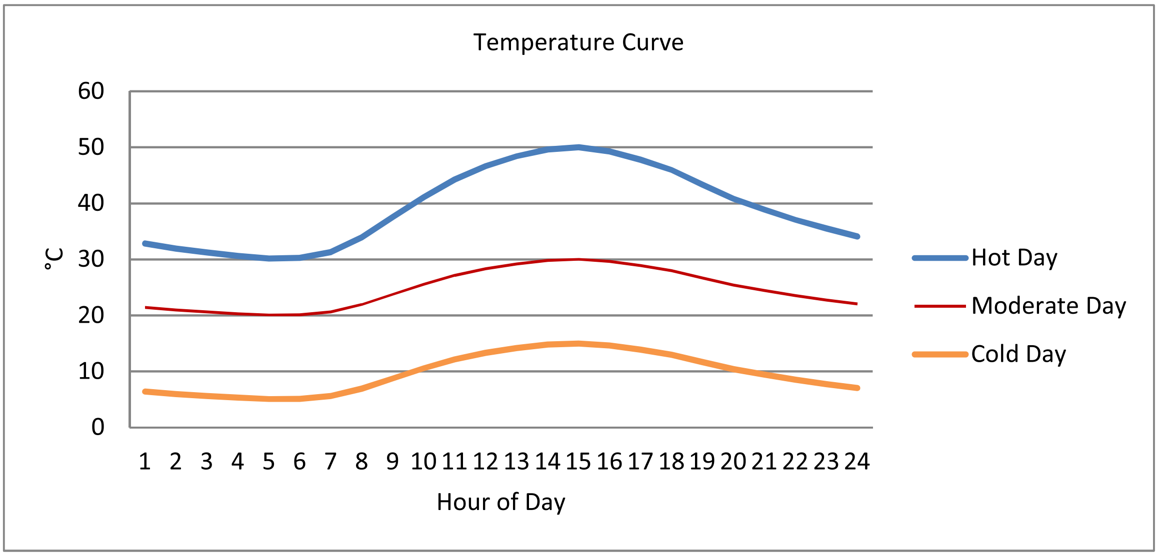

FIGURE 5. **Temperature curve.**

d_{dr} *– demand for energy r*

p_{th} *– timeslot hours. Equals 1 if hour h is in timeslot* $t \in T$*, 0-otherwise*

r_{dh} *– rate per kilo watt hour for hour h, on day d*

Variables:

x_{dhr} *=1 if energy type r is assigned to time h on day d, 0-otherwise*

y_{dt} *=1 if energy type r use office that is assigned to t on day d, 0 - otherwise*

Constrains:

$$\sum_{h=1}^{24} x_{dhr} = d_{dr} \quad \forall r = 1 \ldots 7, d \in D \tag{9}$$

$$\sum_{r=1}^{7} x_{dhr} = 2 \quad \forall h = 1 \ldots 24, d \in D \tag{10}$$

$$\sum_{t=1}^{3} y_{dt} = 1 \quad \forall d \in D \tag{11}$$

$$x_{dhr} = \sum_{t=1}^{24} y_{dt} p_{th} = 1 \quad \forall h = 1 \ldots 24, d \in D, \quad j - \text{office energy} \tag{12}$$

$$x_{dh6} = 1 - x_{dh7} \quad \forall h = 1 \ldots 24 \tag{13}$$

Where HVACd is the schedule of the day, e_{dhr} is a matrix derived from EnergyPlus that incorporates different activities' energy requirements, with rows representing different times of day ('day' being the full cycle with 24 distinct 1-hour intervals) and columns representing the various amounts of energy required by activities such as office work, loading, packing, heavy machine work, moderate machine work with humans, moderate machine work without human involvement, and light machine work. x_{ij} is the matrix of decision variables for selection of energy over specific time slots. In this equation, every activity requires a certain amount of time to finish the activity successfully, constraints are addressed by (1) and (9) in both models A and B. Since we intend to have parallel activities at every hour of the day, we have (2) and (10) that represents this constraint. Similarly, equation (3) & (4) makes sure every activity takes place once and only once in a day. Since activities MM1 & MM2 have special requirements, this constraint is taken care by (5), (6), (7), and (8) for eight hours of activity scheduling. Whereas, for 1-hour activity scheduling office work has special requirement that is taken care by (12) and (13).

IV. RESULTS

Figures 3 and 4 compare the costs of various activity sequences for 8-hour and 1-hour time slots respectively. When comparing the cost consumption of 8-hour time slots and the minimum and maximum case activity sequences, there is the possibility of saving 27% of the usual costs for the hot day, saving 24% on the cold day, and saving 27% on the moderate day. By comparison, when considering a 1-hour time slot we can potentially save up to 33% of HVAC costs for the hot day, 31% for the cold day, and 38% for the moderate day. It is interesting to note that the cost required for heating in the cold day is significantly less than the cost needed for cooling on the hot and moderate days. There are two reasons for this difference: first, the heat is dissipated into the environment by machines and humans. Second, in our simulation we used reverse cycle HVAC because this offers a maximum efficiency of 100% when the electricity is converted to heat [34]. Also, the reverse cycle design allows for the capture of heat from outside and its transmission to the inside environment [35]. Therefore, the costs associated

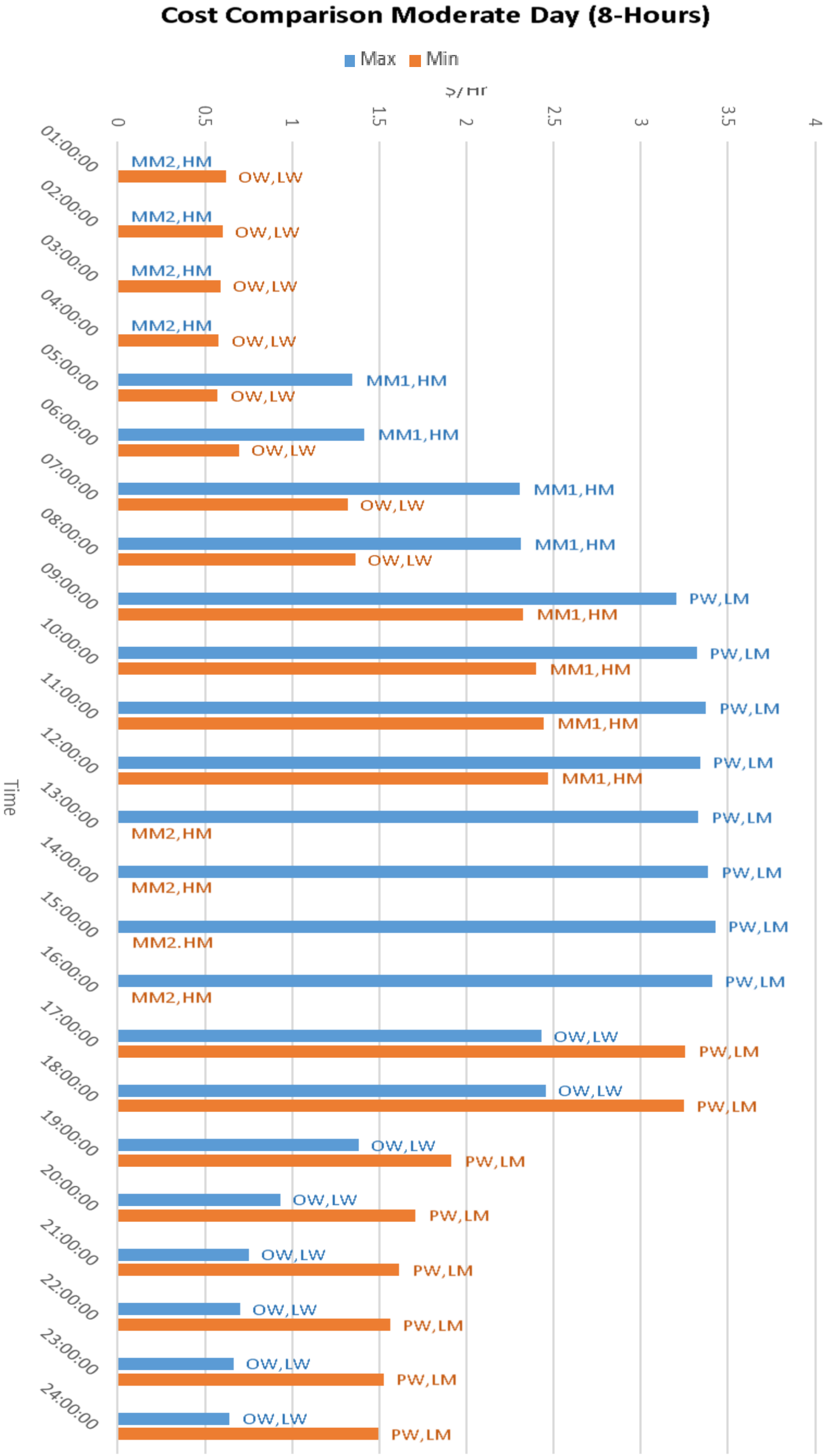

FIGURE 6. Cost comparison moderate day (8-hours).

with heating can be as low as one-third of traditional element heaters [34].

For simplicity, we are using a detailed cost consumption graph of the best possible activity scheduling for one

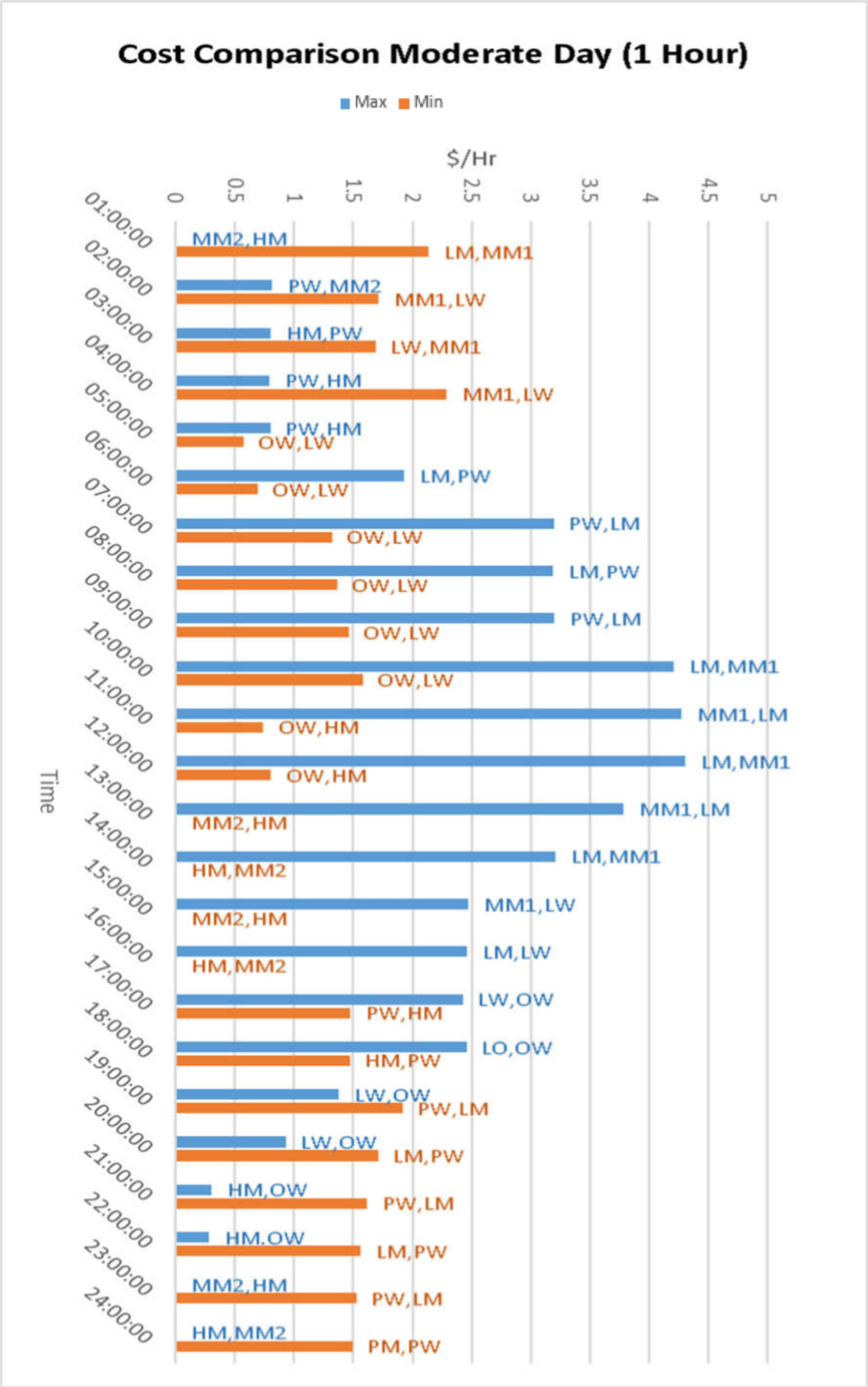

FIGURE 7. Cost comparison moderate day (1-hour).

moderate day rather than demonstrating all 90 combinations of one day 8-hour time slots, since the moderate day has the highest percentage of potential cost savings. As expected, an increase in temperature means a similar increase in cooling demands, which can be seen by contrasting figure 5 with figures 6 and 7. In this manner, temperature changes greatly impact HVAC energy requirements, and result in different cost requirements depending on their severity, but the ultimate consequences differ by the activity being performed in such temperatures. Figures 6 and 7 show the minimum and maximum costs demanded by and during various activities.

TABLE 2. Cost comparison.

Day	Time Slot	Total Cost Maximum	Total Cost Minimum	Saving
Cold	8	15.2129	11.60056	23.74%
Cold	1	15.772	10.7491	31.85%
Hot	8	81.00	59.041	27.11%
Hot	1	82.92	55.497	33.07%
Moderate	8	44.11	32.295	26.79%
Moderate	1	47.195	29.134	38.26%

When considering the maximum cost utilization from figure 6, which is the worst performing scheduling of the activities, the HM group with no need for HVAC was scheduled from 0100 to 0800 hours, which is the coolest time of the day. Furthermore, the moderate machine groups were also scheduled during the same time, i.e. 0100 to 0400. The packing work and the light machine work activities carried out during the hottest time (from 0900 to 1600) of the day, while office work and loading work, which require significantly less energy utilization as compared to other activities (refer to table 1) were scheduled when temperature started dropping (1700 to 2400). However, considering the minimum cost utilization, which is the best case of scheduling the activities over the day, the office work and the loading work were best scheduled during the time when temperature start to rise from cool to warm, i.e. 0100 to 0800. In this version, the HM and MM2 groups were scheduled during the hottest time (0900 to 1600) of the day and HVAC was off except for moderate activity 1. The packing work and light machine work were scheduled when temperature started decreasing (1700 to 2400). The 1-hour time slot gave us more flexibility to schedule activities based on energy consumption and weather forecasting. This flexible scheduling of activities can yield up to 11.47% of further cost savings. Table 2 highlights the maximum cost (worst case scheduling) and minimum cost (best case scheduling) as well as saving percentages for respective days, thus demonstrating how the efficient scheduling of activities can help to decrease HVAC costs significantly.

V. FUTURE WORK AND PRACTICAL APPLICATION

We have shown that cost savings of up to 38% are possible through the efficient scheduling of activities based on HVAC usage while considering weather forecasting for the test data sets used.

Future work could explore real-time weather streams from a weather forecasting bureau to schedule real-time industrial activities. This could be further linked with emerging technologies such as Smart Grid and the Internet of Things (IoT), decreasing costs further by automating the work of weather monitoring and making associated operating changes. Smart Grid, for instance, is a technology that provides electricity to consumers based on usage history as well as provider-sourced signals and incentives [36]–[38]. Different price models such as real-time pricing or Time of Use (ToU) tariffs can also be incorporated depending on a specific business's requirements. Conversely, IoT involves ubiquitous computing and computational networking, utilizing end devices such as sensors to provide an overview of devices' continual exchange of data. An IoT-driven building could offer even greater cost reductions through its constant, synchronous monitoring of HVAC requirements, using smart meters and sensors to automatically maintain appropriate temperatures for the activities then in progress [39].

The most practical application of these possibilities, then, would combine the abovementioned technologies, as perhaps demonstrated by an industrial building in which both the workers and the physical structures would be equipped with smart devices feeding into its IoT. In this model, real-time information on energy cost from the grid operator, combined with real-time data on consumption from the building's IoT, could lead to more efficient, cost-driven scheduling. In this model, factors such as internal temperature, CO_2 levels, etc., could also be monitored via the building's IoT, and real-time information on current and upcoming weather conditions could be added via external devices or third-party information systems.

Our findings thus demonstrate that activity scheduling can significantly decrease an industrial building's energy requirements while also in turn decreasing costs, since a building's requirements for two major HVAC functions – heating and cooling – are highly dependent upon external weather conditions. An optimal solution, such as the smart integrated system we have proposed above, would be able to collect a variety of relevant data from internal and external sources before processing it to create real-time schedules for human- and machine-based activities that consume a minimal amount of energy – and thus, cost – for HVAC activities. Such a system would also provide both the opportunity and the logistics for making more efficient scheduling decisions.

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