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Optimizing HVAC Energy Usage in Industrial Processes by Scheduling Based on Weather Data

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ABSTRACT Industrial buildings are demonstrating increasing rates of energy consumption, with heating, ventilation, and air conditioning (HVAC) typically constituting over 50% of this consumption. However, these energy requirements are heavily influenced by weather conditions based on the season, the time of day, and different in-building activities. These activities take place in industrial setup over 24 h and have different HVAC energy requirements. In this paper, we propose a binary (0,1) integer linear programming approach to efficiently schedule activities based on weather forecasting, thus minimizing the energy required by HVAC. Experimental results show that energy consumption can be reduced by up to 30%.

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

I. INTRODUCTION

Energy is a vital element for growth and development, but the world's energy consumption rates are expected to increase by 33% from 2010 to 2030 [1], making the energy crisis one of the 21st century's most pressing challenges to sustainable human development [2]. One of the most sustainable and effective ways to overcome this problem is by improving efficiency in the commercial, residential and industrial sectors, leading to major interest in finding ways to utilize energy more efficiently in these sectors.

The buildings account for 40% of the world's energy consumption, and 72% of the U.S.'s total energy consumption [3]. Industrial and commercial buildings, though, constitute most of these budgets, as they require far more energy than residential buildings [4]. This difference stems from industrial buildings' special or unusual requirements (such as heating, cooling, health, and safety standards), and meeting or maintaining these standards often has a significant impact on energy requirements [5]. Industrial buildings thus have great potential for reducing both energy requirements and environmental impact, but reducing their energy consumption could also affect cost savings that would play an important role in commercial success [6].

The industrial sector, which consists of buildings, machines, and processes, accounts for 35% of the world's total energy consumption [7]. A major focus of any industry is to cut down its energy cost, which can be achieved by re-scheduling activities and re-arranging processes as long as production continues. Significant improvements in energy consumption could be made by adapting buildings' use of Heating, Ventilation, and Air Conditioning (HVAC) systems around daily activities, since HVAC systems use up to half of any given industrial building's total energy requirements [8] and lighting accounts for a fifth of the remainder [13]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides guidelines and standards for indoor air quality, energy efficiency, refrigeration, and sustainability [9]–[12], creating a comfortable baseline for business and residential purposes. In the industrial and commercial sectors, buildings' dependence on HVAC systems also stems from equipped machinery, which may range from office equipment to assembly lines, production machines, and autonomous self-operating machines. Machines raise the buildings' dependence on HVAC systems because their operating temperatures range from -40 to 85°C [14]. Because optimal human comfort requires an ambient temperature ranging between 19°C to 23°C in the winter and 21°C to 26°C in the summer [15], [16], an industrial or commercial building's HVAC systems must account for cooling down the machines as well as providing these ambient temperatures based on the current season. Thus, the building's internal environment must be suitable both for humans as well as for the proper functioning of machines. Another factor that influences the environment within an industrial building is heat generation from the inhabitants' bodies. The human body on average produces 100 watts heat per hour depending on activities and metabolic rate. The ASHRAE standard 55 explains Metabolic Equivalent of Task (MET) for different activities [16]. For example, an office staffer reading, writing, and performing similar work-related functions while seated already produces 1.0 MET units, which is equivalent to 100 watts of energy per hour. In an industrial set-up people are involved in many high-capacity activities, including loading, packing, and machine work in addition to office work. All of these activities further heat the building, adding further strain on the HVAC systems. Machinery, season, ambient temperature preferences, and human heat generation are all thus important factors in an industrial building's use of HVAC systems. Therefore, more efficient scheduling of different activities inside industrial buildings can help to save both money and energy by decreasing the desperate need for constant, high-capacity HVAC use.

II. SCHEDULING

The scheduling of activities in industrial or commercial buildings is similar to process scheduling in real-time operating systems [17]. Both scheduling systems have deadlines and resource constraints. In real time systems, the scheduling allows processing of tasks within time and resource limitations, while scheduling activities within buildings will be constrained by the need to achieve goals related to business needs. Different process scheduling like First Come First Serve (FCFS), Earliest Deadline First (EDF) etc. can be also applied to industrial activities depending on the nature of the tasks and availability of both resources and workers, providing that the business rules are not disturbed.

This study considers four activities of the industrial setup (Machine work, loading, packing and office work) and aims to find the best possible scheduling strategy for these activities that can save HVAC costs. Recent research has concentrated on energy efficiency in HVAC scheduling [18], [19] while maintaining the comfort level of the occupants and indoor air quality standards [20]–[22].

There are two main strategies of HVAC scheduling within industrial or commercial buildings. The first uses advance control to make sure inside temperature follows pre-specified trajectories with variation in a comfort band, while minimizing the energy consumption. The related work in this strategy, which can be found in [23]–[26], uses Model Predictive Control (MPC) to handle multivariable and uncertainty. The second strategy focuses on conventional scheduling techniques. Using these techniques, 24 hours are divided into occupied hours with accordingly set-point temperatures [27], set-up and line-up techniques [28], [29], which increases/decreases temperature during occupancy based on set-point and linear pattern. The MPC model focuses more on the control and design strategies for HVAC. As this paper focuses on scheduling activities based on energy requirements, this means that energy requirements for buildings' internal ambient temperature will change based on the occupancy, activities scheduled, and outside temperature, thus 24 hours are divided accordingly. To demonstrate, this simulation uses a conventional HVAC model provided by EnergyPlus.

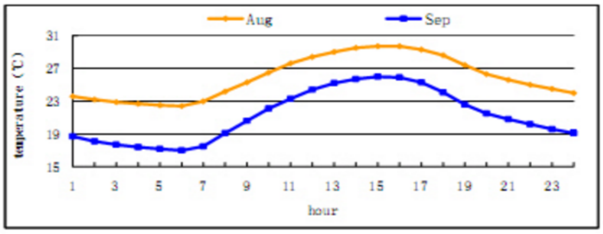

FIGURE 1. Temperature changes of Beijing.

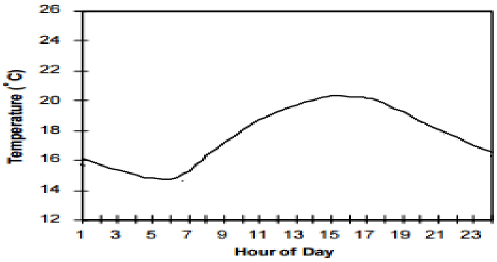

FIGURE 2. Temperature changes for Toronto [31].

The scheduling of activities in an industrial set-up can be influenced by weather, since the inside environment of buildings fluctuates due to weather conditions. Therefore, to maintain a comfortable environment, weather forecasting could be used. In this study, we analysed the temperature curves over one month for several of the world's different industrial cities, namely Beijing, Toronto, Seoul, San Paulo, Mumbai, Jakarta, Karachi, Moscow, Istanbul, Mexico City, Shanghai, Tokyo and New York City. Among these cities, Beijing, Toronto, Seoul, San Paulo, Mumbai, Jakarta, Karachi, and Mexico City typically follow a relatively smooth curve for temperature change. This temperature change can been seen in figure 1 for Beijing [30] and figure 2 for Toronto [31].

In the case of Beijing, the minimum temperature recorded for a given day in September was around 17 degrees centigrade, whereas the maximum temperature was approximately 26 degrees. On the other hand, the temperature range for Toronto was 13 to 20 degrees centigrade. These temperature graphs for both cities follow a relatively smooth curve. Furthermore, the annual weather data figure 3 for Shenyang, Cambria, Tianjin and Washington, used by Liu *et al.* [19] in their study, also follows a smooth curve. This means temperature variations on a particular day for these cities generally follow a smooth change curve rather having abrupt and frequent changes. Therefore, weather forecasting could allow efficient energy management by shuffling different activities to conserve energy. Activities in industrial buildings can be rearranged based on the weather forecast and HVAC energy characteristics of those tasks. For example, on an extremely hot day people can work in the night shifts while the autonomous self-operating machines can be operated in the daytime since machines can operate in high temperatures.

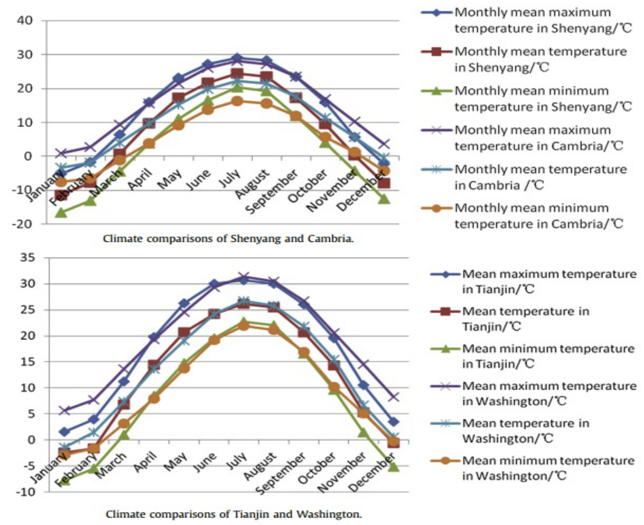

FIGURE 3. Shenyang, Cambria, Tianjin and Washington [19].

TABLE 1. Activity power consumption.

Group	Watts/person (Watt-hour)	Lighting required (Watt-hour)	Electric Machine Consumption (Watt-hour)	Total
Machine (M)	-	684	2500	3184
Office work (O)	110	684	250	1044
Loading work (L)	234	684	1000	1918
Packing (P)	216	684	1200	2100

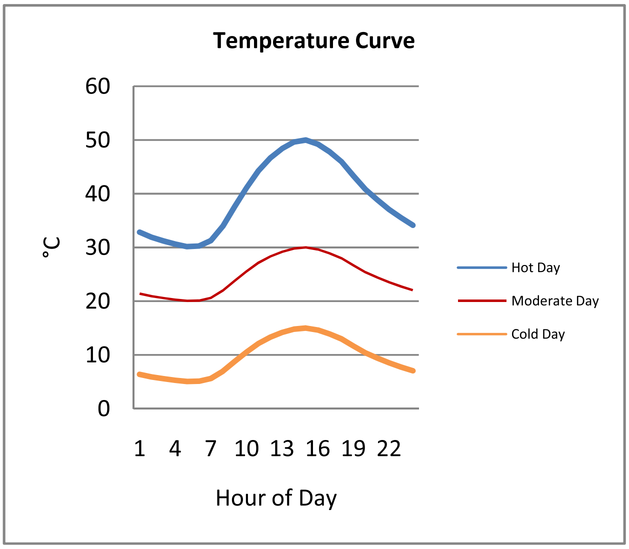

FIGURE 4. Temperature curve.

We use weather data to find the best activity suitable for that particular time period.

This paper simulates four industrial activities: Office work (O), Loading work (L), Packing work (P) and Machine work (M), to be scheduled over a 24-hour timeframe. We will be comparing different scheduling combinations for HVAC energy requirements and propose an efficient scheduling strategy that can save energy. The 24 combinations in which these activities can be arranged are (OLPM, OLMP, MOPL...).

Assumption: The following assumptions were made:

1) Fixed electric tariff is used as we are focusing on energy use rather than cost. However, cost can be analysed in future work.
2) For simplicity, the maximum working hours for any activity is restricted to 6 hours to represent 4 shifts of 6 hours each over a 24-hour period.
3) No parallel activities can be performed to simplify modelling. However, parallel activities can be analysed in future work.
4) Any activity can be performed during any time. As we want to find the optimum scheduling for minimising energy consumption, so we must examine activities performed at all possible times.

III. EXPERIMENTAL SETUP

People are placed into four groups. Within each group the variable of interest are Watt per person, lighting required, and power consumed by the machines. The values of interest are taken from [14], [18]. In an industrial se-tup, machines and light dissipate heat into the environment. The principal factor is how much heat is produced by each type of equipment. The table below highlights these factors and we divide them into four main groups as:

In our simulation, these values are fixed, so we look for HVAC energy consumption based upon them. To find the energy requirements based on Table 1 for HVAC we use EnergyPlus version 8.0.4 with temperature ranges for three different days: a hot summer day, moderate summer day and a cold winter day. Figure 4 shows temperature curves for these three different days. On the hot summer day, the outside temperature varied from 30 °C to 50 °C. On the moderate summer day, the outside temperature varied from 20 °C to 30 °C. During the winter day, the outside temperature was varied from 5 °C to 15 °C. We use a single floor rectangular building 30.5 m (100 ft) × 15.2 m (50 ft) × 3m (10 ft) in the simulation. There are windows on all 4 facades. The inside building temperature was maintained at 22 °C, which is the mean temperature of summer and winter [15], [16] and approximately in the middle of human comfort range. As mentioned earlier, as machines can operate at high temperatures, we turn off HVAC during the shift of machine work for energy conservation.

The values in table 1 are fed into the EnergyPlus simulator along with outside temperature range, inside building set temperature and total building size to compute heating/cooling energy requirements for all the activities. The EnergyPlus outputs hourly energy requirements for heating/cooling, into a solution meter file. We call this as e_d (energy requirement of the day).

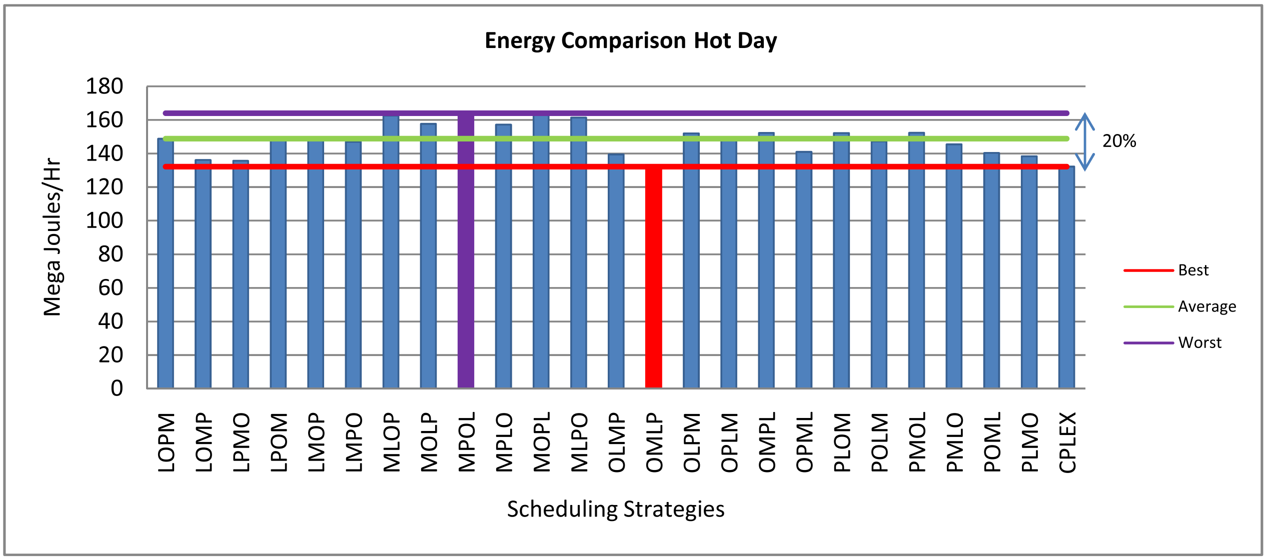

FIGURE 5. Energy comparison of HVAC for hot day.

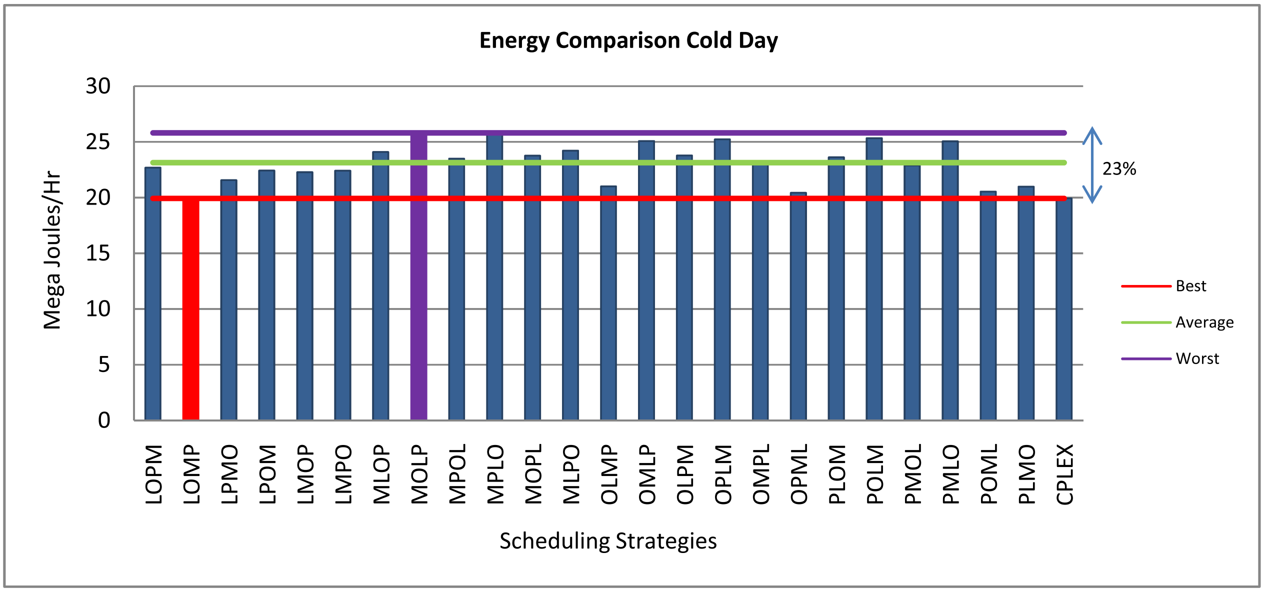

FIGURE 6. Energy comparison of HVAC for cold day.

A. MATHEMATICAL MODEL

In this paper, the activity scheduling problem is formulated into a Binary (0,1) Integer Linear Programming problem with an objective to minimize the energy consumption in a day.

Objective:

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

Parameters:

$D = \text{set of days}, \ \{1, 2, 3\}$

$H = \text{set of hours}, \ \{1, 2 \ldots 24\}$

$R = \text{set of activities energy requirments}, \ \{1, 2, 3, 4\}$

$d = \text{index of day}, \ d \in D$

$h = \text{index of hour of day}, \ h \in H$

$r = \text{index of activity requirment}, \ r \in R$

Variables:

$$x_{dhr} = 1, \text{ if energy type } r \text{ is assigned to time slot } h \text{ on day } d; \text{ else } 0$$

Constraints:

$$\sum_{h\in H} x_{dhr} = 6, \forall r \in R, d \in D \tag{1}$$

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

$$x_{dhr} = x_{1rd}, \quad \forall h \in \{1, 2, 3, 4, 5, 6\}, \ d \in D, \ r \in R \tag{3}$$

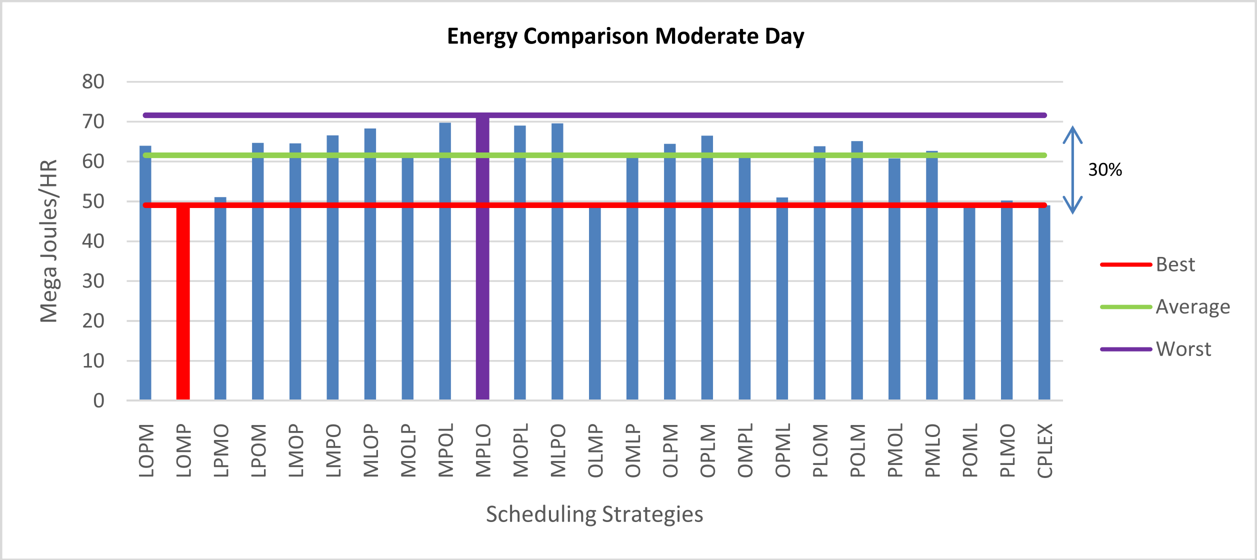

FIGURE 7. Energy comparison of HVAC for moderate day.

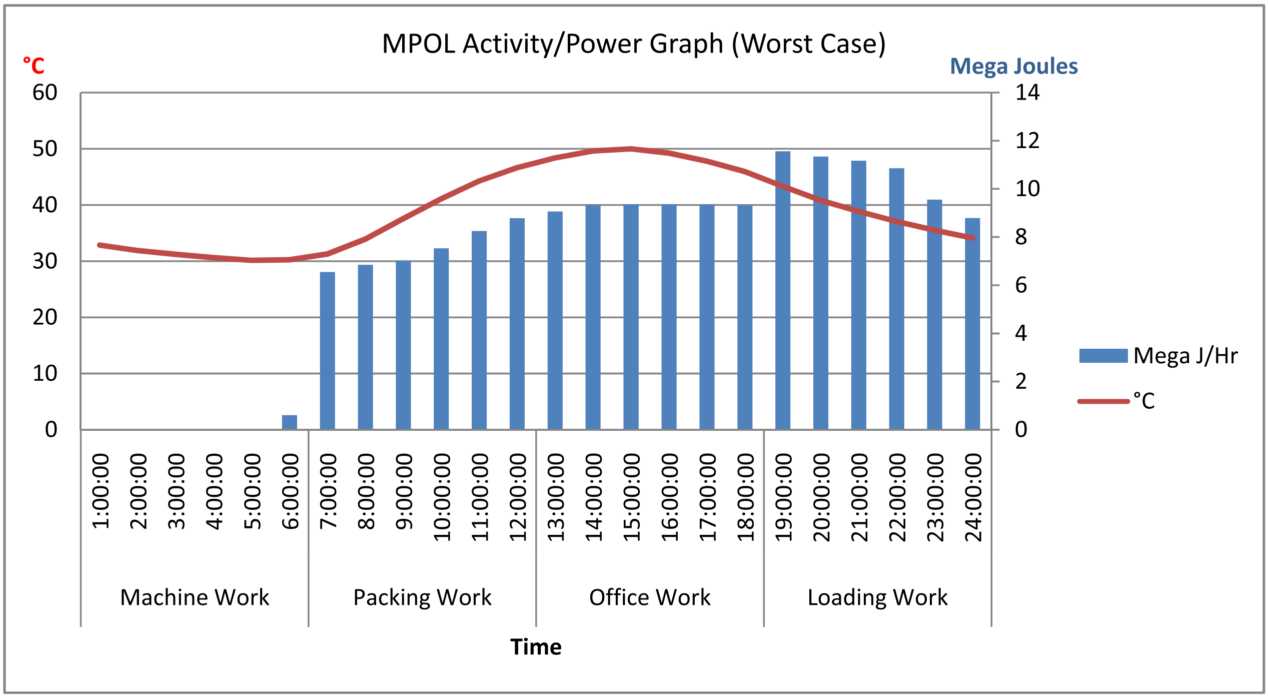

FIGURE 8. Activity/power graph of MPOL (worst case).

$$x_{dhr} = x_{7rd}, \quad \forall h \in \{7, 8, 9, 10, 11, 12\}, \ d \in D, \ r \in R \tag{4}$$

$$x_{dhr} = x_{13rd}, \quad \forall h \in \{13, 14, 15, 16, 17, 18\}, \ d \in D, \ r \in R \tag{5}$$

$$x_{dhr} = x_{19rd}, \quad \forall h \in \{19, 20, 21, 22, 23, 24\}, \ d \in D, \ r \in R \tag{6}$$

Where $HVAC_d$ is the schedule of the day 'd'. e_{dhr} is a matrix obtained from EnergyPlus, containing energy requirements for activities, with rows representing time of the day (24 hours with one hour intervals) and columns representing energy requirements for office work, loading, packing, and machine work. Each activity should be scheduled for 6 consecutive hours in a day and this limitation has been addressed by the constraints (1), (3), (4), (5), (6). To avoid parallel activity scheduling we have added constraint (2) to the model, making sure that each hour of the day is dedicated to only one activity.

TABLE 2. Energy requirements of HVAC for hot day.

	Activity (MJ) 01:00 to 06:00	Activity (MJ) 07:00 to 12:00	Activity (MJ) 13:00 to 18:00	Activity (MJ) 19:00 to 24:00	Total (MJ)	Energy Usage vs Average
Best Case (OMLP)	32.70 **Office**	0 **Machine**	55.804500 **Loading**	43.69 **Packing**	132.20	-17270645 (-10%)
Average Case (LPOM)	48.68 **Loading**	44.98 **Packing**	55.80 **Office**	0 **Machine**	149.47	0
Worst Case (MPOL)	0 **Machine**	44.98 **Packing**	55.80 **Office**	63.27 **Loading**	164.06	+ 14590798 (+10%)

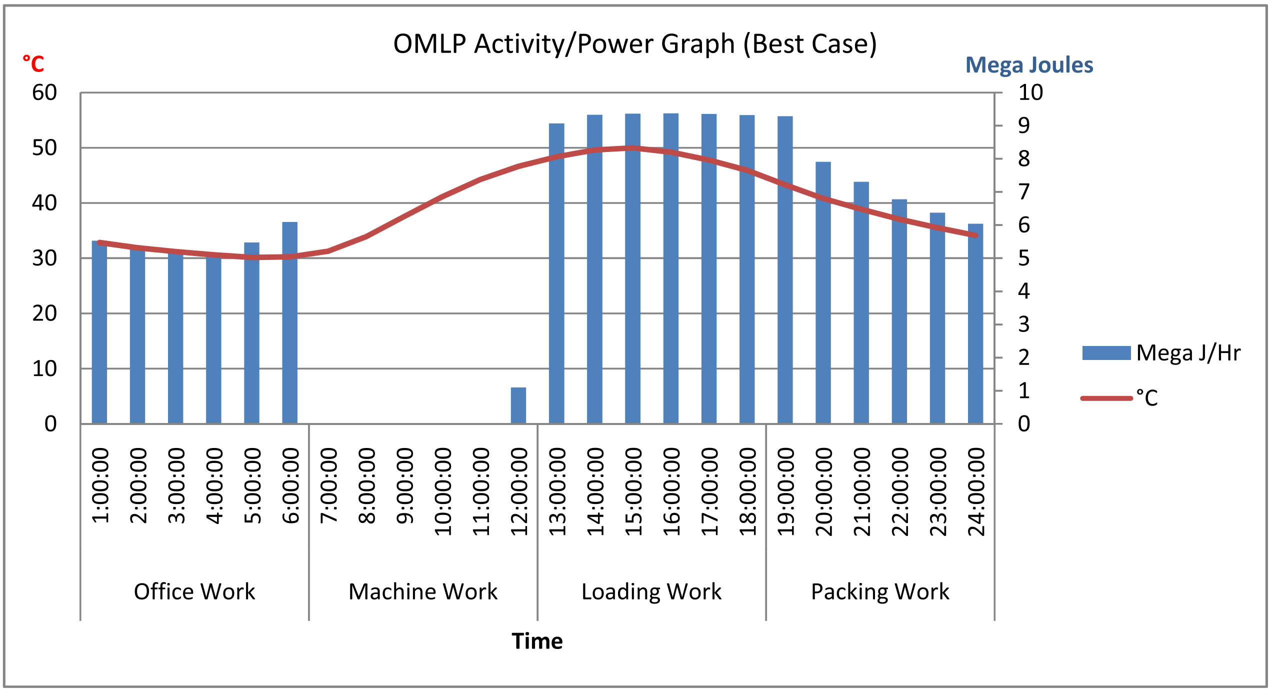

FIGURE 9. Activity/power graph of OMLP (best case).

IV. RESULTS

A. OVERVIEW

Based on figure 4 temperature curves, figures 5, 6 and 7 show energy consumption of all activity sequences for the hot, cold and moderate days respectively. When comparing energy consumption of the best and worst case activity sequences for these days, there is a potential energy saving of 20% for the hot day, 23% for the cold day and 30% for the moderate day.

B. DETAILS

For simplicity, we are showing detailed HVAC power consumption graphs of three activities for one hot day rather than 72 combinations of all three days as the hot day has the highest energy consumption. Figure 8 shows activity and power consumption for MPOL, which is the worst case of energy HVAC consumption. Figure 9 shows activity and power consumption for OMLP, which is the best case of HVAC energy consumption. Figure 10 shows activity and power consumption for LPOM which is the average energy HVAC case.

Figures 8, 9 and 10 show, as expected, that as the temperature increases the demand for cooling also increases. Changes in temperature have a great impact on HVAC energy requirements, but the impact is different for different activities.

Power consumption for activity sequences is based on total power for applicable activities given in Table 1, which changes based on temperature as shown in Figure 3. These changes in temperature have a great impact on HVAC energy requirements. For example, in figure 8 and 10 the office work activity consumes approx. 9 Mega Joules/hour when it was the hottest time of the hot day. Whereas, in figure 9 the office work activity was in the coldest time of the day and consumes approx. 5.5 Mega Joules/hour.

Table 2 summarizes (total joules for the time period) best, average and worst case activity sequences as shown in

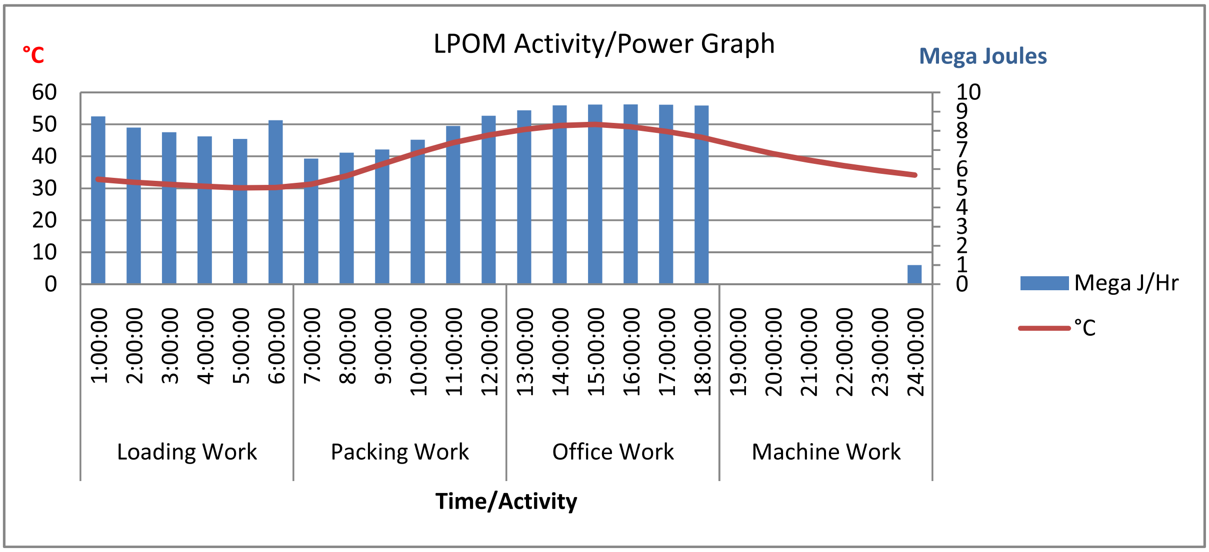

FIGURE 10. Activity/power graph of LPOM (average case).

figures 8, 9 and 10 for the hot day from figure 4. The table shows an energy saving of 10% for the best case activity sequence compared with the average case activity sequence, and a saving of 20% compared with the worst case. Note that the third activity in the best case (Loading) has the same energy requirement as the average case activity (Office). This is because the temperature is at maximum so HVAC is at peak energy usage. In the average case the activity sequence is LPOM, but swapping the Loading with Machine activity gives the worst case (MPOL). Furthermore, we have turned on HVAC at the end of machine activity, so that the comfort level of next activity group may not be compromised. Thus, selecting activities with respect to time and temperature can impact energy usage by up to 20%.

V. SUMMARY

We have shown that estimated scheduling of activities based on weather forecasting can be used to reduce energy consumption. Our CPLEX model will always select the best possible with potential energy savings of up to 30% depending upon the weather conditions. From the experimental analysis, it can be observed that the optimum scheduling strategy is the basis of energy savings. Scheduling activities on an hourly basis rather than in six hour blocks can yield a further 8% reduction in energy usage, however scheduling activities for only one hour at a time may not be practical.

VI. FUTURE WORK AND PRACTICAL APPLICATION

Future work could enable scheduling of activities with cost as the objective measure instead energy usage and allow scheduling of parallel activities, which requires a prediction model to forecast the dynamic prices. This can be assisted by realtime scheduling of activities using Smart Grid and Internet of Things (IoT) instead of estimated scheduling. Smart Grid is an emerging technology that provides electricity to the customers in a controlled/efficient manner considering user behaviors along with signaling information and incentives from the operator [32]–[34]. On the other hand, IoT is the concept of ubiquitous computing of the end devices like sensors. IoT in an intelligent building can be used to save energy with profound applications like controlling and monitoring HVAC systems, monitoring the energy consumption through smart meters, monitoring of sensors, etc [35].

The practical application will be a merger of the mentioned above technologies where in any industrial organization, workers and administration are equipped with smart devices via IoT. The realtime information from the grid operator (cost), combined with realtime data from IoT (consumption) can be used for more efficient scheduling to reduce costs based on incentives from the grid operator. Temperature, pressure, CO2 etc. can be monitored via IoT. Weather data can be fed into the system using sensors as well as through third party weather information systems via the internet. HVAC can be controlled through smart devices. From the experimental results it can be seen that human activities can significantly increase energy requirements for heating and cooling depending upon the weather conditions. The system should be able to collect the relevant data, process it and come up with the real time optimum scheduling strategy for human activities with minimum consumption of energy/cost for heating and cooling. Such systems should also predict the demand and supply and rearrange activities based on the available options. Furthermore, mostly cities weather change follow a smooth curve for temperature variation, however if we apply our approach for cities with abrupt temperature change, further testing is required.

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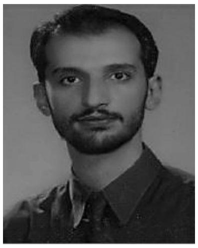

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