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Smart Manufacturing using Control and Optimization

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Abstract: ***Energy management has become a major concern in the past two decades with the increasing energy prices, overutilization of natural resources and increased carbon emissions. According to the department of Energy the industrial sector solely consumes 22.4% of the energy produced in the country. This calls for an urgent need for the industries to design and implement energy efficient practices by analysing the energy consumption, electricity data and making use of energy efficient equipment. Although, utility companies are providing incentives to consumer participating in Demand Response programs, there isn't an active implementation of energy management principles from the consumer's side. Technological advancements in controls, automation, optimization and big data can be harnessed to achieve this which in other words is referred to as "Smart Manufacturing". In this research energy management techniques have been designed for two SEU (Significant Energy Use) equipment HVAC systems, Compressors and load shifting in manufacturing environments using control and optimization. HVAC systems being one of the major energy consumer in manufacturing indus - tries was modelled using the generic lumped parameter method. An Electroplating facility named Electro - Spec was modelled in Simulink and was validated using the real data that was collected from the facility. The Mean Absolute Error (MAE) was about 0.39 for the model which is suitable for implementing controllers for the purpose of energy management. MATLAB and Simulink were used to design and implement the state - of - the - art Model Predictive Control for the purpose of energy efficient control.***

Keywords: HVAC systems, Model Predictive Control, Smart Manufacturing Research Milestones, Demand Side Management

1. Introduction

With the growing population and incessant demands, energy management and con - serration has become a major challenge in the smart grid. Demand side management programs are being initiated around the globe so as to reduce the overall energy load and emissions that pose a threat to the non - renewable forms of energy and environment respectively. As a result, in the recent years, there has been an exponential increase in the interest for energy management research. According to energy. gov, the Department of Energy of United States spends approximately $5.9 on energy re - search for clean and better utilization of energy resources. Besides the United States, South Korea and Germany have been actively implementing "smart" manufacturing techniques to optimize production, energy consumption and cost in response to this activity [2]. Process and other energy intensive industries have already resorted to smart systems to run plants in an economical and productive manner. The purpose of this thesis is to investigate and implement the potential overlooked energy saving practices for major energy consuming systems in manufacturing industry using optimization and control.

Smart Manufacturing

Smart manufacturing is a type of manufacturing where the optimized techniques and processes are used to obtain maximum yield while keeping the energy footprint and costs low. This is made possible with the advanced modelling, controls, op - itemization, and big data that has been on rise in the past decade. In fact smart manufacturing is regarded as the industrial revolution 4.0 as a result of this. Ac - cording to The National Institute of Standards and Technology (NIST) [3], Smart Manufacturing systems are fully integrated, collaborated manufacturing systems that Respond in real time to meet changing demands and conditions in the factory in the supply network and customer needs. This is exactly what this thesis is attempts to achieve by using tapping the energy management techniques using control and optimization.

Demand Side Management

Demand Side Management refers to the energy measures taken from the demand side (consumer) to reduce the electricity bills and utility infrastructure costs. This is usually done by shifting or scheduling the consumption of energy from high demand periods to low demand ones. For example costumers could use renewable resources or energy storage devices like batteries for their energy needs during the high demand periods. Another simple yet effective way would be to prioritize the energy needs and schedule the low priority energy needs during the off peak periods. DSM can also be implemented at subsystem level by carrying out energy audits to find out potential energy saving methods, installing energy efficient equipment like VFDs, improving the schedule of machines, upgrading the control systems of the energy demanding systems such as the HVAC. The following figure shows how load shifting can be used to smoothen the peak demand and hence the demand based charges which is one of the most commonly used DSM techniques.

Research Milestones

Problem Statement: The HVAC systems together with the air compressors and electric motors consume more than half of the total energy in the manufacturing sector. This significant share of energy consumption is a result of inefficient energy management practices which in turn strain the utility companies and increase the utility bills and carbon footprint. Hence, there is a dire need of optimizing the energy consumption through energy management and energy efficient control and optimization system.

Major objectives in this research are

1) Identification and selection of potential energy management techniques and pro - cases to increase energy efficiency and reduce costs
2) Development of a mathematical model that can schedule

the flexible machines with the help of the Demand Side Management.

3) Development of a compressor scheduler that can distribute the loads between compressors so that the demand is satisfied in a cost effective manner
4) Generic modelling of a manufacturing facility using lumped parameter mod - elling and validation using real data
5) Using state - of - the - art MPC to reduce the total energy consumption by the HVAC fans while meeting the temperature requirements of the manufacturing facility.

2. Literature Review

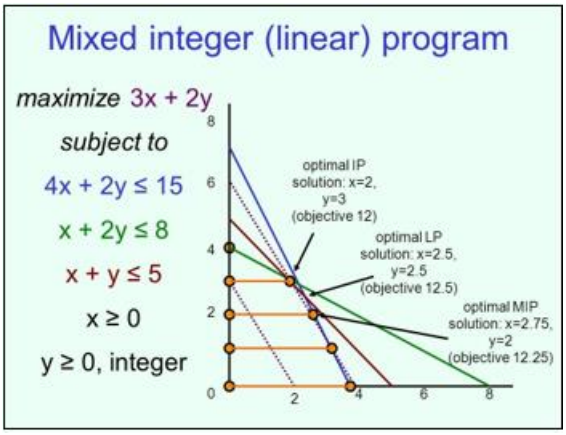
Linear Programming

The purpose of this chapter is to introduce the readers to the concept of scheduling. In a typical scheduling problem, the goal is to find a set of assignments to machines so that a given objective is minimized or maximized. This is a common problem that is solved in the field of Computer Science and is referred to as Job Shop Scheduling (JSP). In such a problem, there are “m” jobs that need to be completed by “n” machines of different processing times and powers. The objective is the assignment of these jobs to the machines such that the jobs are completed in the least amount of time and effort (power consumption.

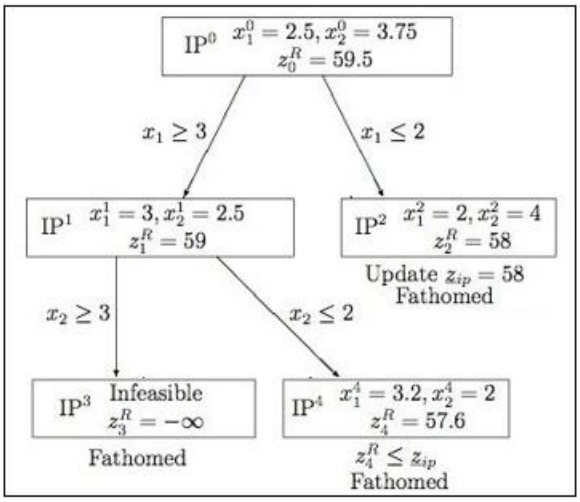
The maximum Z = 34 which occurs at point (6, 4) and the minimum Z = 34 occurs at (- 1, - 3). The above example is a simple illustration of LP, however when there are 3 or more variables LP problems cannot be simply solved by plotting as higher dimension spaces are difficult to visualize. Such problems are solved using simplex, Big M and other advanced LP techniques. MIP has been used in this thesis for the scheduling problems as it is required to find the status of machines (integer) and the power/capacity assignments (variable).

Brand and Bound Algorithm

The complexity of solving MILP problems is NP - hard which means that they cannot be solved by any known algorithm in polynomial time and the complexity of the problem increases exponentially with time [27]. This type of problems are mostly solved using Branch and Bound which searches for the solution by dividing the relaxed problem it into smaller sets of problems and without actually enumerating all the possible solutions which significantly reduces the time complexity of the problem.



This algorithm is similar to how decision trees that have nodes and branches work. The algorithm starts with an initial computation of the relaxed solution (solution with only equalities) at the root node. From the root node, more nodes (or sub problems) are branched out (or explored) by increasing or decreasing the value of the decision variables. Whenever, a node is found to lead to an unfeasible solution (less optimal than parent node) or violate the bounds of the decision variables, that node is fathomed (the children nodes of that node are not explored and other adjacent nodes is explored). This process continues until the optimum solution (min or max) is found.



All of these are input as matrices and the position of each matrix element corresponds to the respective decision variable that is involved in the equation/inequality/cost function. Branch and Bound algorithm is then used to find the optimal solution to the problem.

Optimal Control

This chapter serves to provide a basic understanding about optimal control and the Model Predictive Control that has been used for the energy efficient control of HVAC systems in manufacturing industries. There are several control techniques that are used in industries such as the Programmable Logic Control (PLC), Proportional Integral Derivative (PID) Control and ON/OFF controller. Although these control techniques satisfy the performance requirements but they are not the most optimum input to the actuators. In case of ON/OFF controller, the input goes from zero to full and keeps running the machine until the set point is reached. Although this type of control has its roots from optimal control, the response is oscillatory about the dead band which is undesirable and it starts and stops the machine quite frequently. As for the PID control, it may be able to continuous adapt and follow the set point, however it cannot handle Multi Input Multi Output System (MIMO) and constraints and is susceptible to integral windup. PLC control is purely based on logic for very simple systems like valves and cannot be used for complex systems altogether. Optimal control techniques like the MPC provide the best possible input to the system with respect to the objective function. If the objective function requires minimum energy effort, then the inputs provided by the MPC is energy efficient.

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3. Methodology

Model Predictive Control is one of the most robust multivariate control system primarily that has been used in process and manufacturing industries since the 1980s. It is essentially an optimal control system wherein the past and current states and outputs are used to optimize a cost function along a definite horizon (also known as receding horizon) to track the reference trajectory. One of the major strengths of MPC is its ability to handle constraints of MIMO systems. The following figure depicts the ideology behind the functionality of the MPC.

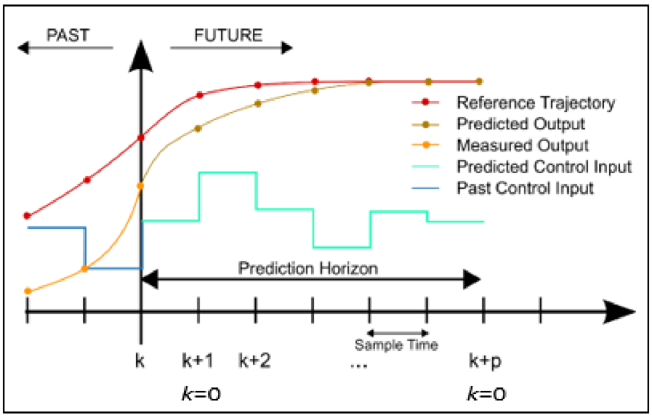
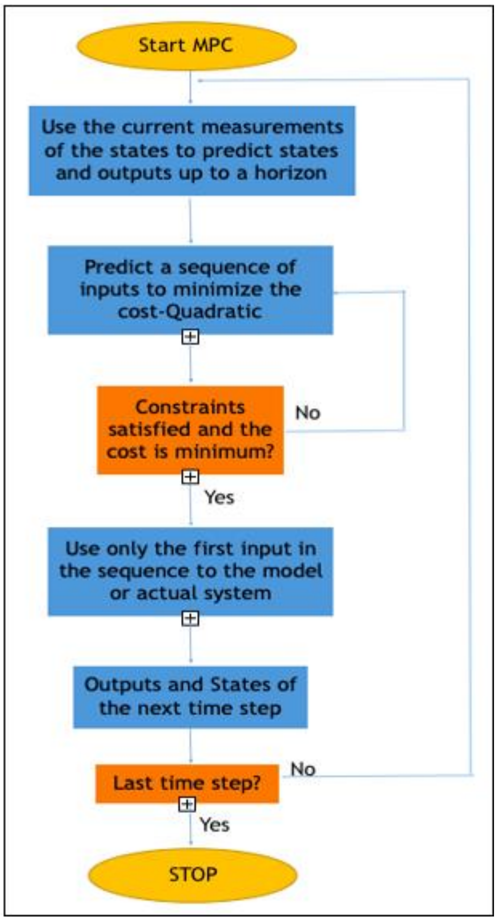


Figure Receding horizon control of MPC showing the Manipur - lated and controlled variables



The most common form of the cost function that is used for MPC is the Quadratic cost function based on that of Linear Quadratic Regulator. This cost function is minimized to obtain predict the outputs and inputs until the end of the horizon (k to k+p). Then the first control input is implemented and the outputs and the states are used as a feedback for optimizing the cost function the next horizon (k+1 to k+p+1). In the above cost function, y is the predicted output and r is the reference output. Delta u is the difference in the between the predicted input. These values are summed until the end of the prediction horizon in the cost function. Q and R are the weight matrices (similar to the LQR controller) that can be used to control the penalty on the inputs and outputs. Starting with the discrete system state space in equation 1. The dimensions of x, A, B, u, C and y are n x 1, n x n, n x 1, n x m, m x n.

To minimize the same cost function with respect to the state space model, input, input rate and output bounds, quadratic programming methods are used which is basically an extension of linear programming discussed in the previous chapter

- Shows the majors steps of the MPC.

4. Project Prerequisites

Mixed Integer Linear Programming is proposed schedule the machines and the compressors, while Model Predictive Control is proposed for the control of the HVAC system. The energy usage is minimized by shifting the flexible loads to time intervals when the demand rate is decreasing or low (load shifting) which is done by the Branch and Bound Algorithm (figure 3.3). This makes sure that only the non - flexible or non - shift able loads are not used at the same time as the flexible ones resulting in overall reduction in the peak demand thus potential cost savings.

The loads can be divided into flexible and non - flexible loads based on their usage priority and time of use flexibility. Flexible loads are the ones that can be scheduled during the low demand periods or in other words can be flexible in terms of when they are used during the day. Non - flexible loads are the opposite i. e they need to be run at a certain time thus being non - flexible in terms of scheduling. HVAC sys - tems and Compressors are the ones most of the industries

As mentioned previously, to avoid peak demand charges the Peak to Average Ratio (PAR) should be reduced. Demand side management techniques includes load shifting, peak clipping, valley filling, electrification, energy efficiency and flexible load shape In the figure below, each of these DSM techniques illustrate how the power peak is modified to reduce energy consumption and/or costs.

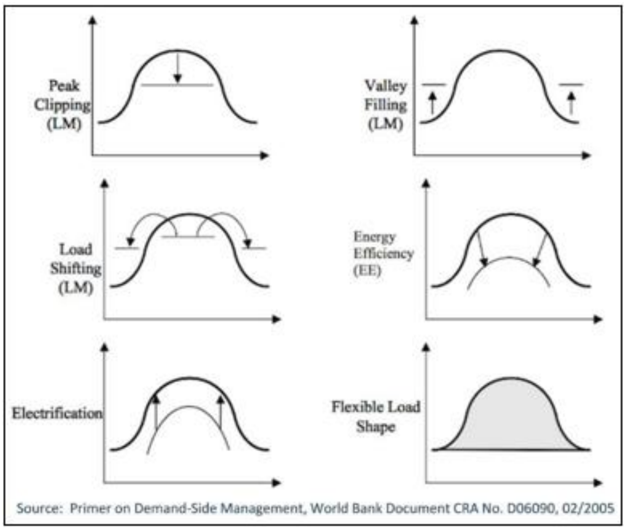


Figure: Commonly used Demand Side Management techniques; Peak Clipping, Valley Filling, Load Shifting, Energy Efficiency, Elect - trifurcation, Flexible Load Shape.

5. Model Architecture

The purpose of this chapter is to prove that the proposed modelling generic technique for the HVAC system is realizable and applicable. This has been done by modelling a real manufacturing facility using the modelling technique and validating it with the input and output data collected at the actual facility. Since the Optimal Load Shifter and the Compressor Load Scheduler are just mathematical formulations rather than models they have been directly tested using the case studies (Results Chapter).

HVAC Model Validation

To represent small scale manufacturing industries, a company named Electro - Spec that specializes in Electroplating, Passivation and Heat treating services [33] has been chosen. To validate the model, the inputs (HVAC mass flow rate and disturbances) and output (Temperature in the plant) of the actual plant were logged for 5 days. Table 5.1 shows the details of the sensor and loggers that were used to log the input and output parameters for model validation.

For heating and cooling purposes, Electrospec uses 3 Rooftop Units and 2 Pack - aged that are based on On/OFF control with a maximum Volumetric flow rate of 47m3/s and minimum volumetric flow rate of 4.7m3/s. Since the actual plant has numerous disturbances affecting the temperature, at least the major temperature disturbances had to be accounted for model validation accuracy. This includes the 1500 T5s light bulbs that are rated 35 W each and are about 10% efficient (90% of the power consumed is dissipated as heat), an oven that releases exhaust gases at 116◦F (46.67◦C) and 40 different chemical tanks (of similar dimensions) that keep releasing heat at an average temperature of 150◦F (65.56◦C).

6. System Implementation

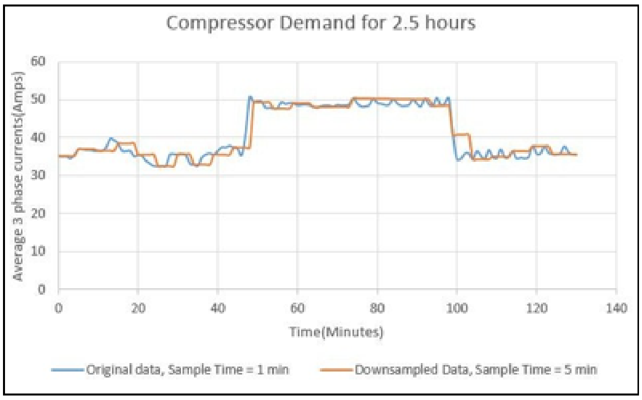
Case Study: Optimal load shifter

As mentioned in the modelling section of the optimal load shifter, real data from a compressor running at Electro - Spec has been used to show how the predicted demand can be useful in energy efficient scheduling of the flexible machines.

The demand data of the compressor is defined as follows
Compressor power = √3∗I∗V

Where I is the current and V is the voltage The data had been logged at a sample time of 1 min. This was adequate enough to capture the changes in the 3 phase current of the compressor and any lower sampling times would result in the inclusion of high frequency noise. Since the model requires the sample time of the predicted data to be at least as much as the minimum run time (the minimum amount of time the machine has to run once it has been started) of the machine, it may sound feasible to use existing data. Without down sampling the number of decision variables increase with the number of machines and scheduling horizon. For example, for a scheduling horizon of 2.5 hours and two machines, the number of variables would be at least 300 which is undesirable. However, down sampling too much has its drawbacks in that some of the surges of the demand would not be recorded due to the loss of the data points. Thus, it is crucial to first analyze the data in terms of the surge times and minimum run time of the machine. Figures 6.1 shows the actual demand data (1 minute sample time) and down sampled (5 minute sample time) demand data for of a compressor for 2.5 hours

The objective was to schedule all the machines in the low demand period while not violating the machine runtime constraints (figure 6.2). As discussed earlier, flexible



Machines can be interruptible or uninterruptable. Interruptible machines just need to run for a minimum run time that is equal to the sample time of the demand data before they can be stopped or continued. Uninterruptable machines can have a minimum run time that is equal to n times the sample time of the demand [35].

Load Shifting case 1: Flexible and Interruptible loads

Problem Statement: Two machines both of which have a minimum runtime of 5 minutes need to be scheduled for a total runtime of 75 minutes and 50 minutes respectively.

6.1 Case Study: Compressor Scheduler

In this case study, 6 industrial grade compressors with VSDs have been chosen to test the heavy - duty mode and light duty mode of the load scheduler. The specification of the compressors are detailed in table 6.1. The objective here is to schedule in an energy efficient way while meeting the demand thus reducing costs.

Table 6.1: Light duty and heavy duty compressors used for the case study

Sr. No.	Name	Max CFM at 100 PSI	HP
1	Quincy QT - 54	16	5
2	Emax ERVK070003	29	7.5
3	CPVSd 10 BM	43	10
4	Atlas GA37 125 AFF	229	50
5	J75 Mohawk VSD	341	75
6	EMAX 100 - HP Rotary Screw Air Compressor	423	100

The first three compressors would be tested using the light duty mode and the last three will be tested using the heavy duty mode as per their HP ratings.

HVAC MPC

The validated Simulink model representing the Electro - Spec plant was used to show the effectiveness of the MPC in decreasing energy consumption hence the costs. In terms of the practical implementation of such a control system, the blower fans need to equipped with Variable Frequency Drives (VFDs) so that the fans can run just enough to meet the heating or cooling loads without wasting energy unnecessarily. The model that was built using the RC modelling technique is first the model was first linearized about the equilibrium points (294K) and converted into continuous state space form. Then using the zero order hold and sampling time, it is converted to discrete state space form. This has to be done for two reasons 1) MPC works with only discrete models and 2) the disturbances and the inputs that were measured at the facilities are obviously discrete in time (sampled at 1 sample per second).

7. Conclusions & Recommendations

In this thesis, the potential energy saving strategies have been explored for the SEU systems which are the HVAC, Compressors and machines driven by electrical motors. The proposed energy management techniques have been proved to be effective in reducing the energy and costs. The OLS was used to achieve load shifting and valley filling which resulted in lower peak demand and costs. The CLS was used to distribute loads among compressors such that all the compressor run in their most efficient conditions for energy efficiency. The lumped parameter HVAC model was used to model a manufacturing facility and the MPC was implemented as the HVAC control for the validated model to improve the energy savings.

In case of the optimal shifter, there is potential for cost saving even though the energy consumption is same due to the load shifting that reduces the peak demand. This is usefully manufacturing industries that are located in regions with utilities that have TOU and Peak Demand schemes. The Compressor scheduler was able to reduce the energy and cost for both the heavy and light duty compressors and this is a generic formulation that can be used regardless of the compressor type as long as the compressor is VFD type and works with other compressor in parallel config - uration. The MPC pertaining to its optimal nature was able to reduce the overall energy consumption by running the fan only when needed. The total framework when implement has a potential of saving up to 40% of energy and costs as summarized in the below table. Table 7.1 summarizes the cost and energy savings of the proposed energy management framework.

Table 7.1: Estimated energy savings with the proposed framework

Sr. No	Energy Management Technique	Type	Savings
1	Optimal Load Shifter	Optimization	27.6% Energy and Cost saving
2	Compressor Scheduler	Optimization	14.6% (Heavy duty) and 16% (Light duty) Energy and Cost saving
3	HVAC MPC	Control System	Cost Savings depending on the peak demand price or TOU price

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