Improving Energy Efficiency in a Pharmaceutical Manufacturing Environment – Office Building

by

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ABSTRACT

Reducing energy consumption without compromising the quality of products in a pharmaceutical manufacturing environment and maintaining the comfort of employees is of critical important in maintaining the financial viability and competence of the company.

Heating, Ventilation and Air Conditioning (HVAC) system was identified as the major energy consumer in both office building and manufacturing building. The step response model of the office indoor temperature to the operating states of the Air Handling Unit (AHU) was developed. Combined with the working schedule of employees, the AHU operation schedule in the office building was modified to accommodate the working schedule of employees while reducing waste. Motion detection lighting control was implemented in the office area to reduce waste by turning off unnecessary lighting automatically.

As a result of new AHU operation schedule, AHU motor electricity usage can be reduced by 10,868 kWh/year and chilled water consumption can be reduced by 79,403 kWh/year. Motion detection lighting control could also result in estimated savings of 54,082 kWh/year.

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[1] The company name has been changed to protect confidentiality.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

This thesis is the result of eight-month internship at Company AFT Singapore. The project focused on energy saving in an office building and a production facility, with special focus on the Heating, Ventilation and Air-Conditioning (HVAC) system.

Section 1.1 briefly introduces the company background of AFT. This is followed by the project motivation in Section 1.2. Section 1.3 introduces the concept and procedure of energy auditing. Section 1.4 explains the overview of the energy usage in the company. Section 1.5 introduces the environmental requirements for pharmaceutical production areas. Section 1.6 discusses the current energy performance in the company, and finally Section 1.7 explains the objectives of this project.

1.1 Company Background

AFT Singapore is wholly owned subsidiary of Ace & Co., headquartered in Whitehouse Station, NJ., USA. Located at Singapore Tuas Biomedical Park, the manufacturing facilities of AFT Singapore are comprised of a bulk active pharmaceutical ingredient (API) plant, which is a flexible and multi-product operation capable of producing various APIs including etoricoxib and montelukast sodium, and three tablet-producing pharmaceutical facilities (PF).

1.2 Project Motivation

Reducing energy consumption is crucial to maintain the company's competitiveness, especially at this time of global economic crisis and increasing concern for more environmentally friendly factory operations. Since 2003, Singapore Ace Manufacturing Division (AMD Singapore) started expanding its manufacturing facilities. Floor area almost doubled from 33,400 m^2 in Year 2004 to 61,557 m^2 in Year 2008. Site electricity cost from Year 2005 to 2007 was S$4.5, 6.8 and 8.3 million respectively. In 2008, the total energy cost amounted to about S$13.7 million, which accounted for more than 20% of the total operating cost. As site expansion will continue in the future and if oil price remains flat, site energy cost will increase.

In this context, a site energy blue print was established in October 2007. Strategies will focus on a three-year cycle (2008 – 2010) to optimize electricity usage on site by eliminating waste and improving the equipment energy efficiency. Energy consumption in other areas such as the process equipment, lighting, and office equipment is relatively lower. The major energy consumer for the site is the HVAC system, which maintains indoor environment conditions. An increase of 2300 m^2 additional air-conditioned foot print has added extra energy load onto the HVAC utility equipment on site.

Our project at AFT is one part of the energy-saving blueprint to reduce energy consumption in the office building and the production facility.

1.3 Energy Audit

An energy audit, or energy survey, is a study of how energy is used in a facility and an analysis of what alternatives could be used to reduce energy costs. It requires collaboration from the utilities team to collect the energy usage and cost data, and support from the top management to provide the necessary funding to implement the most cost-effective solutions. In this era when manufacturing facilities strive towards leaner and more environmentally friendly operations, reducing energy consumption without compromising productivity, quality or user comfort is relevant and important. Therefore, an energy audit should be performed regularly and considered as an integral part of the company's effort to pursue continuous improvement in operations, which is in line with the six-sigma management strategy that many companies have adopted today.

The procedure of an energy audit involves several standard steps. First, type and costs of energy use must be identified, so that how energy is being used, and possibly wasted can be understood. Next, more cost-effective ways of using energy should be identified and analyzed. Improving operational techniques and investing in new equipment and technology which are more energy efficient are some examples. Lastly, economic analysis on those alternative solutions should be performed. After calculating all the costs for investment and estimating the returns, the energy saving strategies that are worth continuing are identified [1].

A widely used measure to gauge a facility's energy performance is the Energy Utilization Index (EUI), which states the total energy consumed in a building per square meter in a year. During an energy audit, a facility's EUI should be calculated and benchmarked against industrial standards. Such benchmarking practice would help the manager to know the building's position in terms of energy efficiency and set specific energy saving targets.

1.4 Site Energy Overview

In this section, electricity and natural gas and their applications in the plant are introduced.

Figure 1 shows the aerial view of the whole plant. The General Services Building (GSB), Administration Building (Admin) and Engineering Services Buildings (ES) are office buildings. The utility building (UTL) is the place where the equipment for chilled water generation, steam generation, compressed air generation is located. API, PF1, PF2 and PF3 are production facilities.

Figure 1: Site Aerial View [2]

AFT purchases electricity and natural gas from suppliers and uses these energy resources to generate all forms of utilities to support manufacturing process, office activities and to provide an indoor environment that is bound by specific requirements. The detailed usage of each form of energy is explained below:

1.4.1 Electricity

Electricity is purchased directly from power plants in Singapore and it is measured by kWh. The substations in the plant distribute electricity to various manufacturing buildings and office buildings.

In the UTL, electricity is used by cooling towers and chillers to generate chilled water for the plant's HVAC system, by air compressors to generate compressed air for the plant's building automation system (BAS), and by boilers to generate steam for production facility environmental controls. The chilled water, compressed air and steam are then distributed to other buildings through pipelines and then consumed by the equipment in those buildings.

The electricity used to generate these secondary energy forms is attributed to each building according to the proportional consumption of that particular secondary energy form. For example, the assigned electricity consumption in generating chilled water to GSB is the percentage of total chilled water used in GSB multiplied by the total electricity used to generate all chilled water in the utility building. The allocation of electricity used to generate compressed air and steam is calculated in the same way. Chilled water and compressed air are consumed in all office buildings and all production facilities while steam is only consumed in production facilities.

In GSB and other office buildings, electricity consumption can be divided into direct consumption and indirect consumption. The former refers to the electricity distributed directly by substations. It is used for motors in the air handling units (AHU) lighting, computers, printers and other miscellaneous equipment, and can be directly measured by the motor control center (MCC) in the building. The latter refers to the proportional consumption used for generating chilled water and compressed air, which are transported from UTL as explained earlier.

In production facilities, direct electricity consumption is used for AHU motors, process equipment, lighting, and other miscellaneous equipment. Indirect electricity consumption refers to the proportional consumption used for generating chilled water, compressed air and steam which are transported from UTL.

1.4.2 Natural Gas

Natural gas (NG) is purchased in an energy unit of mmBTU which could be converted to kWh of equivalent value. Natural gas is used in boilers to generate steam for production facility environment control. Each building's NG consumption is then calculated from its proportional steam consumption.

1.5 Requirements of Pharmaceutical Production Environment

Manufacturing of pharmaceuticals requires stringent production environmental control. Among all environmental parameters, indoor temperature, relative humidity, air change rate, room pressurization and ventilation are the most important ones. These parameters must be kept within tight specification limits to minimize microbial load and ensure the safety and quality of the finished products, as well as to keep the working environment comfortable for the operators.

The floor area of a pharmaceutical production facility is classified into three types: white, gray and black. The white area (or the white hygienic zone) is where the manufacturing processes and direct material handling like chemical reactions, separation, crystallization, purification and drying are carried out. There is potential open product exposure (meaning the products are not packaged and thus open to contamination) in the white area. The black area (or the black hygienic zone) is the non-production area in the building. Examples are electrical rooms, mechanical rooms and BAS control rooms. The gray area (or the gray hygienic zone), is the transition or buffer space between the white and the black, such as the goods lift and the gowning room, where transport of materials and movement of people between the black and the white take place. There is no potential open product exposure in the gray or the black areas.

The white, gray and black areas are separated by walls and doors. The energy requirements in the three types of floor areas are different. Generally, the white area which needs the strictest environmental control consumes the greatest amount of energy. This is followed by the gray area and the black area, whose energy intensity may only be a fraction of that in the white area.

1.5.1 Temperature and Relative Humidity

The design indoor temperature and relative humidity in the manufacturing facilities are shown in Table 1. The white area temperature and relative humidity in AFT are typically designed to be 21.1 °C ± 1.1°C and 50% ± 5% respectively. This applies to the rooms for compression, dispensing and blending. Operators in the white areas need to dress in heavy gowns, wear goggles and hair covers. Therefore, cool and dry air is needed to maintain a comfortable work environment. In some areas where moisture sensitive products are processed, even lower relative humidity of 27% ± 5% is needed.

The design temperature for the gray area varies from 21.1 °C ± 1.1°C to 22.5 °C ±2°C, and the design relative humidity ranges from 50% ± 5% to 53% ± 5%, depending on the specific room functions. Higher design temperature and relative humidity are seen in the black areas. In the storey spine (the corridor connecting PF1, PF2 and PF3) and BAS control room where operators and technicians are usually present, the specifications are similar with those in a regular office building. For the places infrequently visited, such as the mechanical rooms and purified water room, temperature and relative humidity are loosely controlled [3].

Table 1: Designed Room Temperature and Humidity

Rooms or Areas	*Design Temperature*	*Design Relative Humidity*
1st Storey Compression and Stage in	21.1 °C±1.1°C	27%±5%
Tool Storage	21.1 °C±1.1°C	27%±5%
Dispensing	21.1 °C±1.1°C	50%±5%
Blending and Associated Access Corridor	21.1 °C±1.1°C	50%±5%
2nd Storey Compression	21.1 °C±1.1°C	50%±5%
Wash Area	21.1 °C±1.1°C	50%±5%
Other White Areas	21.1 °C±1.1°C	50%±5%
Gray Areas	21.1 °C±1.1°C	50%±5%
Shipping/Receiving	22.5 °C±2°C	53%±5%
Sampling Room	22.5 °C±2°C	53%±5%
Warehouse	22.5 °C±2°C	53%±5%
1st Storey Spine	23 °C±1.1°C	60%±5%
2nd Storey Spine	23 °C±1.1°C	50%±5%
Offices, Break Room and Other Support Areas	23 °C±1.5°C	60%±5%
Telecom/CSR Room	23 °C±1.1°C	50%±5%
BAS Room	23 °C±1.5°C	60%±5%
Tech. Areas and Adjacent Mechanical Rooms	26 °C±3°C	60%±10%
All Other Mechanical Rooms	30 °C±3°C	60%±10%
Electrical Room	30 °C±3°C	60%±10%
Purified Water Room	30 °C±3°C	60%±10%
Elevator Machine Room	30 °C±3°C	60%±10%
Waste Dock	Ambient±5°C	Not Controlled

1.5.2 Air Change Rate

There are no particulate classification requirements within the non-sterile dosage manufacturing and packaging areas. Table 2 shows the minimum design air change rates in the white and gray areas. The actual airflow rates may be higher based on equipment heat load, exhaust rates and pressurization requirements. Sufficient air change rates in the production areas would reduce the rate of microbial growth, and ensure air and product quality [3].

Table 2: Designed Air Change Rates

Rooms or Areas	*Hygienic Zone*	*Air Changes Per Hour*
1st Storey Compression, 2nd Storey Compression, Lab, Dispensing, Blending, Tooling, Compression Staging, and Main access corridor to the manufacturing rooms	white	15
Equipment Wash Rooms	White	12
Other White/Gray Areas	White/Gray	6
Shipping/Receiving	Black	As required for cooling or ventilation
Warehouse	Black	As required for cooling or ventilation
1st Storey Spine	Black	As required for cooling or ventilation
2nd Storey Spine	Gray	6
Offices, Break Room and Other Support Areas	Black	As required for cooling or ventilation, minimum 10 CMH per SQM
Locker Rooms and Toilets	Black	12
Telecom/CSR Room	Black	As required for cooling or ventilation
BAS room	Black	As required for cooling or ventilation
Tech. Areas	Black	As required for cooling or ventilation
Mechanical Rooms	Black	As required for cooling or ventilation
Electrical Room	Black	As required for cooling or ventilation

1.5.3 Room Pressurization

In general, non-sterile dosage manufacturing processing rooms are maintained at a negative pressure to the adjacent white access corridor. The philosophy is to maintain containment in each room to reduce the potential for product cross contamination. In addition, differential pressures shall also be maintained between the various hygienic zones, cascading downward from white to gray to black.

Wash facilities require that the unwashed staging area shall be maintained at a lower pressure than its surrounding white areas. In addition, manual wash areas shall maintain a pressurization cascade from clean equipment storage to manual wash room to unwashed equipment staging to minimize the potential migration of water vapor from the wash area to the clean equipment storage area.

Normally, the minimum design differential pressure between the production rooms and the adjacent production corridor shall be maintained at 12.5 Pa with all doors closed [3].

1.5.4 Ventilation

For systems serving the white and gray areas, a minimum of 10% fresh air shall be provided. Other areas shall be provided with a minimum 34 CMH per person. In rooms where toxic or flammable products are handled, higher rates of exhaust with equivalent fresh air make-up may be necessary. Rooms with high moisture levels or potential odor issues shall be 100% exhausted to avoid accumulating humidity and odor.

As shown in Figure 2, for all systems, 30% filters and 95% filters shall be provided upstream of the cooling coils in the central AHUs. For manufacturing suite areas and primary packaging rooms, 95% filters shall also be provided at the AHU outlet. To minimize the potential for product cross contamination, High Efficiency Particulate Air (HEPA) filters, which have minimum efficiency of 99.97% on 0.3 micron size particles, shall be included for return air as dictated by specific product requirements. When HEPA filters are used, 30% pre-filtering is needed [3].

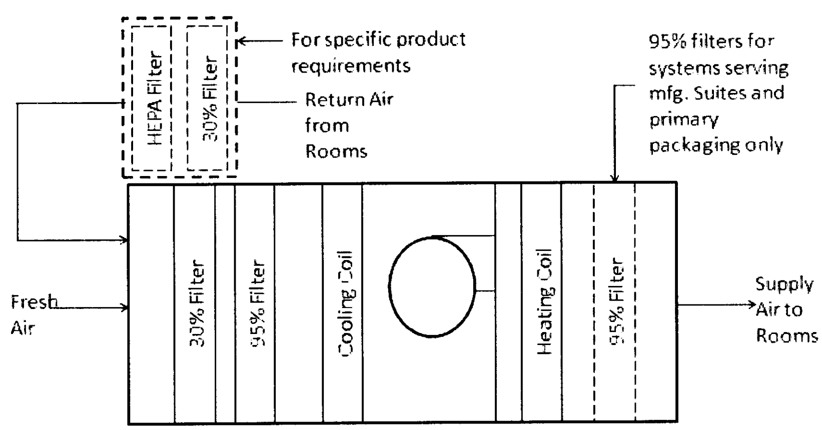


Figure 2: Filters in a Typical Air Handling Unit Diagram

The above design conditions are for common pharmaceutical manufacturing activities. In case the product needs specific environmental requirements, the product specific considerations would dictate the environmental parameters.

1.6 Current Performance of the Plant

Before we engaged in this project, there was limited work on energy consumption performance evaluation in AFT. GSB was the only building whose EUI had been calculated, and it was found to be 296.5 kWh/m^2/year, while the industrial average for office buildings is 215 kWh/m^2/year and the best practice is 95 kWh/m^2/year in Singapore [4, 5]. From this comparison, it is clear that GSB in AFT had been consuming more energy compared to other office buildings in Singapore. Therefore, there could be opportunities to reduce energy consumption in the building and bring EUI down to the industrial average. For other office buildings and manufacturing buildings, no energy consumption performance had been evaluated yet.

The focus of energy saving on site has been on the utility equipment such as the efficiencies of chillers and boilers. AFT Singapore spent S$4 million in Year 2007 on generating chilled water, which was about 47% of its total electricity bill. A chilled water generation optimization project has been in smooth progress for about two years aiming to improve chiller efficiency from 1.013 kW/RT to 0.682 kW/RT, and save chiller energy consumption per month by 5% from average monthly consumption of 1.9 million kWh.

A boiler efficiency optimization project is another ongoing project to reduce energy cost. By implementing waste heat recovery, boiler flue gas O_2 trim firing control and boiler blow down flash steam heat recovery, the boiler efficiency could be improved from current value of 83% to 87%. With the current natural gas unit price of S$12/mmBTU, the expected annual saving is S$70,000.

1.7 Objectives

The previous projects on energy saving were all focused on the efficiency of utility equipment, or the upstream of the energy system. In this project, we focus on the energy consumption in all general equipment in the plant, or the downstream of the energy system. The objectives of this project are:

1. To verify the EUI in GSB.
2. To evaluate the energy consumption performances of PF by calculating EUI of each building.
3. To identify the causes of high energy consumption of buildings if the EUI is higher than industrial benchmark.
4. To strategize solutions and to implement energy saving measures to minimize waste in energy consumption.

In the project, we emphasized teamwork and leadership. Mr. Haoyu Liu led the part of the project that developed a general energy management tool to monitor and analyse energy consumption performance in both office building and manufacturing building. Mr. Endong Zhang led the part of the project that reduced energy consumption in PF2. He identified energy saving opportunities and implemented optimum strategies in the manufacturing facility. Mr. Wu Li led the part of the project that reduces energy consumption in GSB. He explored various energy saving opportunities and chose to focus on two strategies to reduce energy consumption in GSB. In the progress of the project, it is evident that Liu's work supported Li and Zhang's work. At the same time, Li and Zhang's work in turn supported Liu's theoretical work. In this thesis, the focus is on the energy saving strategies for the GSB office building. The methodology and results from Liu and Zhang's work are briefly summarized in this thesis.

In Chapter 2 preliminary analyses and problem statement, historical data are used to calculate the EUI of the buildings in the company. Based on the energy performance of each building and industrial benchmark, problem in this project is defined. Chapter 3 first introduces the working principles of the HVAC system, both in general and in particular to the equipment used in AFT. This is followed by some previous work on energy saving particular in HVAC system is illustrated in details. Chapter 4 methodology illustrates two energy saving methods applied to the office building. The first method is reschedule HVAC operation hours, and the second method is motion detection lighting control. The results of the two implemented strategies for GSB are presented and discussed in Chapter 5 results and discussion. Savings are calculated or measured and then discussed using statistical tool. Chapter 6 conclusion summarizes the work done and results for this thesis. In the last chapter, Chapter 7 recommendations and future work, discusses some recommendations for the company. Some potential future work is also presented in this chapter.

2. PRELIMINARY ANALYSIS AND PROBLEM STATEMENT

The energy management team in the company had suspected of high energy consumption, but had yet to obtain strong evidence to support their claim. To find out how the energy consumption on site compares with industrial average, we perform preliminary data collection and analysis. The result indeed shows higher energy usage, which helps us to formulate the problem statement and find the focus of the work.

2.1 Preliminary Analysis

In this section, the EUI of GSB and the three production facilities are discussed. The EUI of GSB had previously been found to be much higher than the industrial average for office buildings. After we calculate the EUI of GSB using more updated data and more accurate assumptions, the result turns out to be 381 kWh/m^2/year. This is even higher than the previously calculated value. The average EUI value of office buildings in Singapore is obtained from the Energy Sustainability Unit website, which is a professional associate in National University of Singapore. Therefore, we have verified that GSB's energy consumption was higher than average.

The next step is to investigate where energy is consumed in this building so that we can explore opportunities to reduce energy consumption. Figure 3 shows energy consumption structure in GSB. Chiller electricity is the major part of total energy consumption. If we break down the 34% of the direct electricity, we can find that 24% of it is consumed by AHU motors in the building. Because the HVAC system includes chiller and AHUs, we can calculate that HVAC system in GSB consumes 68% of its total energy.

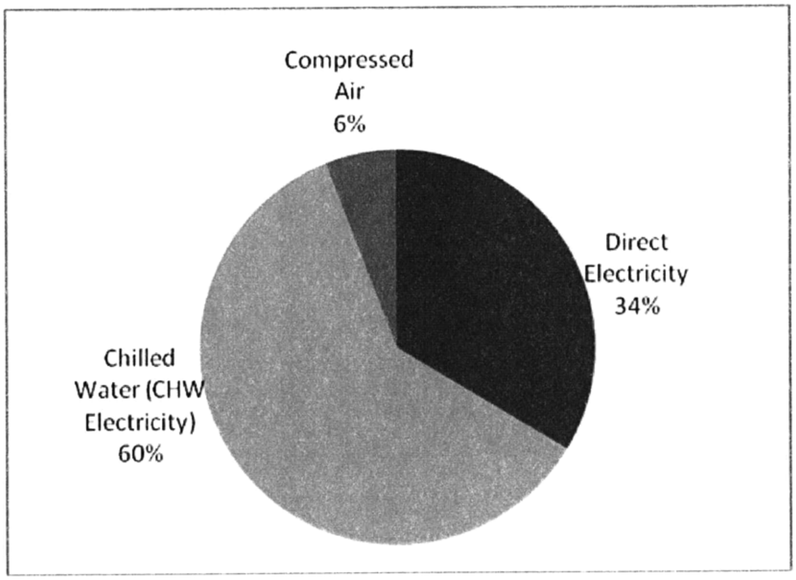


Figure 3: GSB Energy Consumption Structure

Since the HVAC system consumes most of the energy in the building, we could focus energy saving strategies on the HVAC system, from which most energy saving opportunities are expected to be found.

Similarly for the production facilities, we calculate the EUI for the white, gray and black areas. The EUI for each area in the three production facilities are shown in Table 3.

Table 3: EUI of Three Pharmaceutical Facilities (kWh/m^2/year)

PF1			*PF2*			*PF3*		
White	*Gray*	*Black*	*White*	*Gray*	*Black*	*White*	*Gray*	*Black*
6513	4032	69	4050	1526	122	8759	1490	225

EUI benchmarking data for pharmaceutical plants is not readily available in the literature. As a substitute, the internal benchmarking data from the AFT plant in North Carolina, U.S. is used. The average for the white area is about 2000 kWh/m^2/year, which is much lower than what we have calculated for the Singapore site.

The weather difference between North Carolina and Singapore could be a main cause of difference in the EUI values. In North Carolina, the plants need heating in winter and cooling in summer, whereas in Singapore, where temperature is invariably high, the facilities need intense cooling all year round.

In a separate exercise, an EUI calculator for pharmaceutical plants developed by Energy Star is used. The tool also helps to benchmark the plant energy efficiency against data from other pharmaceutical plants in similar weather conditions in the United States. EUI of AFT Singapore's production facility is compared with data from Miami, where the weather condition is thought to be the closest to that in Singapore. The result also shows that our production facilities rank at the bottom end in term of energy efficiency.

Figure 4 shows the energy consumption pattern in PF2. The HVAC system comprising chiller, boiler and AHU consumes about 95% of total energy. The manufacturing process equipment, lighting, and other equipment only consume 3% of total energy. From this chart, we can see that reducing the energy consumption in steam generation and chilled water generation are still to be the focus of the work.

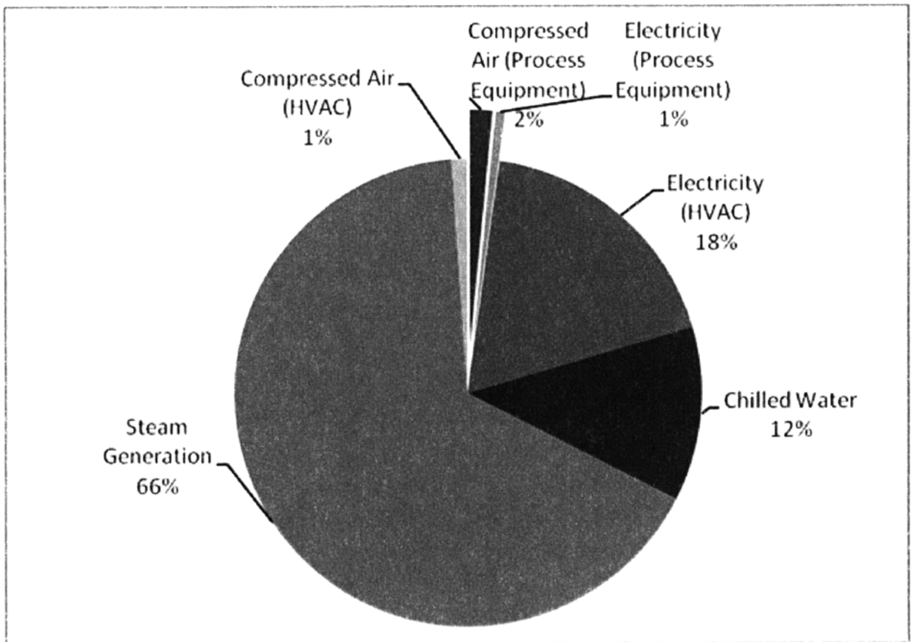


Figure 4: PF2 Energy Consumption by Usage

2.2 Problem Statement

The office building and production facilities of AFT are consuming more energy than the industrial average. HVAC system is the major energy consumer in the plant. This provides us opportunities to reduce energy consumption with particular focus on AHUs, chilled water and steam usages.

Currently the plant is lacking general energy management tools that help to regularly monitor and control energy consumption. The company is also in need of theoretical models, which would enable the energy engineers to better understand the system behaviors and find energy management opportunities, to support the energy saving endeavor.

3. THEORETICAL BACKGROUND AND PREVIOUS WORK

In this chapter, the working principle of HVAC system and AFT's HVAC equipment are introduced as theoretical background in Section 3.1. Section 3.2 reviews some previous HVAC energy saving strategies that are potentially applicable in AFT. Section 3.3 introduces the Define-Measure-Analyze-Improve-Control (DMAIC) approach, the seven wastes in Lean Six Sigma (LSS) and their relationship with this project.

3.1 Heating, Ventilating, and Air Conditioning

3.1.1 HVAC Introduction

The purpose of the HVAC system is to add or remove heat and moisture, as well as to remove undesirable air components from the facility in order to maintain the desired indoor environment. Usually, an HVAC system consists of motors, ducts, fans, controls and heat exchange units which deliver cooled or heated air to various parts of the facility. In AFT Singapore, almost all the office and manufacturing areas are air conditioned all year around, due to the high temperature and humidity in Singapore and the strict requirement for pharmaceutical plants. In this section, we describe the major components of HVAC system and their fundamental operating principle.

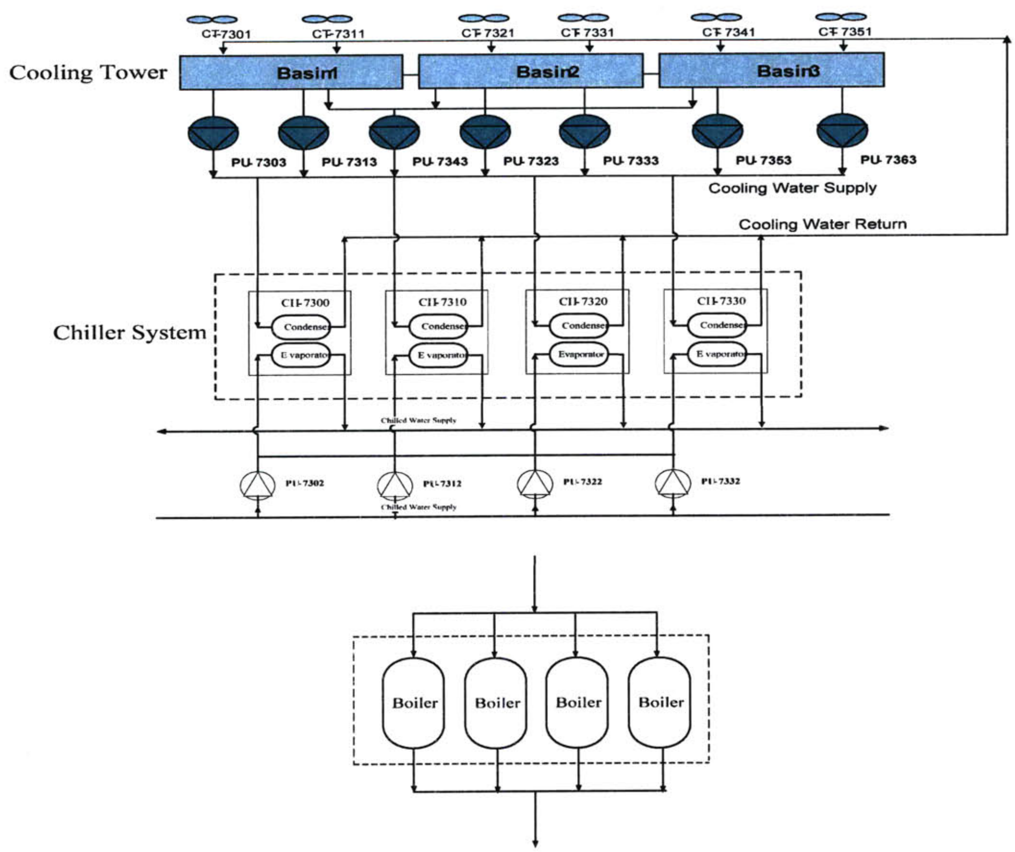
An HVAC system functions to provide an environment in which some control factors are maintained within desired ranges. Examples of some standard parameters are

- Dry bulb temperature of 23 ^{o} C
- Relative humidity of 40%-60%
- ASHRAE 62-1999, 2001 and 62.1 – 2004 ventilation standard
  - CO^2 less than 1000 PPM or
  - 10 LPS outside air per person

In order to achieve these goals, an HVAC system must have a source of cold to remove heat and a source of heat to reduce humidity. Furthermore, a distribution network is needed to deliver this air to the points of use and control the air change rate. We divide an HVAC system into two parts to discuss them separately: the HVAC primary equipment which is to produce hot and cold fluids and distribute the fluids to each AHU, and the HVAC secondary system which uses the cold and hot fluids to transfer heat with outside air in order to adjust the air temperature and humidity and distribute the air into each room [6].

3.1.2 Primary Equipment

Figure 5 shows the primary equipment of HVAC in AFT and the ductwork. In this section, the functions of each device will be explained.



Boiler System

Figure 5: HVAC Primary Equipment and Ductwork

Chiller

A typical chiller generates cold water or other cold fluids such as glycol which is supplied to areas where secondary units such as AHUs are used to provide cooling. Chillers have capacities that vary widely, from a few hundred tons to several thousand tons. AFT Singapore installed four chillers with 1500 RT of cooling capacity each. Usually, only two chillers are operating and the other two are backups. The majority of chillers including those at AFT use the vapor-compression cycle as the basic cooling mechanism, and have secondary fluid loops that dispel the heat to the outside air or water, and provide the cold fluids to the areas where needed. Figure 6 is a schematic diagram illustrating the typical cooling process in a water chiller.

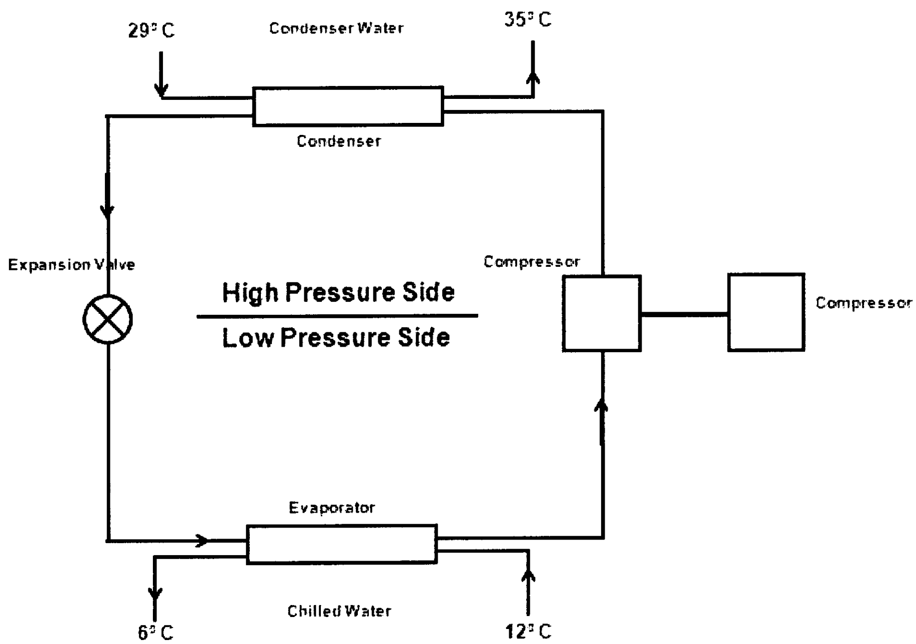


Figure 6: Water Chiller Cooling Process

Condenser is where the refrigerant rejects heat to the condenser water or air, causing refrigerant's phase change from gas to liquid. The condenser water is usually supplied by a closed loop that goes to a cooling tower. The cooling tower is an evaporative cooler that transfers the heat from the water to the outside air through the process of evaporation as the water is sprayed or falls through the air. The plant runs three of the six cooling towers it owns, each having a capacity of 4088 m^3/hour [7]. Figure 7 shows the cooling towers used on site.

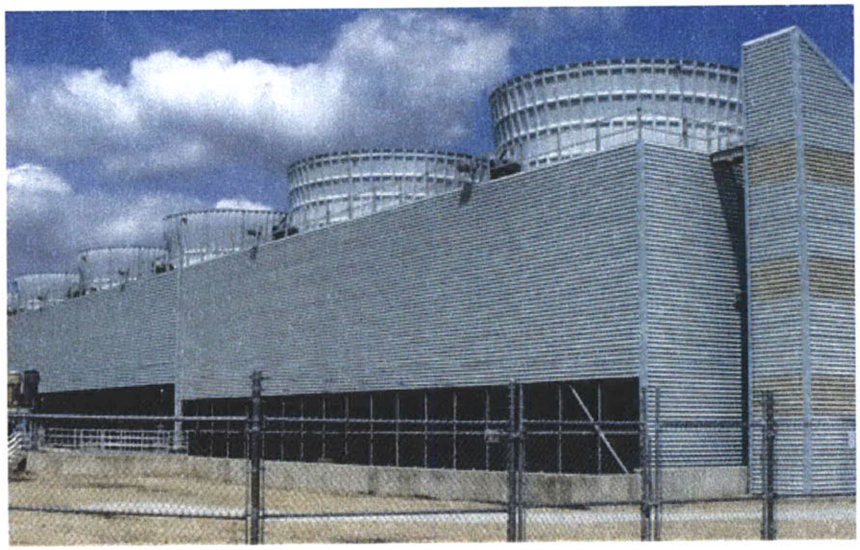


Figure 7: Cooling Tower [2]

High-pressure liquid refrigerant passes through expansion valves, reducing pressure and flashing to a gas within the evaporator, absorbing energy from the chilled water. The chiller water produced by the evaporator is circulated in another secondary closed loop to parts of the facility where is will be used to provide air conditioning. The secondary closed loop consists of two kinds of systems. One is the fan cool unit (FCU) which can be used in individual rooms. The other is the AHU which can be used to handle a larger quantity of cooled air and distribute it to various parts of the facility. AFT Singapore has both of these secondary systems.

The compressor takes the low-pressure vaporized refrigerant coming out of the evaporator, compresses it to a higher pressure, and discharges it into the condenser. There are three types of compressor for chillers: scroll compressor, screw compressor and centrifugal compressor. AFT Singapore uses centrifugal compressors, which have the biggest maximum capacity of these three types of compressors [7].

Boiler and Furnace

Boilers and furnaces can burn a fossil fuel such as natural gas, oil or coal, or use electricity to provide the primary heat which is then transferred to air or water. Direct production of hot air or hot water is accomplished by a furnace which takes the heat of combustion of fossil fuels or electric resistance heat, and transfers it to moving air or water. A boiler might also be used to produce steam which is then distributed to its areas of need. Steam is primarily used for hot water loop heating and reactivation air heating in dehumidifiers. In hot water loop, water is heated up to 85° C by steam, and used to adjust the temperature of the supply air in production facilities. Reactivation air heating in the dehumidifier will be explained in later sections.

AFT Singapore has installed three boilers with capacity 9400 Kg/hour each. Usually the site only operates one of the three. Figure 8 shows the boiler used in AFT Singapore.

Figure 8: Boiler [2]

3.1.3 Secondary System

Two types of HVAC secondary systems are introduced in this section: the single-duct, terminal reheat system, which is commonly used in pharmaceutical production facilities, and the variable air volume (VAV) system, which is mainly used in office buildings.

In the single-duct, terminal reheat system, outside air enters through dampers, and then mixes with return air from rooms. The air is then driven though the cooling coil by a supply fan. The overcooled air, which has lost moisture, is transported along the ductwork. A heat unit of some type (hot water loop in the case of AFT) will then reheat the air to desired temperature, when its relative humidity also drops to the desired level as temperature increases. The air is then supplied to each room. The overcool-reheat method is to remove moisture and control temperature with continuous supply of air. Thus it is used in production facilities where high air change rates are usually needed.

In a VAV system, the fan motor has an adjustable speed drive so that the volume of supply air can be carefully controlled, responsive to the indoor temperature. The advantage of this system is that only the amount of air needed for cooling is supplied, and reheating is not required. AFT office buildings utilize this system.

Typical components found in HVAC secondary system include dampers, filters, cooling coils, fans, ductwork, and control system. Figure 9 is a schematic drawing of a typical AHU used in AFT. Each component is described in the following paragraphs.

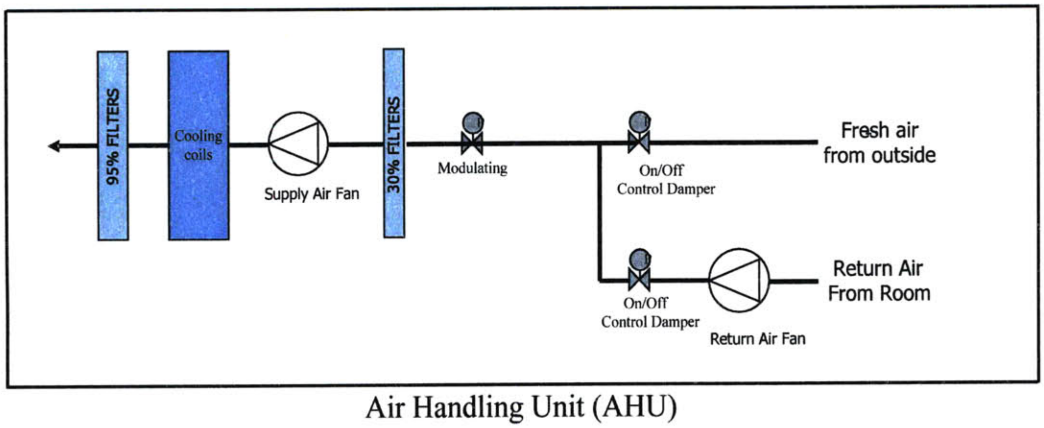


Figure 9: Schematic Diagram of AHU [7]

A damper controls the flow of air. Usually, there are two types of dampers in HVAC: the return air damper, which adjusts how much air is re-circulated, and the outside air damper, which determines how much fresh air goes into the system. In practice, both of the two types of damper are open. Fresh air is supplied to meet the requirement for CO_2 levels, whereas cool recirculation air exerts less cooling load and saves energy.

Filters are necessary in any HVAC system. Fresh air usually includes some tiny particulates which can affect the air quality and the manufacturing environment. These particulates must be filtered out. 30% filters, 95% filters and HEPA filters are used in AFT's AHUs.

Fans provide the power to move air through the distribution system. A typical fan has three main parts: a motor, belts or a chain, and the blades. Usually, the motors in these fans consume a lot of electricity. One commonly used method in industry is to reduce the supply electricity frequency from 50 Hz to about 30 Hz, which reduces the motor power and realizes enormous energy saving [1].

Cooling coil is the place where heat exchange occurs between air and chilled water. The air higher in temperature transfers heat to the chilled water. The cooled air is then released to the desired space, and chilled water takes the heat back to chillers.

Ductwork directs and conducts air from AHUs to the points of use. It also conducts the exhaust air from these rooms back to the mixing plenum and to the outside. This function is impaired if the ducts leak or loose insulation.

Feedback control system is usually used in the HVAC system. The room temperature and relative humidity requirements are transformed into control signals to the AHU motors, dampers etc. For example, if the temperature in the office area is too high, control system would send a signal to the corresponding AHU motor requesting higher motor speed to supply more cool air to the area.

Dehumidification is usually achieved by two means: cooling the air to condense the water vapor and desiccant drying with dehumidifier. The two methods can be used solely or in combination. When lower humidity is required in certain production rooms where a humidity sensitive process is carried out, a dehumidifier is used in conjunction with cooling-based dehumidification to reduce moisture content in the air. Figure 10 shows an AHU with dehumidifier. In such systems, fresh air is pre-cooled by a cooling coil, reduced in moisture content and enters the system as make-up air. After mixed with return air, it goes through the desiccant rotor, where the vapor in the air is absorbed. Therefore, the humidity of supply air will decrease. The air temperature increases after passing through the hot desiccant rotor, and is cooled down by a post-cooling coil, before supplied to the rooms. In the upper part of the figure, the air that passes the filter and damper is heated up to dry the desiccant rotator. In this way, the desiccant can keep its function all the time.

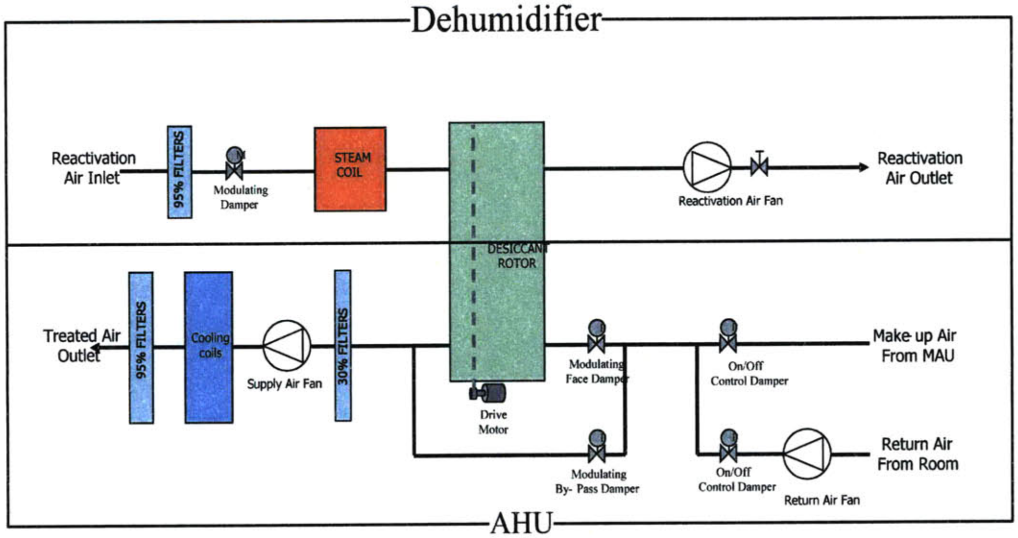


Figure 10: AHU with Dehumidifier [8]

3.2 Previous Works

3.2.1 General HVAC Energy Management Strategies

The strategies listed below apply to the HVAC system in general, regardless of the building types.

Duct Leakage Repair

Duct leakage can waste significant amount of energy in HVAC systems. Installing duct insulation and performing regular duct inspection and maintenance can reduce the chance of duct leakage. According to studies by Lawrence Berkeley National Laboratory, repairing duct leaks in industrial and commercial spaces could reduce HVAC energy consumption by up to 30% [9].

Operation Schedule of HVAC System

In many cases, the HVAC system is running for longer time than necessary. The energy manager needs to find out during what time of the day are cooling and mechanical ventilation needed, and schedule the HVAC operation accordingly. Tremendous saving on chilled water electricity, AHU and pump electricity can be realized by rescheduling the HVAC system with shorter operation time that just sufficiently satisfies the need of the occupants [9].

Higher Base Set Point Temperature

According to Singapore's National Environmental Agency's (NEA) regulation, the indoor temperature should be kept in the range of 22.5 °C to 25.5 °C. Overcooling in Singapore is sometimes observed. By raising the set point temperature by 1 °C, cooling load, which is proportional to cooling degree days, would be reduced and huge amount of energy could be saved.

Rooftop Water Evaporative Cooling

Water spray on the roof during the sunny daytime could take away heat from the top of the building by evaporation and reduce the cooling load of the HVAC system. It essentially simulates rainy weather, when the HVAC related energy consumption is thought to be lower than that in sunny weather [10, 11].

Building Insulation and Reflection

To reduce the cooling load of HVAC system, an effective way is to shield the building from direct solar radiation. A building envelope of various forms helps to establish such a shield. Some potential opportunities include adding window glass films and growing rooftop turf with watering device. Use of reflective coating on the roof of buildings in sunny, hot climates can save on air conditioning costs inside [12].

Sizing Chillers

As chiller efficiency is positively correlated to the percentage utilization of the chiller capacity, properly sizing chillers to balance chiller load with cooling demand could significantly increase chiller efficiency. Effort should be made to operate the chillers at as close to full load as possible [13].

Filter Changing and Coil Cleaning

Over prolonged time of usage, the filters and cooling coils of AHUs may be blocked by dust particles. Accumulated particles makes it more difficult for air to pass through, thus requires the motors and pumps to work at higher power. Changing filters and cleaning coils at regular intervals would save energy by reducing the pump powers [13].

3.2.2 HVAC Energy Management Strategies in Pharmaceutical Facility

Adjustment of HVAC System during Non-production Hours

Many pharmaceutical facilities fix the indoor environment throughout the year. Setting back temperature (turning temperature up in the Singapore's case), reducing ventilation and air change rate, and shutting down unnecessary equipment such as the dehumidifier during periods of non-operation would significantly save the HVAC energy. If the interruption of production activities is not frequent, the HVAC system adjustment can be done manually. If the interruption is frequent or random, a specifically designed control system may be needed to allow automatic HVAC adjustment [13, 14].

Heat Recovery System

Heat recovery systems, such as heat recovery wheels, heat pipes and run-around loops, can reduce the energy required to cool the fresh air by harnessing the thermal energy of the facility's exhaust air. Studies have shown that for areas requiring 100% make-up air, heat recovery systems can reduce a facility's heating/cooling cost by about 3% for each degree (Fahrenheit) that the intake air is raised/lowered [13, 14].

Off-coil Air Temperature Management

In facilities with make-up air handling systems, significant amount of energy can be wasted when overcooled make-up air needs to be reheated. By setting higher off-coil air temperatures when demand for cooling decreases, unnecessary reheating of the make-up air supply can be reduced [13, 14, 15].

Fan Modification

Changing the size or shape of the sheaves of a fan can help to optimize fan efficiency and airflow, thereby reducing energy consumption [13, 14].

3.3 DMAIC Approach

Define-Measure-Analyze-Improve-Control (DMAIC) approach is a popular method developed from the Lean Six Sigma (LSS) management principle. AFT extensively applies DMAIC to execute its projects. The basic method consists of the following five steps [16]:

1. Define high-level project goals and the current process.
2. Measure key aspects of the current process and collect relevant data.
3. Analyze the data to verify cause-and-effect relationships.

4. Improve or optimize the process based upon data analysis.
5. Control to ensure that any deviations from target are corrected before they result in defects.

Particular to this project, the tasks involved in each stage of the DMAIC are listed in Table 4.

Table 4: DMAIC Procedure in This Project

Stage	*Tasks*
Define	Calculate EUI, benchmark against industrial average, state the problem.
Measure	Collect and organize energy consumption data, breakdown consumption into various areas and identify the major consumer, in which more opportunities may be found.
Analyze	Study the energy consumption pattern and find the root cause of high waste.
Improve	Develop and implement strategies to minimize waste and reduce energy consumption.
Control	Monitor the process after change and observe the level of improvement using statistical methods.

One of the most effective ways to reduce energy consumption in the plant is to eliminate waste. In LSS principle, there are seven typical wastes. We could focus on these seven wastes and explore opportunities to reduce energy consumption in the plant.

1. *Overproduction* -- Overproduction is to manufacture an item before it is actually required. Overproduction is highly costly to a manufacturing plant because it prohibits the smooth flow of materials and actually degrades quality and productivity. Regarding the HVAC system, overproduction could refer to the extra supply of cool air when cooling is not needed.

2. *Waiting* -- Waiting occurs when goods are not moving or being processed. Waiting causes long lead time and occupies the manufacturing capacities.
3. *Transportation* -- Transporting product between processes adds no value to the product. Excessive movement and handling cause damage and increases risks of quality deterioration. Specific to the HVAC system, transportation waste could refer to the heat loss when fluid goes through ductwork or air leakage from pipelines.
4. *Over-Processing* -- This means that the product of the process has higher quality than specifications. In the HVAC system, if the set point temperature or humidity is lower than specified, more energy would be needed to produce the supply air with exceedingly low temperature or humidity, which incurs waste in the energy consumption. Another example concerns the single duct, terminal reheat system. If the supply air is cooled to temperature that is too low, it will then require more energy to reheat it back to the supply temperature.
5. *Unnecessary Inventory Work in Progress (WIP)* – Unnecessary WIP is a direct result of overproduction and waiting. Excess inventory tends to hide problems on the plant floor, which must be identified and resolved in order to improve operating performance.
6. *Unnecessary Motion* -- This waste is related to ergonomics and is seen in all instances of bending, stretching, walking, lifting, and reaching.
7. *Defects* -- Quality defects resulting in rework or scrap are a tremendous cost to organizations.

4. METHODOLOGY

Based on the previous calculation and literature review, we have proposed several energy saving strategies that have been implemented in GSB and NPF. In Section 4.1, the energy management tool for office building as well as production facility is introduced. Section 4.2 presents the energy saving strategies that are implemented in PF2. In Section 4.3, two energy saving strategies that are implemented in GSB are explained in details. Section 4.3.1 presents new HVAC operation schedule and the procedure to formulate this new schedule. Section 4.3.2 presents motion detection lighting control including locations of motion sensors and configurations.

4.1 Developing Energy Management Tool

A sophisticated energy management tool is developed using Microsoft Excel. After inputting the various forms of energy consumption and building floor area, the tool generates the EUI. This analysis helps to guild improvements and to monitor the energy consumption effectively.

Another usage of the tool is to theoretically calculate the cooling load that the building exerts on the HVAC system. There are both internal and external heat sources. Building architectural plan, material specifications and weather data are used to calculate the external heat gain, while the equipment list and head count which are housed inside the building are used to calculate the internal heat gain.

Understanding the cooling load and heat sources will be valuable in formulating energy saving strategies. Effort can be concentrated on reducing the heat gain from the major heat source. In addition, as the cooling load adds a cap to the HVAC energy consumption, it is possible to calculate the theoretical minimum amount of energy that needs to be used to bring the indoor environment to the desired specifications.

More details of the work of developing the tool can be found in Liu's thesis [17].

4.2 PF2 Energy Saving

The energy saving methods that have been implemented in NPF include shutting down the house vacuum (HV), process vacuum (PV), dust collector (DC) and dehumidifier during non-production hours.

The house vacuum, process vacuum and dust collector are only needed during the production for environmental control purposes. The BAS technician who controls the operation of these equipment would turn them off when there is no production activity in the pharmaceutical facilities. Electricity savings from this measure are estimated. No effects on the building environment and product quality are expected.

One dehumidifier (DH-2001) is installed on one of the AHUs in NPF (AH-2001). The dehumidifier unit was designed to reduce the relative humidity (RH) in the room for RH sensitive products. For example, Product MK-974 requires a production environment with relative humidity less than 27%. If there is no product specific requirement, a 50% RH should be maintained. According to current production plan, ultra-low RH is not required, thus the dehumidifier unit was disabled in July. Energy and cost savings from chiller electricity, boiler electricity, natural gas are estimated.

More details, including analysis of the energy and cost savings resulting from these measures, can be found in Zhang's thesis [18].

4.3 GSB Energy Saving

In this section, two energy saving strategies are explained in details. In Section 4.3.1, the procedure of formulating new HVAC operation schedule is presented. The measurement of electricity consumed by the AHU motors is also introduced. In Section

4.3.2, the working principle of motion detection lighting control is illustrated. Hardware installation and software configuration are also discussed.

4.3.1 Rescheduling of HVAC Operation Hours

According to the old HVAC operating schedule, the AHUs in GSB are turned on for some period of time when there is no occupant working in the building (this can be considered as an overproduction in the HVAC system). Energy can be saved by rescheduling the HVAC operating hours and turning off the AHUs during time of building vacancy. In order to find out the optimum HVAC operation hours, we need to first determine the building occupancy hours. Next we need to find out how long it takes the HVAC system to bring the temperature to set point after it is turned on and also how long the room temperature rises above upper comfort limit after HVAC is turned off.

Employee Work Schedule and Comfort Level Survey

A survey was carried out to find out the work schedule of each employee and the comfort level at current HVAC operation schedule in GSB. The objective of this survey was to investigate how we can shorten the HVAC system operation time to reduce energy consumption without compromising the comfort level in the office. The survey questions and results are shown in Appendix A. The survey results help us determine the period of time that we need the indoor environment to meet the requirement.

Time Constant of the Office Building

We considered the GSB building as a thermal system that we approximate as a first-order, linear time-invariant system. The output of the system is the indoor temperature; the input to the system is the on/off status of the HVAC system. The on/off of the HVAC system is modeled as a step input to the system. We can measure the room temperature versus time. This is the response of the system to a step input. By identifying the time constant of the system, we can estimate a more accurate time at which we need to turn on and turn off the HVAC system to maintain the required indoor environment when the building is occupied. According to Lei, the best temperature range for an office area is 21 °C to 25 °C and workers' productivity is highest when room temperature is at 23 °C [19].

The office temperature is measured using a YOKOGAWA MW100 Data acquisition unit for eight days, 24 hours per day. There are three temperature sensors located at different positions in the office area so that temperatures at different locations could be monitored at the same time. Two of the sensors are type K thermocouple sensors, while the other one is a Resistance Temperature Detector (RTD). The three temperature sensors are connected to three channels on the Data acquisition unit, temperature is recorded at every five seconds. Figure 12(a) shows the setup of the YOKOGAWA data acquisition unit connected with temperature sensors. Figure 12(b) shows the thermocouple temperature sensors used in the measurement. As shown in Figure 12(c) and (d), the thermocouples are placed at the top of cubicle wall near where employees are sitting. The positions of the thermocouple are chosen to be in the middle between four outlets of cooled air duct to avoid biased temperature reading. The RTD is placed on the office desk. The position of all three temperature sensors avoids heat generating devices such as computers and printers. The locations of the temperature sensors make sure that the temperature recorded in the data unit is as accurate to real human feeling as possible.

The temperature data are processed and displayed by MW100 View software associated with the YOKOGAWA data acquisition unit. Figure 11 shows one snapshot of the software in use. The curves indicate the measured temperature in the office area. With these temperature data, we can observe the temperature changes versus time in the office area. We can also find out the response of the temperature to the HVAC system operation status, which lead to the time constant of the building.

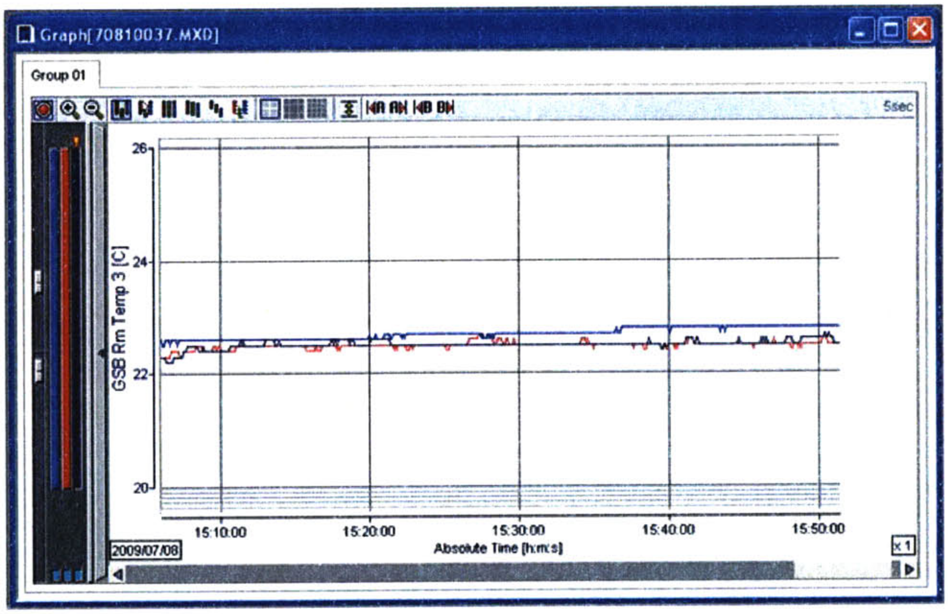


Figure 11: MW100 Viewer snapshot.

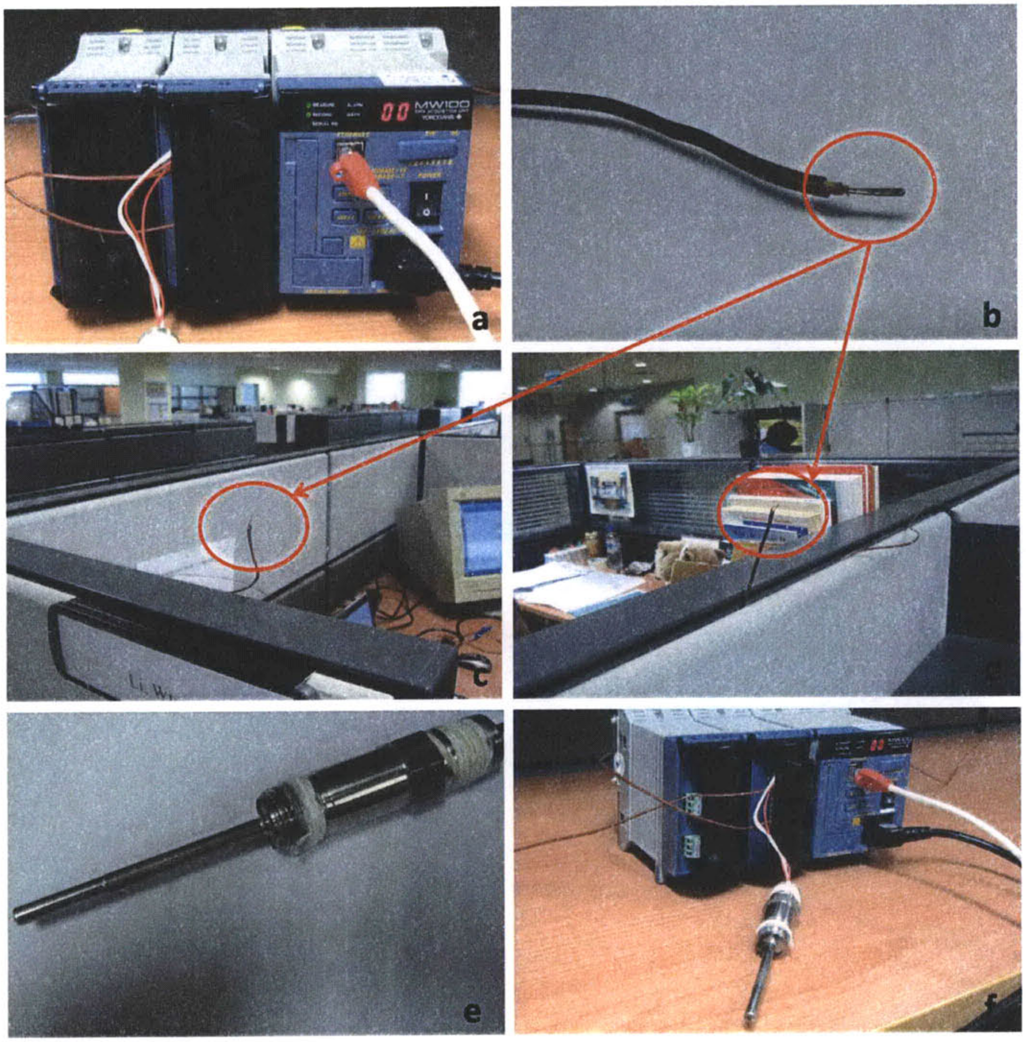


Figure 12 (a) YOKOGAWA MW100 Data acquisition unit. (b) Thermocouple temperature sensor. (c) and (d) Positions of thermocouple temperature sensor in measurement. (e) RTD. (f) Position of RTD in measurement.

New HVAC Operating Schedule

Based on the survey results, and the time constant of the building internal environment, we can formulate new operating schedules of HVAC system in GSB. Table 5 shows the old operating schedule of the GSB HVAC system.

Table 5: HVAC Old Operation Schedule

Equipment	***Existing Operation Schedule***	
	Monday – Friday	*Saturday & Sunday*
B200-AH-0109	Always run	Always run
B200-AH-0104	Always run	Always run
B200-AH-0105	Always run	Always run
B200-AH-0106	7:00 - 20:00	8:00 - 17:00
B200-AH-0107	7:00 - 20:00	8:00 - 17:00
B200-AH-0108	7:00 - 20:00	8:00 - 17:00
B200-AH-0110	7:00 - 20:00	8:00 - 17:00

AHU-0109 supplies cool air to the locker rooms on the first floor. The locker rooms are for the operators working in the plants to change their attire before and after work. Therefore, the AHU must be on in the night and during weekends when operators are still working. AHU-0104 is the pre-cool AHU for the whole building. All fresh air is taken into the building through this AHU, pre-cooled and then distributed to other AHUs and further cooled to supply the office areas. AHU-0105 controls the dining area and the kitchen. AHU-0106 and AHU-0107 supply cooled air to GSB level two. AHU-0108 and AHU-0110 supply cooled air to GSB level three.

The objective of formulating a new HVAC operation schedule is to save energy by only running the AHUs when the building is occupied and the indoor temperature is required to remain within the comfort level. After the new HVAC operation schedule is formulated, the AHU operation hours are changed and thus the savings calculated. In order to verify the savings, the electricity directly consumed by the AHU motors is measured by a portable power meter. Then statistical tools are used to analyze the measured electricity consumption and verify the savings from the new HVAC operation scheduling.

3169-20/21 Clamp on Power HiTESTER power meter is used to measure the electrical power consumed by the AHU motors in GSB directly. The power meter measures instant voltage and current of the three phase power supply cables connecting the distribution board and the motors. Then instant power and average power is calculated by the power meter. Figure 13 shows the setup of the measurement inside the power distribution board cabinet in the AHU equipment room. Figure 13 (a) shows that the voltage cords and current clamp sensors are connected to the power meter channels. As shown in Figure 13 (b), three clamp current sensors are clamped on three power cables of the three phase system to measure the currents. Figure 13 (c) shows the display on the power meter. Figure 13 (d) shows the clamp sensors and voltage cords.

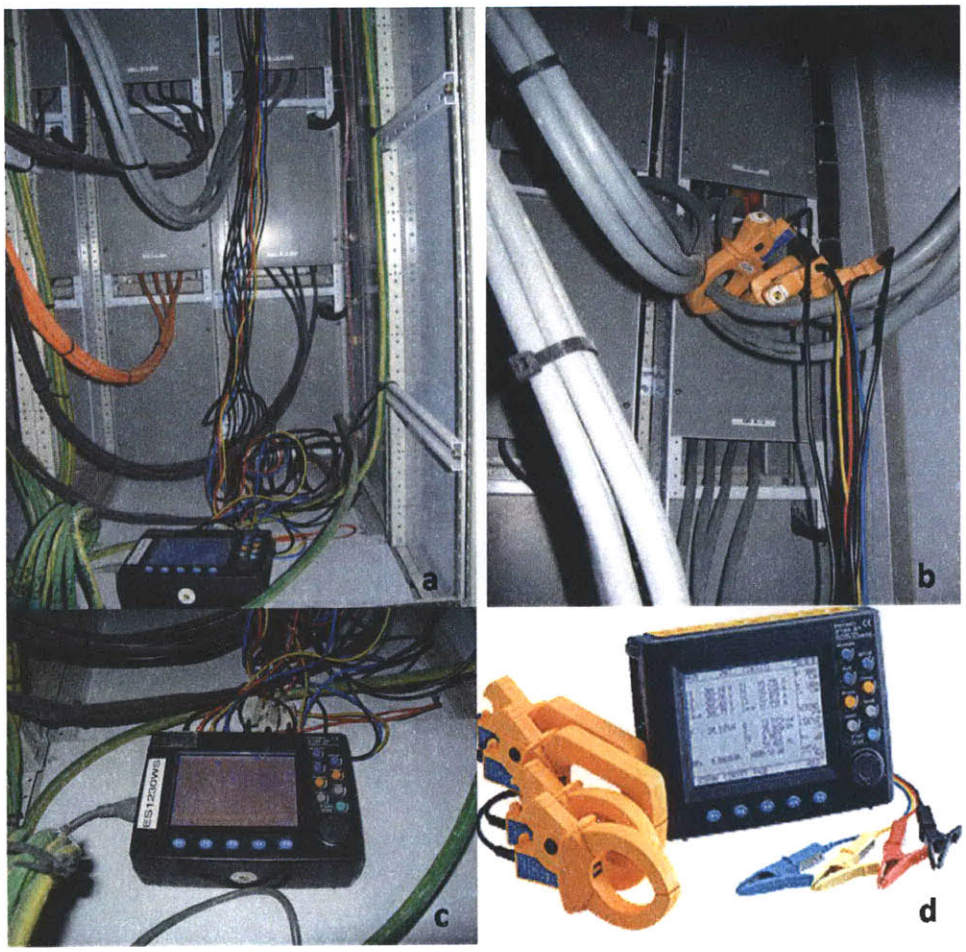


Figure 13 (a) Setup of power meter in the distribution board cabinet. (b) Clamp sensor on three phase power cable. (c) Power meter data collection unit in measurement. (d) Power meter with four clamp sensors for current measurement and four voltage cords for voltage measurement.

4.3.2 Motion Detection Lighting Control

Sometimes, employees leave the office area without turning off the lights in the evening, and so the lights are on for the whole night. This causes waste in two ways. First, it directly wastes electricity when no one is in the office area. Second, it generates extra heat inside the building and contributes to the heat gain which increases the cooling load of the HVAC system in the next day.

From the office equipment list created by us, we can see that the power rating of the lighting in GSB is estimated to be 44% of the total direct power rating in the building. Hence, if the waste from lighting could be reduced, the energy cost in GSB can be reduced significantly.

In order to solve this problem, motion detection lighting control is implemented in GSB level two and level three office areas. The hardware of the motion detectors is provided and installed by an external contractor. Six motion detectors are installed on the second floor and eight are installed on the third floor. The locations of the motion detectors are shown in Figure 14. The exit lights, meeting room lights are not controlled by the motion detector. Some of the lights in the office area are not connected to motion detector to ensure safety. During office hours, lighting is controlled by normal switch. After office hours, lighting is controlled by motion detectors.

Each motion detector has a detecting range of four meters in radius on the floor. The expiration of the timer on each detector can be set from 10 seconds up to 1 hour. All the timer expirations are set to be the same in our implementation. All the detectors on the same floor are interconnected and the timers are synchronized. Once any one of the detectors is activated, all the detectors' timers will be set zero and the controlled lights are turned on. Then the synchronized timers will start to count until their preset expiration is reached. Within the expiration of the activated detector, if any other detector in the network is activated, the timers will be reset to zero again. If none of the detectors is activated within the preset expiration time, all controlled lights will be switched off.

A survey was carried out to find out employees' opinion on the time period of the day that is suitable to implement motion detection lighting control and how long the timer expiration should remain on once the timer is activated. The specific settings, and the resulting savings, are discussed in the next chapter.

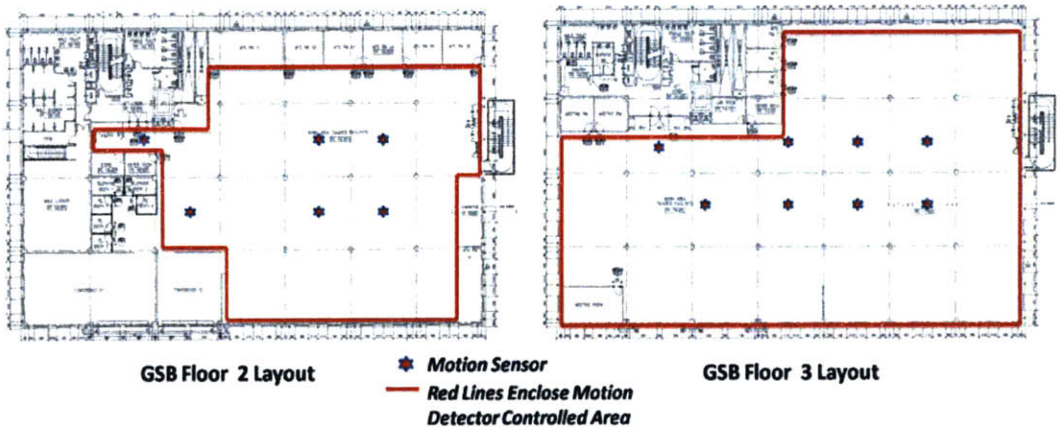


Figure 14. Floor layout with the location of motion sensors.

5. RESULTS AND DISCUSSION

In this chapter, the results of formulating a new HVAC operation schedule in GSB are presented. This includes the results from GSB employee work schedule and comfort level survey which is presented in Section 5.1.1. Section 5.1.2 discusses the indoor temperature data and time constant of the office area. The new HVAC operation schedule is formulated in Section 5.1.3. AHU motor electricity consumption measurement data after implementing the new HVAC operation schedule are presented in Section 5.1.4. The indirect electricity savings from the new operation schedule are presented and discussed Section 5.1.5. In Section 5.2, motion detection lighting control estimated savings are presented and discussed.

The EUI values of GSB and PF2 are verified by detailed calculation. Heat gain and cooling load from various sources are identified and calculated. The minimum possible energy consumption in HVAC system is calculated and can be used as a goal for continuous improvement. For detailed analysis of this part of the project, please refer to Liu's thesis [17].

Shutting down house vacuum, process vacuum and dust collector during non-production could result in the potential cost savings from June to December 2009 to be as high as S$52,767. And disabling the dehumidifier can save another significant amount of energy in the PF2. For detailed analysis of this part of the project, please refer to Zhang's thesis [18].

5.1 New HVAC Operation Schedule

In this section, the employee work schedule and comfort level surveys results are presented and discussed. Then the time slot that requires a comfortable indoor environment is determined. The temperature measurement results indicate the time that we need to turn on and off AHUs to optimize energy efficiency without compromising office comfort level. The electricity consumed by the AHU motors before and after the implementation of new scheduling are compared. The cost savings are discussed in this section.

5.1.1 Employee Work Schedule and Comfort Level Survey

The complete survey and survey results are shown in Appendix A. Only the important results that affect the operation hours of HVAC system are presented in this section. In all, 50 out of 137 employees working in GSB responded to the survey.

Office Occupancy Hours

When the employees were asked the percentage of time that they arrive the office in the three time slots, the results are shown in Table 6. Each respondent had 100 points to distribute to the three time slots. The response total column is the total points from 50 respondents. For this particular case for the before 7 a.m. slot, the inputs are 25, 40, 40, 75 which adds up to 175 points. But the average value among the 50 respondent is 3.5 percent. This estimates that on average only 3.5% of the time, sample employees come to office before 7 a.m. while the other 96.5% of time, employees come to office after 7 a.m.. Figure 15 shows the percentage of time employees arrive GSB in three time slots. If the service level of the HVAC system is 95%, then it is reasonable to set the starting time of required indoor environment at 7 a.m.. The set point for office temperature is at 22 °C.

Table 6: Arriving time of employees.

	Response Average	Response Total	Response Count
Before 7 a.m.	3.5	175	50
Between 7 a.m. to 9 a.m.	92	4600	50
After 9 a.m.	4.5	225	50

The next step was to find out the time when most employees leave the office and when the AHUs in the HVAC system could be turned off for energy saving. Similar to the arriving time to the office in the morning, employees were asked for the percentage of time they leave the office in the three time slots. The results are shown in Table 7. The calculations of the response total and response average are the same as that of the arriving time of employees to the office in the morning. Three respondents entered 50, 50, 90 for the percentage of the time they leave the office after 8 p.m.. From the table we can see that only 3.8% of the time employees leave the office after 8 p.m.. Therefore, on average, 96.2% of the time, employees leave the office before 8 p.m.. Figure 16 shows the percentage of time employees leave office in the three time slots. Hence, it is reasonable to set the ending time of office indoor environment requirement at 8 p.m..

Table 7: Leaving time of employees

	Response Average	Response Total	Response Count
Before 6pm	85	4250	50
Between 6pm to 8pm	11.2	560	50
After 8pm	3.8	190	50

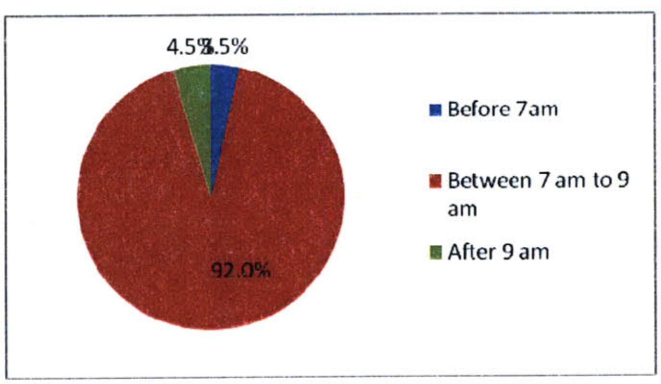


Figure 15: Percentage of time employees arrive GSB in 3 time slots.

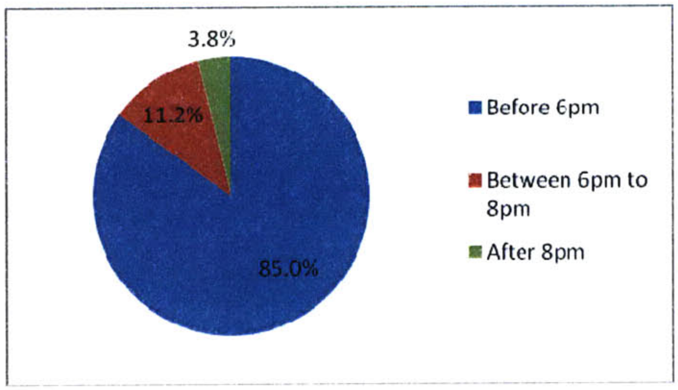


Figure 16: Percentage of time employees leave GSB in 3 time slots.

Previously, the HVAC was running during weekends. Therefore, it is necessary to find out how many people come back to work during weekends. If employees seldom come back to the office on the weekends, the HVAC can be turned off. As shown in Figure 17, only 4% of the respondents have ever come back to the office during weekends in year 2009. As shown in Figure 18, out of the people who have the experience of working in GSB on the weekends, which includes only four people, three of them came to the office only for one to two times during year 2009. And the other one came back more than twice but less than six times. Hence, it is clear that most employees do not work in GSB during the weekend, it is not necessary to turn on HVAC every weekend. Other policies on HVAC operation can be proposed to serve employees who want to work in GSB on weekends.

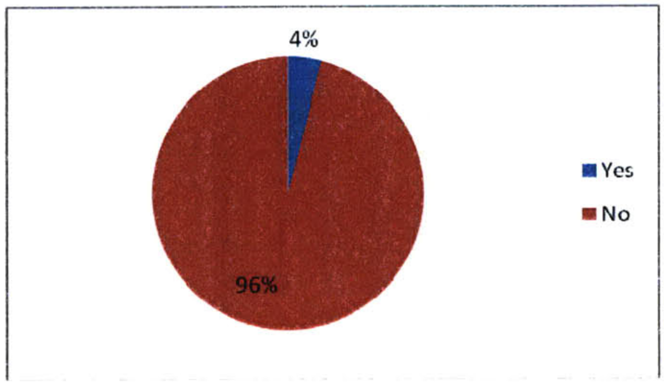


Figure 17: Percentage of employees have experience of working in GSB during weekends.

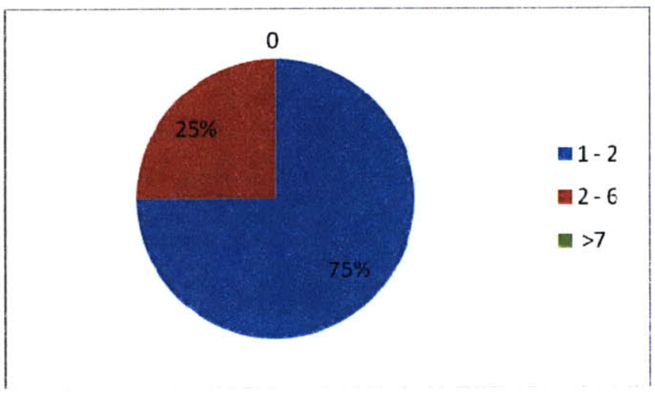


Figure 18: Number of times worked in GSB on weekends.

In summary, the GSB indoor environment needs to meet the requirement of temperature being in the range of 21 °C to 25 °C with set point at 22 °C from 7 a.m. to 8 p.m. on weekdays. It is not necessary to meet the requirement during weekends unless there are particular requirements from employees; the HVAC can be turned on for them during weekends upon their request.

5.1.2 GSB Indoor Temperature Trend and Time Constant

The office area temperature data are collected at three different locations for two weeks. The most useful temperature data are the temperature trend after the HVAC AHU motors are turned on in the morning, and the temperature trend after the HVAC AHU motors are turned off in the evening. The temperature change data after turning on and off the AHU motors can be used to identify the time constants of the office environment. Once we obtain the time constant of the step response to AHU motor states, we can identify the required time to turn on and off the AHU motors so that the office temperature meets the requirement while keeping the energy consumption at minimum.

Time Constant When AHU Motors are Turned On

The steady state of the system before the AHU motors are turned on has an average temperature of 25.97 °C. The average temperature is calculated by taking the average temperatures measured by each of the three sensors first, and then taking the average of the three mean temperatures from the three sensors to find the overall mean value. The time period that is used to calculate average temperature is between 3:30 a.m. and 4:50 a.m. before the AHU motors are turned on as shown in Figure 19. There are slight temperature variations measured by the three sensors because they are located at different positions. However, the variation is within 0.2 °C at the steady state.

Assuming that the office indoor environment is a thermal system, this thermal system is a first-order, linear time-invariant (LTI) system. We also assume that the heat gain from the outside environment such as sun radiation, outside air temperature fluctuations and the internal heat generated by equipment are noises to the system. Since the step input to the system is the on/off status of the AHU motors (assuming constant motor power during start up period), the output, which is the room temperature, can be modeled as a step response:

$$T(t) = T_0 e^{-t/\tau} \quad (1)$$

Where $T(t)$ is the temperature as a function of time t, T_o is the steady state temperature before the step input and τ is the time constant of the system.

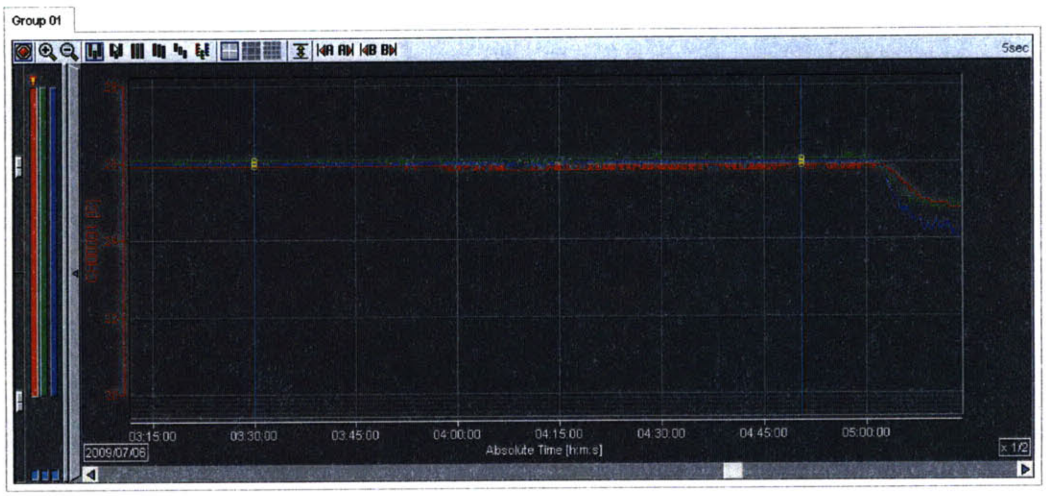


Figure 19: Average temperature at steady state before AHU motors are turn on.

The steady state temperature of the system after turning on the AHU motors is calculated in the time period from 7:40 a.m. to 9:00 a.m. as shown in Figure 20. The average temperature in this steady state is 21.93 °C. The temperature is controlled by variable volume of cooled air supply. The control algorithm used in the system is PID control. The temperatures measured by the three sensors differ more than that of the steady state before turning on the AHU motors. This might be due to the different locations of the sensors and the cooled air flow inside the office.

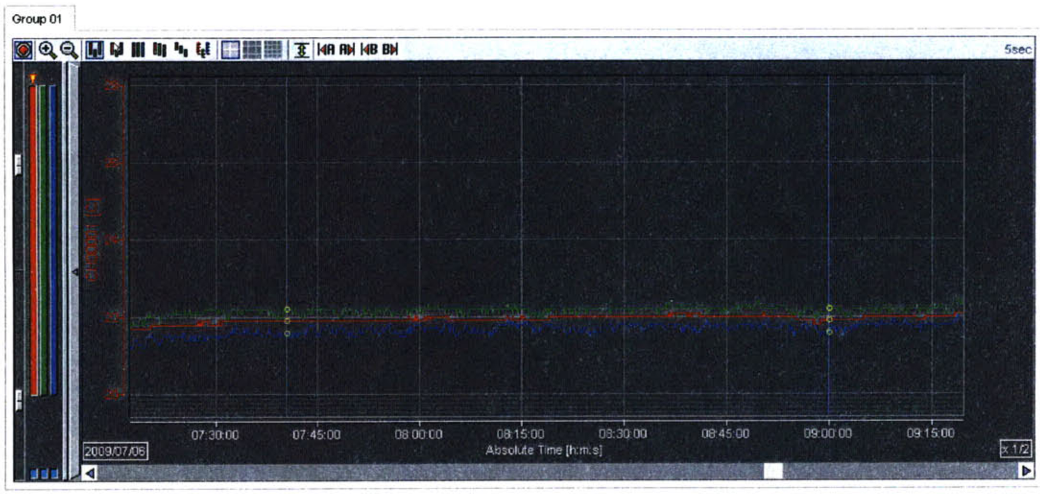


Figure 20: Average temperature at steady state after AHU motors are turn on.

The time period within which we can use the temperature trend to model the step response is from 5:00 a.m. when the AHU motors have just been turned on to 7:40 a.m. when the temperature is already at steady state as shown in Figure 21.

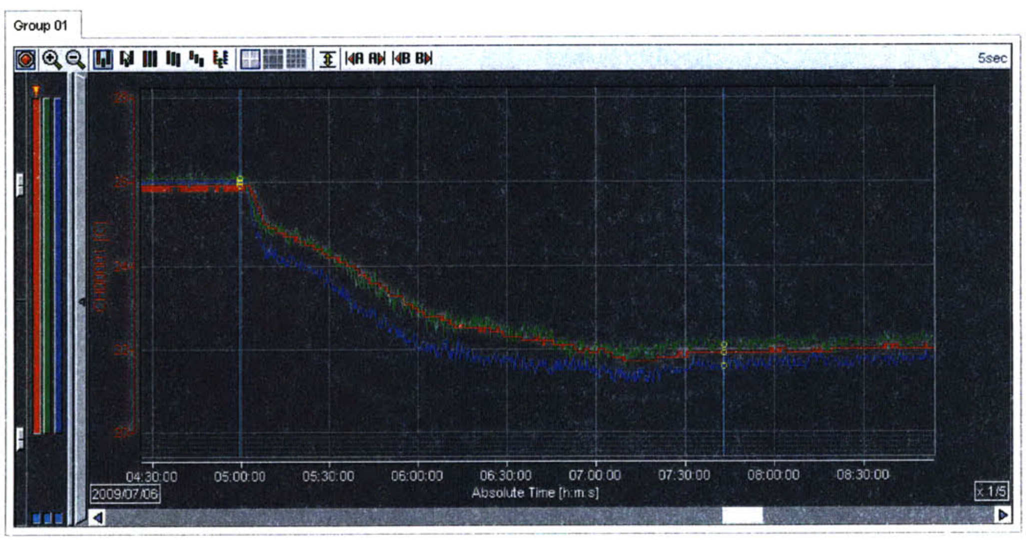


Figure 21: Exponential decay of temperature after turning on AHU motors.

The model of the temperarue trend is formed by setting T_o to be the steady state temperature before turning on AHU motor, which is 25.97 °C. Temperature T can be read from MW100 viewer directly, so we can find the time constant τ by substituting T_o, T and the corresponding time t values into equation (1). The time t is in minutes starting from 5:00 a.m., and T is the average temperature from three sensors at the particular time t. Then we can solve for the values of τ. The average value of τ is considered as the time constant of the thermal system in GSB. The values of T and corresponding time t and calculated τ values are shown in Table 8. From Figure 21 it is estimated that the average temperature overshoots the set point and the room temperature goes below the set point of 22 °C at 7:20 a.m.. Therefore, in the calculation of time constant, we take 10 pairs of samples from 5:00 a.m. to 7:00 a.m.. Sample points will be evenly distributed along the time, so samples are taken every 12 minutes.

Table 8: Calculation of time constant from measured data.

T_o = 25.97 °C				
T (°C)	*t (Min)*	*T / T_o*	*ln (T / T_o)*	*Calculated τ (Min)*
24.733	12	0.952368	-0.0488	246
24.333	24	0.936966	-0.06511	369
23.800	36	0.916442	-0.08726	413
23.267	48	0.895918	-0.10991	438
22.667	60	0.872815	-0.13603	441
22.267	72	0.857412	-0.15384	468
22.333	84	0.859954	-0.15088	557
22.200	96	0.854832	-0.15685	612
21.967	108	0.845861	-0.1674	645
21.833	120	0.840701	-0.17352	692
			Average = 488	

Hence, the temperature trend in GSB office area after the AHU motors are turned on can be modeled as:

$$T(t) = 25.97e^{-t/488}$$

Then we can calculate the time required for the HVAC system to cool the office area from 25.7 °C to 22 °C. Substituting $T(t) = 22$, and solving the equation, we obtain $t = 81$ minutes. This result can also be estimated by reading Figure 21. So we can conclude that the HVAC AHU motors must be turned on 81 minutes before 7:00 a.m. so that at 7:00 a.m. when most employees start to arrive, the room temperature will reach the set point.

Time Constant When AHU Motors are Turned Off

Similarly to the time constant of the thermal system after the AHU motors are turned on, it is necessary to find out the trend of the office temperature after the AHU motors are turned off in the evening. In a similar way to that used to determine time constant after the AHU motors are turned on, we can determine the time constant of the system after the AHU motors are turned off in the evening. Then we can identify the best time to turn off the AHU motors to save energy without compromising employees' comfort.

The steady state average temperature before the AHU motors are turned off in GSB is calculated using the measured temperature data from 17:00 to 18:30. The average temperature is slightly above the set point temperature of 22 °C, which is at 22.23 °C as shown in Figure 22.

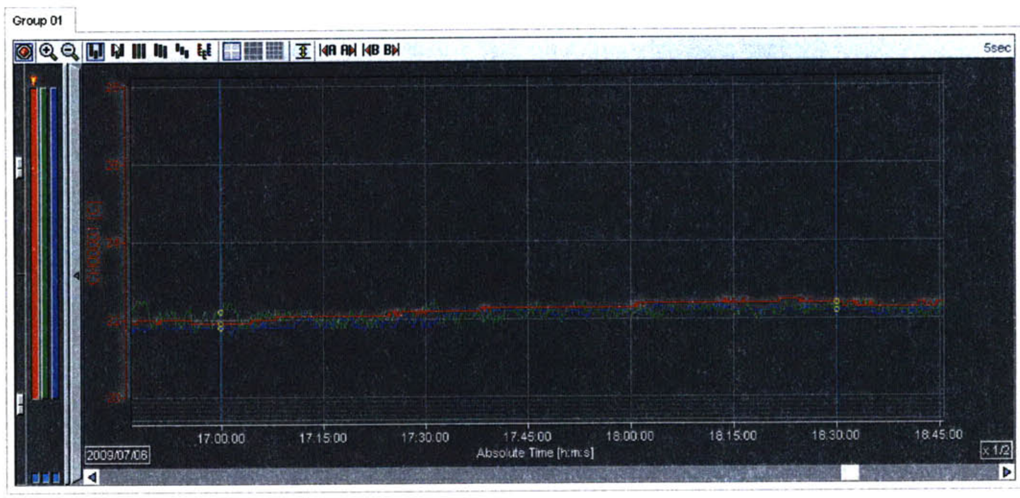


Figure 22: Average temperature at steady state before AHU motors are turn off.

The steady state temperature after the AHU motors are turned off in GSB is calculated using the measured temperature from 22:00 to 23:30 in the evening. Although the temperature is still increasing, the rate is so small that it can be ignored here for the purpose of calculating time constant. The average temperature at this steady state is calculated to be 24.26 °C as shown in Figure 23. The upper specification limit of the office temperature in GSB is set at 24 °C.

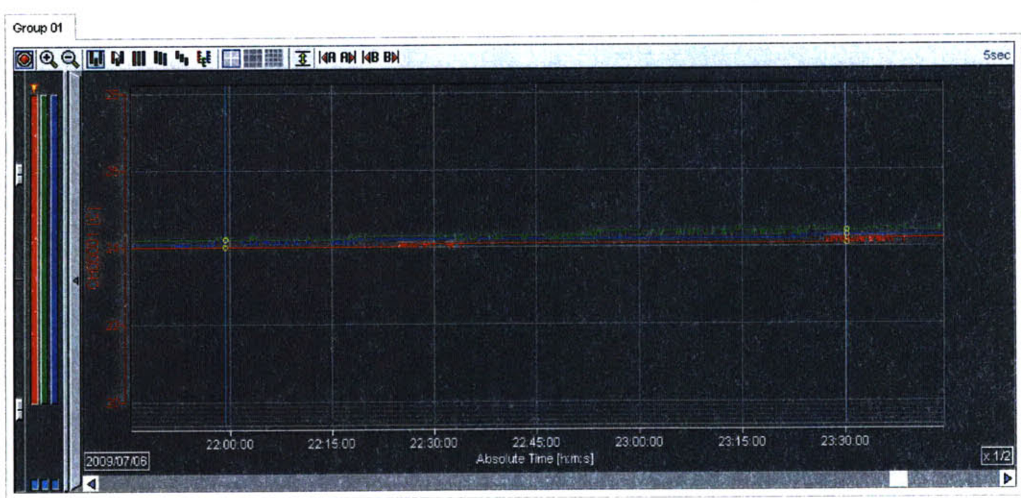


Figure 23: Average temperature at steady state after AHU motors are turn off.

The step response model applied to the office temperature after the AHU motors are turned off will be slightly different from the one used for this thermal system in the morning. The model chosen here is:

$$T(t) = C - T_o e^{-t/\tau} \quad (2)$$

Where $T(t)$ is the temperature as a function of time t, T_o is the steady state temperature before the step input, τ is the time constant of the system and C is a constant value need to be determined.

The constant value C can be easily calculated by setting time t equals to zero, hence, $C = 2\ T_o = 2 \times 22.23 = 44.46$. T_o find the time constant in the model, 10 pairs of sample temperatures are taken between 19:00 and 21:00 shown in Figure 24, and the calculation is shown in Table 9. The steady state temperature before step input is at 22.23 °C. Once the time constant is determined, we can obtain the model of the temperature after the AHU motors are turned off as:

$$T(t) = 44.46 - 22.23e^{-t/954}$$

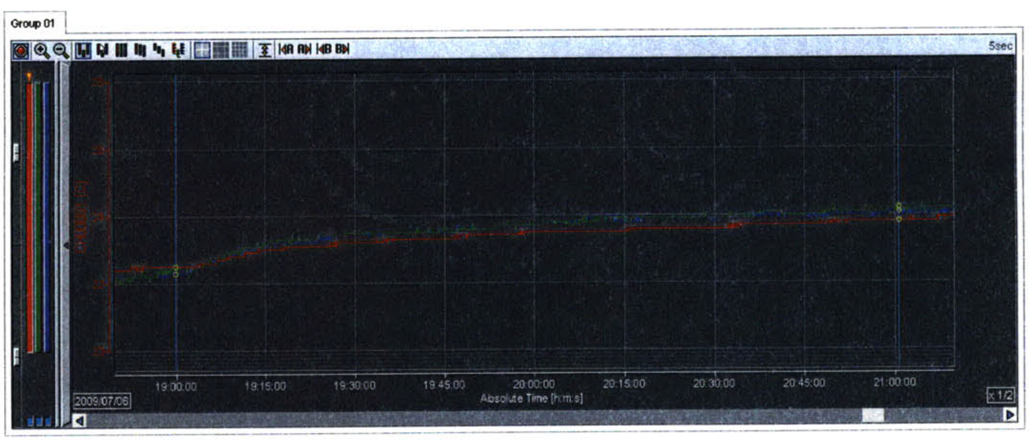


Figure 24: Exponential increase of temperature after turning off AHU motors.

Table 9: Calculation of time constant from measured data

T_o = 22.23 °C		C = 44.46			
T (°C)	*t (Min)*	*T - C*	*-(T - C)/To*	*ln (-(T-C) / To)*	*Calculated τ (Min)*
23.00	12	-21.46	0.965362	-0.035251991	340
23.30	24	-21.16	0.951867	-0.049330121	487
23.43	36	-21.03	0.946019	-0.055492738	649
23.53	48	-20.93	0.94152	-0.060259192	797
23.63	60	-20.83	0.937022	-0.065048473	922
23.70	72	-20.76	0.933873	-0.06841467	1052
23.80	84	-20.66	0.929375	-0.073243264	1147
23.83	96	-20.63	0.928025	-0.074696401	1285
23.86	108	-20.6	0.926676	-0.076151652	1418
24.00	120	-20.46	0.920378	-0.082970967	1446
					Average = 954

Then we can calculate the time it takes for the office temperature to rise above 24 °C.

$$24 = 44.46 - 22.23e^{-t/954}$$

We can solve the equation and obtain t = 79 minutes. However, we could estimate the time for the room temperature to rise to 24 °C from Figure 24 to be 100 minutes because the temperature rises at a low rate. But conservatively, we can conclude that the AHU motors should be turned off 79 minutes before 8 p.m. when most employees have left the office and the room temperature requirement is not necessary.

The significance of these two room temperature models is that, given the HVAC system capacity, the heat sources inside the building, and the building envelop (external thermal insulation), we can set the set point temperature and upper specification limit (USL) and lower specification limit (LSL) at any value and find out how long the HVAC system takes to bring the room temperature from steady state to the set point. The model can also determine how long it takes the room temperature to increase from the set point to upper specific limit after the AHU motors are stopped. This modeling method could be applied to other buildings easily.

5.1.3 New HVAC Operation Schedule

From the conclusion in Section 5.1.1 we can see that in the GSB office, the temperature requirement ranging from 21 °C to 24 °C must be satisfied from 7 a.m. to 8 p.m.. And in Section 5.1.2, we showed that in the morning, it takes 81 minutes for the office temperature to decrease from steady state temperature to set point temperature of 22 °C. In the evening, it takes 79 minutes for office temperature to rise from steady state temperature of 22.23 °C to the upper specification limit of 24 °C. Therefore, ideally, the HVAC AHU motors could start at around 5:40 a.m. and stop at around 6:40 p.m..

However, some other factors need to be considered when finalizing the HVAC AHU operation schedule. In the morning, the kitchen on level one operates at 5 a.m. and generates some exhaust gas; the AHU motors must be turned on to blow out the exhaust gas to avoid an unpleasant smell in the office area on level two. Furthermore, according to Liu's work, the heat gain from the ventilation is much higher than sun radiation and thermal conduction from outside environment [17]. This means that a large part of the heat gain to the GSB is carried in by fresh air intake to the rooms. And the outside air temperature is at its minimum at 5 a.m. as shown in Figure 28. Hence, it is reasonable to start the AHU motors at 5 a.m. and intake the fresh air when it is at lowest temperature. In this way, the cooling load is shifted earlier and thus electrical power demand is shifted forward to avoid higher maximum demand at noon.

Therefore, the AHU operation hour starts at 5 a.m. in the morning, which is 40 minutes earlier than the ideal time. Turning on HVAC 40 minutes earlier could also accommodate some employees who arrive the office before 7 a.m.. In the evening, although temperature increases slowly so that the temperature remains below 24 °C until 9 p.m. for most days, people feel uncomfortable because of higher CO_2 level when no fresh air is transported into the office for too long. Hence the AHU motors are stopped at

7 p.m.. Because there are only a few employees working in the office after 7 p.m., the comfort level could be easily maintained until 8:30 p.m. without running the AHU motors. During weekends, the HVAC AHU motors that supply cooled air to GSB level two and level three are stopped. The new HVAC AHU operation schedule is shown in Table 10.

In the new operation schedule, from Monday to Friday, AHU-0109 and AHU-0104 operate 24 hours per day. The other AHUs operate from 5 a.m. to 7 p.m.. AHU-0109 and AHU-0104 operate 24 hours per day, seven days per week because locker rooms are open for operators in the night shift as well. During weekends, other AHUs do not operate.

Table 10: HVAC AHU new operation schedule

AHUs	Old Operation Schedule		New Operation Schedule	
	Monday - Friday	Saturday & Sunday	Monday - Friday	Saturday & Sunday
B200-AH-0109	Always run	Always run	Always run	Always run
B200-AH-0104	Always run	Always run	Always run	Always run
B200-AH-0105	Always run	Always run	5:00 - 19:00	Stop
B200-AH-0106	7:00 - 20:00	8:00 - 17:00	5:00 - 19:00	Stop
B200-AH-0107	7:00 - 20:00	8:00 - 17:00		
B200-AH-0108	7:00 - 20:00	8:00 - 17:00		
B200-AH-0110	7:00 - 20:00	8:00 - 17:00		

5.1.4 Direct Savings from New HVAC Operation Schedule

The new HVAC operation schedule was implemented by MSD soon after the schedule was proposed because this energy saving strategy does not incur any extra cost. In this section, two parts of electricity savings from the new HVAC operation schedule are discussed. The first part is the savings from reduction of direct electricity consumed by the AHU motors. The second part is the savings from reduction of chilled water consumption which indirectly reduces electricity consumed by chillers in the facilities building. Figure 25 shows the two parts of energy input to the AHUs, which are reduced by the new HVAC operation schedule.

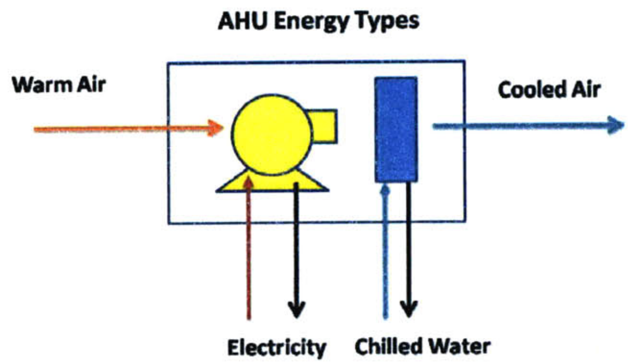


Figure 25: Two forms of electricity consumption by AHU.

In this section, the savings of direct electricity consumption by the HVAC AHU motors are calculated based on assumptions and simplifications. The actual electricity consumption is measured using a power meter. The actual savings and the calculated savings are compared. The savings from reduced consumption of chilled water are calculated in the next section, there is no measurement data. This is because there is no chilled water flow meter in GSB. And the chiller electricity power meter only measures the total power consumed by the chiller. The electricity saved by GSB chilled water consumption could be easily covered by fluctuations of chilled water consumption in other buildings.

Electricity Savings By AHU Motors Base On Calculation

In order to find the daily electricity savings from the reduction of the AHU motors running time, we need to know the average operating power of each motor and the corresponding running hours before and after the new operation schedule is implemented. Since the motor speeds are controlled by Variable Frequency Drive (VFD), the Building Automation System (BAS) monitors the operating frequency of each motor. Then the average operating power of each motor is calculated by monitoring the average operating frequency of each motor.

Some assumptions and simplifications are made in the calculations of electricity consumed by the AHU motors:

1. Average AHU motor speed is different in the office hours and non-office hours due to different cooling load. For weekdays, the time slot from 7 a.m. to 8 p.m. is considered as day time peak hours. During this period, human activities, lighting, office equipment and external environment are all heat sources to the building. Hence the cooling load for the HVAC system is heavy. The time slot from 8 p.m. to 7 a.m. is considered as night time off-peak hours. During this period, there is little human activity, little lighting, little office equipment, external air temperature is low and there is no sun radiation. Hence the cooling load for HVAC system is low. This assumption also applies to weekends.
2. During the day time peak hours, we assume a flat AHU motor operating power rating. The same assumption applies to the night time off-peak hours.

The average operating frequencies of each AHU motor on weekdays and weekends are shown in Table 11. With these data, the operating power of each motor can be calculated using the affinity laws.

Table 11: AHU motor operating frequencies.

AHU Motor Operating Frequency (Hz)				
AHUs	Weekday Day	Weekday Night	Weekend Day	Weekend Night
B200-AH-0109	30.5	25	28	22
B200-AH-0104	32	30	30	26.5
B200-AH-0105	25	20	23	20
B200-AH-0106	30.5	25	27.5	0
B200-AH-0107	30	25	27.5	0
B200-AH-0108	35	30	31	0
B200-AH-0110	30.5	28	28.5	0

According to affinity laws, the motor power is proportional to the cube of motor shaft speed:

$$\frac{P_1}{p_2} = \left(\frac{N_1}{N_2}\right)^3$$

where P is the power (kW) and N is the motor speed (RPM).

The motor speed is calculated by this formula:

$$N = \frac{120 \times F}{P}$$

where N is the motor speed (RPM), F is the supply frequency (Hz) and P is the number of motor winding poles.

Therefore, we can derive the relationship between motor power and operating frequency as:

$$\frac{P_1}{P_2} = \left(\frac{F_1}{F_2}\right)^3 \quad (3)$$

We can set P_2 to be the motor rated power and F_2 to be the rated frequency which is 50 Hz in Singapore. Then the average operating power of the motors can be calculated using this formula. But according to VFD supplier's suggestion, in the power calculation we need to add a factor of 0.8 in practice.

The electricity consumed by the AHU motors on weekdays before rescheduling is calculated in Table 12. The motor power is calculated using equation (3) with a factor of 0.8. The day time consumption and night time consumption calculations are separated because of different motor operating power. In day time, all the AHU motors operate from 7 a.m. to 8 p.m. which is 13 hours. In night time, only AHU-0104, AHU-0105 and

AHU-0109 motors run from 8 p.m. to 7 a.m. which is 11 hours while the other motors are stopped.

Table 12: AHU Weekday electricity consumption before rescheduling.

AHU WEEKDAY Daily Electricity Day Time Consumption BEFORE Rescheduling					
AHU Tag Name	**AHU Rated Power (kW)**	**Average Op Frequency (Hz)**	**Average Op Power (kW)**	**Operation Hours / Day**	**Electricity Consumption (kWh)**
				Weekday	**Weekday**
B200-AH-0109	5.5	30.5	1.00	13	13
B200-AH-0104	11	32	2.31	13	30
B200-AH-0105	15	25	1.50	13	20
B200-AH-0106	5.5	30.5	1.00	13	13
B200-AH-0107	11	30	1.90	13	25
B200-AH-0108	11	35	3.02	13	39
B200-AH-0110	11	30.5	2.00	13	26
AHU WEEKDAY Daily Electricity Night Time Consumption BEFORE Rescheduling					
B200-AH-0109	5.5	25	0.55	11	6
B200-AH-0104	11	30	1.90	11	21
B200-AH-0105	15	20	0.77	11	8
B200-AH-0106	5.5	0	0.00	0	0
B200-AH-0107	11	0	0.00	0	0
B200-AH-0108	11	0	0.00	0	0
B200-AH-0110	11	0	0.00	0	0
				Total Weekday Daily AHU Consumption / Day / kWh	
					201

Similarly, we can calculate the electricity consumed by the AHU motors during weekends before implementing the new HVAC operation schedule as shown in Table 13.

The operating frequencies of each motor are calculated by taking the average value of sampled historical data before implementing the new operation schedule on weekdays and weekend. Therefore we can assume that these operating frequencies are the average frequency on weekdays and weekends. Hence the operating power of each motor represents the average power of that motor in the particular time slot. Therefore, we can estimate the daily average electricity consumed by all the AHU motors on weekdays to be

201 kWh/day as calculated in Table 12. The daily average electricity consumption by all the AHU motors on weekend is estimated to be 130 kWh/day as calculated in Table 13. These two estimated daily electricity consumptions before implementing the new operation schedule can be compared with the electricity consumed after the implementation of the new schedule.

Table 13: AHU Weekend electricity consumption before rescheduling.

AHU WEEKEND Daily Electricity Day Time Consumption BEFORE Rescheduling					
AHU Tag Name	AHU Rated Power (kW)	Average Op Frequency	Average Op Power (kW)	Operation Hours / Day	Electricity Consumption (kWh)
				Weekend	Weekend
B200-AH-0109	5.5	28	0.77	13	10
B200-AH-0104	11	30	1.90	13	25
B200-AH-0105	15	23	1.17	13	15
B200-AH-0106	5.5	27.5	0.73	9	7
B200-AH-0107	11	27.5	1.46	9	13
B200-AH-0108	11	31	2.10	9	19
B200-AH-0110	11	28.5	1.63	9	15
AHU WEEKEND Daily Electricity Night Time Consumption BEFORE Rescheduling					
B200-AH-0109	5.5	22	0.37	11	4
B200-AH-0104	11	26.5	1.31	11	14
B200-AH-0105	15	20	0.77	11	8
B200-AH-0106	5.5	0	0.00	0	0
B200-AH-0107	11	0	0.00	0	0
B200-AH-0108	11	0	0.00	0	0
B200-AH-0110	11	0	0.00	0	0
				Total Weekend Daily AHU Consumption / Day / kWh	
					130

By the similar method, electricity savings on weekdays and weekends can be calculated as shown in Table 14 and 15 respectively. For weekday day time, there is no change for AHU-0109 and AHU-0104. All other AHU motors are stopped at 7 p.m. instead of 8 p.m.; hence day time operation of each motor is reduced by one hour. In the night time, AHU-0109, AHU-0104 have no change. AHU-0105 is shut down from 7 p.m.

to 5 a.m., so compared to the old schedule, its night time operation hours are in fact reduced from time slot of 8 p.m. to 7 a.m. to time slot of 5 a.m. to 7 a.m.. This results in nine hours of reduction in night time operation. For the other four AHU motors, the night time operation hours are increased from zero to two hours, which is from 5 a.m. to 7 a.m.. The weekday daily electricity savings are calculated to be six kWh per day as shown in Table 14.

Table 14: AHU Weekday electricity savings after rescheduling.

AHU WEEKDAY Day Time Savings in Electricity Consumption AFTER Rescheduling					
AHU Tag Name	**AHU Rated Power (kW)**	**Average Op Frequency**	**Average Op Power (kW)**	**Operation Hour Changes / Day**	**Electricity Consumption (kWh)**
				Weekday	**Weekday**
B200-AH-0109	5.5	30.5	1.00	0	0
B200-AH-0104	11	32	2.31	0	0
B200-AH-0105	15	25	1.50	-1	-2
B200-AH-0106	5.5	30.5	1.00	-1	-1
B200-AH-0107	11	30	1.90	-1	-2
B200-AH-0108	11	35	3.02	-1	-3
B200-AH-0110	11	30.5	2.00	-1	-2
AHU WEEKDAY Night Time Savings in Electricity Consumption AFTER Rescheduling					
B200-AH-0109	5.5	25	0.55	0	0
B200-AH-0104	11	30	1.90	0	0
B200-AH-0105	15	20	0.77	-9	-7
B200-AH-0106	5.5	25	0.55	2	1
B200-AH-0107	11	25	1.10	2	2
B200-AH-0108	11	30	1.90	2	4
B200-AH-0110	11	28	1.55	2	3
			Total Weekday Consumption Savings / Day/ kWh		
					-6

For weekends, the savings calculation is similar. In the day time, AHU-0109 and AHU-0104 have no change from the old schedule. For AHU-0105, it is shut down for 24 hours; hence in the day time, its operating hours are reduced by 13 hours. For the other four AHUs, the operating hours are reduced by nine hours, which is reduced from time slot of 8 a.m. to 5 p.m. to zero hours. In the night time, there are only savings from AHU-

0105. Its night time operation from 8 p.m. to 7 a.m. the next day morning is removed and results in 11 hours of operating hour reduction. The weekend daily electricity savings are calculated to be 77 kWh per day as shown in Table 15.

Table 15: AHU Weekend electricity savings after rescheduling.

AHU WEEKEND Day Time Savings in Electricity Consumption AFTER Rescheduling					
AHU Tag Name	AHU Rated Power (kW)	Average Op Frequency	Average Op Power (kW)	Operation Hours Changes / Day	Electricity Consumption (kWh)
				Weekend	Weekend
B200-AH-0109	5.5	28	0.77	0	0
B200-AH-0104	11	30	1.90	0	0
B200-AH-0105	15	23	1.17	-13	-15
B200-AH-0106	5.5	27.5	0.73	-9	-7
B200-AH-0107	11	27.5	1.46	-9	-13
B200-AH-0108	11	31	2.10	-9	-19
B200-AH-0110	11	28.5	1.63	-9	-15
AHU WEEKEND Night Time Savings in Electricity Consumption AFTER Rescheduling					
B200-AH-0109	5.5	22	0.37	0	0
B200-AH-0104	11	26.5	1.31	0	0
B200-AH-0105	15	20	0.77	-11	-8
B200-AH-0106	5.5	0	0	0	0
B200-AH-0107	11	0	0	0	0
B200-AH-0108	11	0	0	0	0
B200-AH-0110	11	0	0	0	0
			Total Weekend Consumption Savings / Day/ kWh		
					-77

Electricity Savings By AHU Motors Base On Measurement

Due to the immediate implementation of the new schedule, we did not have a chance to measure the daily electricity consumed directly by the AHU motors before implementing the new schedule. Only the electricity consumption by the AHU motors after rescheduling was measured. In this section, the measurement data are presented and analyzed using statistical tools.

Figure 26 shows the average real power of all the AHU motors measured every five minutes using power meter. June 13 and 14 are weekends; the rest are weekdays. Figure 27 shows the daily average total AHU power. Here are some observations we can make from the power plots.

1. For weekdays, the real power consumption patterns are almost the same. The AHU motor power shoot up to the maximum at 5 a.m. when all motors are turned on at the same time. The power is at maximum because at this time, the room temperature is at the maximum and far from the set point. First, the PID controller would require AHU-0104 motor to run at high speed to intake fresh air from outside. Second, the PID temperature feedback controller requires all the AHU motors to run at high speed to blow air through the cooling coil to reduce the room temperature.
2. Once the room temperature reduces, PID controller would reduce the AHU motor speed to stop room temperature from falling below the lower specification limit of 21 °C. Hence the AHU motor power decreases as the room temperature decreases. Comparing Figure 26 and Figure 21, we can see that the AHU power reaches its lowest point at about 7:20 a.m. when the room temperature reaches a minimum.
3. From 7:20 a.m., AHU power starts to increase slowly and reaches another local maximum at about 12:30 to 13:30. Then the AHU power decreases slowly until motors are shut down at 7 p.m.. The AHU motor power change is due to the heat gain to the building and causes the cooling load to change. We can assume that the heat gain from human activities, lighting, computers and other office equipment are constant during the office hours. The major variation of heat gain is from the external weather changes during the day. This can be verified by the average weather data shown in Figure 28. The figure shows the monthly average external air temperature versus time in hours. The daily maximum temperature

occurs around 12:30 to 13:30, which matches the maximum AHU power consumption of each day. Furthermore, the curvature of the AHU power consumption curve is similar to that of the external air temperature curve from 7 a.m. to 7 p.m..

4. During weekdays, from 7 p.m. to 5 a.m., the AHU power is almost at a constant value of two kW. This is because only AHU-0109 and AHU-0104 operate during this time slot. And since the locker room to which these two AHU supply cool air at night is at an interior location in GSB, the heat gain from the external environment is minimum. The heat gains are only from lighting, little human activity and some heat carried by fresh air intake from AHU-0104, which are almost constant at night. Therefore, the cooling load is almost constant for AHU-0109 and AHU-0104 in the night. During weekends, the power consumption is also at a constant value of about two kW for 24 hours.

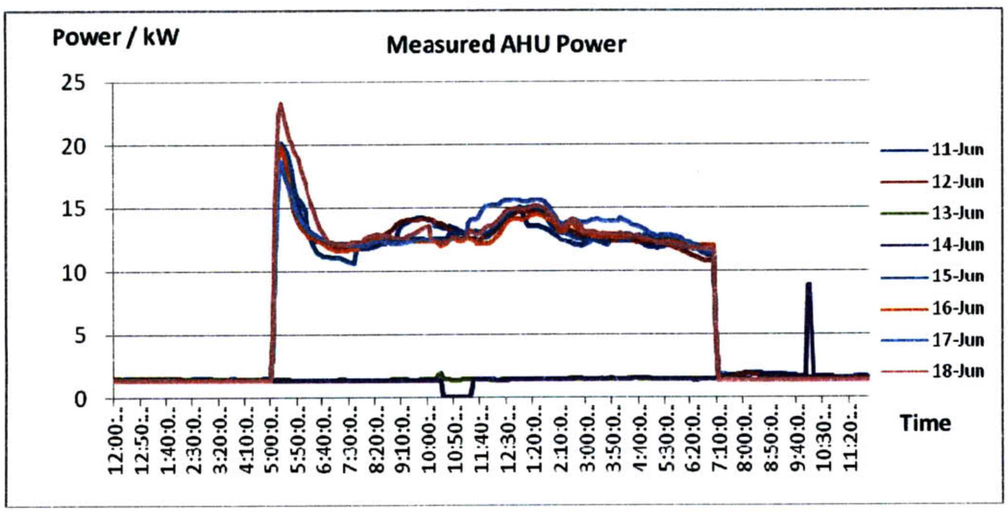


Figure 26: Power rating of total AHU motors.

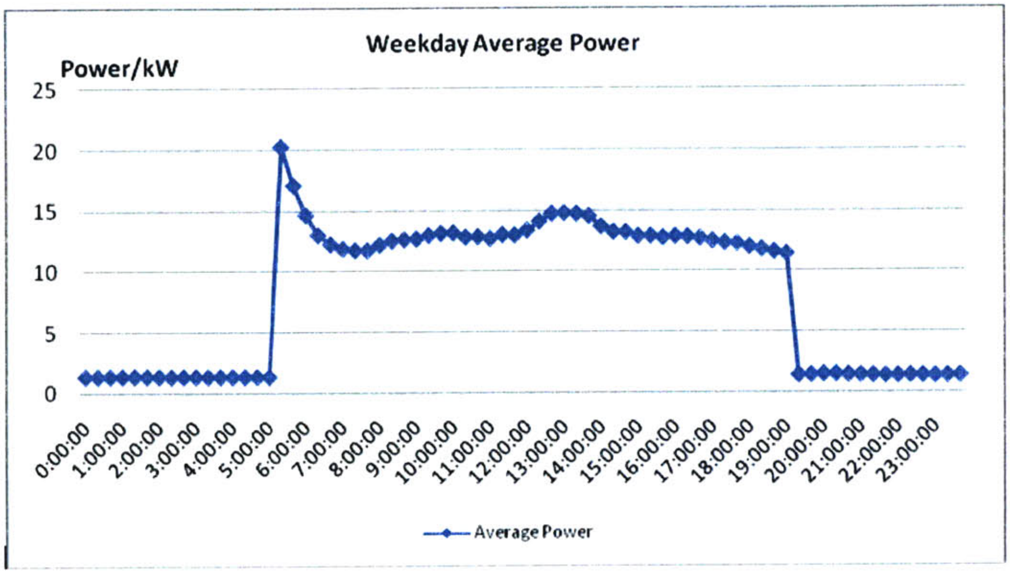


Figure 27: Daily Average total AHU power.

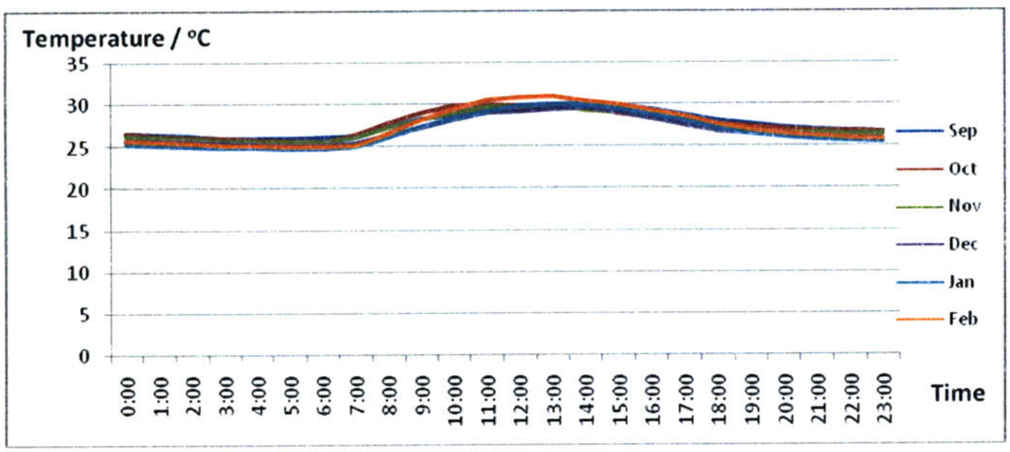


Figure 28: Average dry bulb temperature data from September 08 to February 09

With the power data of the AHU motors, the daily electricity consumed could be calculated by multiplying the average power with the five minutes sampling interval and finding the sum. Table 16 lists the daily electricity consumption and savings of the AHU motors. For weekdays, the average electricity consumption is 197.6 kWh / day. For weekend, the average electricity consumption is 34 kWh / day.

Table 16: Measured AHU electricity consumption and savings.

	Daily Electricity Consumption and Savings (kWh)							
Date	11-Jun	12-Jun	13-Jun	14-Jun	15-Jun	16-Jun	17-Jun	18-Jun
Consumption	196.5	197.5	33.9	34.2	195.1	193.1	201	202.2
Savings	4.5	3.5	96.1	95.8	5.9	7.9	0	-1.2

Table 17 summarizes the daily electricity consumptions and savings by the AHU motors before and after implementing the new operation schedule. In the previous section, we only calculated the savings on weekdays and weekends after implementing the new schedule. The calculated consumption after rescheduling is just the subtraction of the calculated savings from the calculated consumption before rescheduling. The measured average savings are the subtraction of measured consumption from the calculated average consumption before rescheduling. The measured average savings on weekdays and weekends are different from their respective calculated savings. However, we cannot make any conclusions based on these average values before we do some further analysis.

Table 17: Average daily electricity consumption comparison.

Average Daily Electricity Consumption Comparison		
	Weekday (kWh/day)	**Weekend (kWh/day)**
Average Consumption Before (Calculated)	201	130
Average Consumption After (Calculated)	195	53
Average Consumption After (Measured)	197.6	34
Calculated Savings	6	77
Measured Average Savings	3.4	96

Statistical Analysis of the AHU Motor Savings

In this section, data summarized in Table 12 and Table 13 are analysed using statistical tools. Since we only have the average electricity consumption with unknown variation before rescheduling, we need to use Student-t test. First, a t test is applied to see whether the measured consumption after rescheduling is smaller than consumption before. Second, the t test is applied to see whether the measured savings equal to the calculated savings or not for weekdays and weekends. In order to do these tests, we assume the daily electricity consumption data follows a normal distribution.

Weekday Consumption: To test whether the weekday measured consumption after rescheduling is smaller than the average consumption before rescheduling, we set the null hypothesis and the alternative hypothesis to be:

$$H_o : \mu = 201\ kWh,\ H_1 : \mu < 201\ kWh$$

Using Minitab to analyze the six weekday samples, we have the following results:

One-Sample T: Weekday Measured Consumption

Test of mu = 201 vs < 201

Variable	N	Mean	StDev	SE Mean	90% Upper Bound	T	P
Measured Weekday	6	197.57	3.48	1.42	199.66	-2.42	0.030

The 90% confidence interval upper bound is 199.66 kWh which is below 201 kWh and the P value 0.03 is smaller than (1-90%). Hence at 90% significance level or better, there is strong evidence against the null hypothesis. We reject H_o and accept H_1. So we conclude that the weekday average daily consumption after rescheduling is indeed smaller than before accounting for the observed variation in the data.

Weekend Consumption: Similar to weekdays, we can make the following null and alternative hypothesis:

$$H_o : \mu = 130\ kWh,\ H_1 : \mu < 130\ kWh$$

Using Minitab to analyse the two weekend samples, we have the following results:

One-Sample T: Weekend Measured Consumption

Test of mu = 130 vs < 130

Variable	N	Mean	StDev	SE Mean	95% Upper Bound	T	P
Measured Weekend	2	34.050	0.212	0.150	34.997	-639.67	0.000

The 95% confidence interval upper bound is at 35 kWh which is below 130 kWh. The P value is less than 0.0005 (appearing as zero to three decimal points). Hence at 95% significance level or better, there is strong evidence against the null hypothesis. So we reject H_o and accept H_1, and we conclude that on weekends, electricity consumption is smaller after rescheduling.

Weekday Savings: For the weekday savings, we want to test whether the measured savings (3.43 kWh) equal the calculated savings (6 kWh). Hence, we will do a two-tail t-test here. The null and alternative hypotheses are:

$$H_o : \mu = 6 \text{ kWh}, H_1 : \mu \neq 6 \text{ kWh}$$

Using Minitab we can obtain the following results:

One-Sample T: Weekday Measured Saving

Test of mu = 6 vs not = 6

Variable	N	Mean	StDev	SE Mean	95% CI	T	P
Saving Weekday	6	3.43	3.48	1.42	(-0.22, 7.08)	-1.81	0.130

From the result we can see that the 95% confidence interval for the measured weekday savings is from zero to seven kWh. This indicates that the measured savings might be anywhere in the range of zero to seven kWh. This is consistent with the theoretical calculated weekday savings of six kWh.

Weekend Savings: Similarly to weekdays, we can make the following hypothesis for weekend savings:

$$H_o : \mu = 77\ kWh,\ H_1 : \mu \neq 77\ kWh$$

Using Minitab, we can obtain the following results:

One-Sample T: Weekend Measured Saving

```
Test of mu = 77 vs not = 77

Variable          N     Mean  StDev  SE Mean        95% CI               T
Saving            2   95.950  0.212    0.150  (94.044, 97.856)  126.33
Variable               P
Saving             0.005
```

From the result we can see that the measured data of savings on weekends indicate 95% confidence interval of electricity savings ranging from 94 kWh to 98 kWh. The measured savings are larger than the theoretically calculated value of 77 kWh. This shows that there are indeed electricity savings by the new HVAC operation schedule.

From the above statistical analysis, we can conclude that to certain confidence level, the daily electricity consumption is indeed reduced. From the analysis of the measured data, we can see that for weekdays, the electricity savings range from zero to seven kWh at 95% confidence interval. For weekends, the electricity savings range from 94 kWh to 98 kWh at 95% confidence interval. For weekdays, the measured values are consistent with theoretical calculated savings. For weekends, the measured values are more affirmative than the theoretical calculated savings. There are two reasons that the calculated savings are smaller than actual measured data. The first one is that we only have two samples for weekends; the scattering of samples could be large. The second reason could be that the calculation of electricity savings is too conservative and resulted in smaller calculated savings.

In summary, by implementing the new HVAC operation schedule, annual electricity savings from AHU motors (using the measured data) are estimated to be:

$$(3.4 \text{ kWh} \times 5 + 96 \text{ kWh} \times 2) \text{ / week} \times 52 \text{ weeks} = 10868 \text{ kWh / year}$$

The annual electricity consumption by the AHU motors is:

$$(201 \text{ kWh} \times 5 + 130 \text{ kWh} \times 2)\text{/week} \times 52 \text{ weeks} = 65780 \text{ kWh / year}$$

So the overall annual savings are about 16.5% of the total AHU motor electricity consumption for one year.

5.1.5 Indirect Savings from New HVAC Operation Schedule

As mentioned previously, there are two parts of electricity input to the HVAC AUHs. The first part is the electricity consumed directly by the AHU motors; the second part is the electricity consumed by the chiller to generate chilled water. In this section, the electricity savings from reduced chilled water consumption are calculated.

Table 18 shows the basic information of the chiller capacity and GSB demand. The average operating power of the chillers in the facility building is about 1900 RT. The designed capacity for GSB is 6.67% of the total capacity; hence we can calculate GSB cooling capacity demand. The current chiller efficiency is the efficiency that converts electrical energy to chilled water internal energy. Table 19 shows the calculations of electricity savings.

Table 18: Basic information of chiller

Total Cooling Capacity demand for plant (RT)	1900
GSB % cooling capacity	6.67%
GSB cooling capacity demand (RT)	126.73
Current Chiller Efficiency (kW/RT)	0.861

The supply chilled water (CHW) temperature, return chilled water temperature and supply air temperature are measured by BAS and the data shown in the table are a snapshot at a particular time. Return air temperature is estimated to be 23 °C which is a little higher than the set point temperature of 22 °C. There is heat transfer between the chilled water and air, and the temperature differences are calculated accordingly. The air flow rate is also obtained from BAS. In the calculation, we assume they are the average air flow rate throughout the operating hours.

Since there is no chilled water flow meter in each AHU, we cannot measure the individual chilled water flow rate. In order to calculate the individual chilled water demand in the AHUs, we calculate the normalized chilled water flow rate in each AHU as follows. We assume that heat is transferred from air to chilled water with 100% efficiency.

(CHW flow rate * CHW ΔT) is proportional to (air flow rate * air ΔT)

Then, Normalized CHW flow rate = (air flow rate * air ΔT)/CHW ΔT

This is not the true chilled water flow rate, but it can be used to calculate the percentage of chilled water flow into each AHU, which is proportional to the percentage of cooling capacity. The percentage of cooling capacity each AHU requires is calculated by dividing the corresponding normalized chilled water flow rate by the sum of all CHW flow rate. Then the cooling capacity demand in RT of each AHU is calculated by multiplying the percentage by the total GSB cooling capacity demand shown in Table 18. Then the cooling capacity is converted to the required electrical power by the current chiller efficiency. The reduction of operation hours is calculated by comparing the new and old operating schedule.

Table 19: GSB chilled water electricity savings from new HVAC schedule.

GSB CHW Electricity Savings With New HVAC Schedule							
AHU	AH0104	AH0105	AH0106	AH0107	AH0108	AH0109	AH0110
Supply CHW T (C)	5.6						
Return CHW T (C)	14.7						
CHW ΔT (C)	9.1						
Air Flow Rate CMH	13000	5111	33608	9500	15000	7500	36500
Supply Air T (C)	12.1	15.0	12.9	13.0	15.6	18.0	12.4
Return Air T (C)	23.0						
Air ΔT (C)	10.9	8.0	10.1	10.0	7.4	5.0	10.6
Normalized CHW Flow rate	15571.4	4493.2	37301.2	10439.6	12197.8	4120.9	42516.5
% of cooling capacity	12.3%	3.5%	29.5%	8.2%	9.6%	3.3%	33.6%
Cooling capacity demand (RT)	15.58	4.50	37.33	10.45	12.21	4.12	42.55
Power required to operate (kW)	13.42	3.87	32.14	8.99	10.51	3.55	36.63
Total Reduction of Option Time/year (hr)	0	5096	676	676	676	0	676
CHW electricity savings (kWh/year)	0.0	19728.5	21726.0	6080.5	7104.6	0.0	24763.6
Total Annual CHW electricity savings (kWh/year)	79,403						

The calculations above are just an estimated values. To improve the accuracy, we need to measure the chilled water flow rate in each AHU. And we need to obtain the average supply and return chilled water temperature, supply and return air temperature. In addition, we need to consider the variation of the GSB cooling capacity demand. The estimated calculation result shows 79,403 kWh / year savings from the rescheduling. This is much larger than the savings by the AHU motors. Hence in total, there would be total electricity savings of :

(10,868 kWh / year + 79,403 kWh / year) = 90,271 kWh / year.

We cannot measure the chilled water flow rate because there is no chilled water flow meter in each individual AHU. Although we can measure the electricity consumed by the chillers, we cannot attribute the electricity consumption changes to the reduction of usage in GSB because it is too small compared to the total electricity consumption by chillers.

Hence, there is no reliable method to measure and verify the savings from chilled water reduced consumption in this stage.

5.2 Motion Detection Lighting Control

In this section, the employees' opinions on when should the motion detectors be activated and the expiration of motion detectors' timers are presented. The estimated electricity savings from implementing this strategy are calculated.

Eighty-five percent of employees prefer motion detection lighting control from 7 p.m. to 7 a.m. when most employees are not in the office. The employees also prefer 30 minutes of timer expiration. Hence the motion detection lighting control is implemented between 7 p.m. and 7 a.m. from Monday to Friday. During weekends, the lights are controlled by motion detectors 24 hour a day.

From the equipment list we created, we can find the total power of four feet long fluorescent lights on GSB level two and level three to be 11.44 kW and 15.50 kW respectively. These lights provide major lighting in the office area which is to be controlled by motion detectors. We assume that 50% of the time these lights are not switched off in the night from 8 p.m. to 7 a.m. when no one works in the office. With the motion detection lighting control implemented, 11 hours of lighting would be saved. So the annual savings from this strategy are estimated to be:

$$26.94 \text{ kW} \times 11 \text{ hours/day} \times 365 \text{ day/year} \times 0.5 = 54{,}082 \text{ kWh / year}$$

This is a significant amount of savings in the office building. Furthermore, when the lights are turned off, less heat will be generated. Hence the cooling load for the HVAC system in the next day will be lower.

Currently, all the motion detectors are interconnected: once one detector is activated, all the controlled lights are turned on for 30 minutes. This may not maximize the savings because all the lights are turned on while only a few lights are needed by a few people. If we could disconnect the motion detectors and configure the network in such a way that one detector is only connected to a few lights in a small area, then there would be only a fraction of lights turned on when there are only a few people. This can further reduce electricity consumption and heat generation.

There are six motion detectors installed on the second floor and eight motion detectors installed on the third floor. From 7 p.m. to 9 p.m., we assume that there are only two detector covered areas on the 2nd floor, and that two detector covered areas on the 3rd floor are occupied daily from Monday to Friday. We also assume that each motion detector controls equal units of lights. Furthermore, the lights in the unoccupied areas are turned on by motion detector for 1.5 hours daily between 7 p.m. to 9 p.m.. Thus, we can have further electricity savings calculated as:

$$\{11.44 \text{ kW} \times (6-2)/6 + 15.50 \text{ kW} \times (8-2)/8\} \times 1.5 \text{ hour/day} \times 260 \text{ day/year}$$

$$= 7{,}508 \text{ kWh / year}$$

5.3 Summary of Savings

In this chapter, the procedure to form the new HVAC operation schedule is discussed. The results of implementing HVAC new operation schedule and motion detection lighting control are discussed. The savings from these two strategies are summarized in Table 20.

Table 20: Summary of savings.

	HVAC Rescheduling		Motion Detection Lighting	
	Direct	Indirect	Current	Further
Savings (kWh/yr)	10,868	79,403	54,082	7,508
Electricity Unit Price	S$ 0.213/kWh			
Savings (S$/yr)	2,315	16,913	11,519	1,599
Total Savings (S$)	19,228		13,119	

6. CONCLUSION

Energy cost accounts for about 20% of the total operating cost in MSD Singapore. Reducing energy consumption in the manufacturing building and office building is essential in maintaining the financial viability and competence of the company. Furthermore, energy consumption reduction also achieves more environmentally friendly operation.

Data on electricity and natural gas consumption are collected. The Energy Utilization Index is calculated for the office building and manufacturing buildings. These EUI values are benchmarked against industrial average figures. It is evident that the current energy efficiency is not satisfactory. The HVAC system is the major consumer of energy in the plant.

The focus of this thesis is on the energy management in the GSB office building. The room temperature and relative humidity in the office building must be maintained in a specific range to achieve comfort level of the employees. In GSB, the temperature range is set between 21 °C and 24 °C with set point temperature at 22 °C. The objective is to reduce electricity consumption in the building while maintaining the comfort level for all employees.

Running the HVAC system in the office building during unoccupied time periods is identified as one of the major wastes in energy consumption. Step response models of the room temperature to the operating states of the AHU motors are developed. The models help us to determine the time to turn on and off the AHU motors to achieve satisfactory indoor environment requirements while reducing waste in energy consumption. An employee working schedule survey determines the time period during the working days that the office room temperature must be maintained within the specifications.

Combining the two results, the new HVAC operation schedule is formulated. The new operation schedule is rapidly implemented. The electricity consumed by the AHU motors after implementing the new schedule is measured. Statistical tools are used to analyse the measured data. The new operation schedule resulted in 10,868 kWh/year of direct electricity savings in operation of the AHU motors. This accounts for 16.5% of the total electricity consumed by the AHU motors annually. It also reduces chilled water generation electricity consumption by 79,403 kWh/year.

Motion detection lighting control is implemented in the office building. This turns off the lights when the office area is unoccupied. This method can reduce electricity consumption by 54,082 kWh/year.

7. RECOMMENDATIONS AND FUTURE WORK

In this chapter, some recommendations and suggestions for possible future work are presented. The recommendations are based on the methodologies and results discussed in previous chapters. The future work includes additional energy saving strategies that could be studied and implemented in MSD in the future.

7.1 Recommendations

7.1.1 Standardize the Procedures of HV, PV and DC Shutdown

HV, PV and DC shutdown would realize more than S$50,000 savings in PF2 electricity if executed properly during non-production time. This would not affect the product quality or occupant's comfort.

7.1.2 Disable the Dehumidifier and Adjust the Pre-cooling Off Coil Temperature

The RH of the supply air would be within 50% even without the use of the dehumidifier. To achieve minimum energy consumption while satisfying the supply air criteria, the pre-cooling off coil temperature should be set to 10.28 ^{o}C. Above this temperature, the room RH requirement may not be met.

7.1.3 Increasing set point temperature of post-cooling coil

As shown in the AHU-dehumidifier design data, after passing through the dehumidifier, the air is cooled down by the post-cooling coil to 10 ºC. The air is then reheated by a hot water loop before sending to each room.

The low set-point temperature at post-cooling coil is unnecessary as the air will be eventually reheated until its temperature is appropriate to supply the room with an air change per hour (ACH) of 15 times. Increasing the post-cooling set point temperature can save a tremendous amount of energy from the chiller and the boiler aspects.

For the detailed discussion related to Section 7.11 to 7.13, please refer to Zhang's thesis [18].

7.1.4 Reschedule HVAC Operating Schedules Regularly in GSB

The HVAC operation schedule should be modified regularly. The HVAC operation hours should match the office occupancy so that the comfort level for employees is maintained while eliminating wastes. When employees' working schedule changes, the HVAC operation schedule needs to change accordingly. The operation of HVAC should be more flexible. If during certain weekends, there are more than five people returning to the office, they could require the technician to turn on the AHUs manually from the control room. To achieve this, a communication platform between GSB office users and BAS technicians must be build.

The set point temperature could be set at a higher value. From the GSB comfort level survey, we can see that 35% of employees feel that the temperature is too low sometimes. And no one complained that the temperature is too high. Hence, the set point temperature could be increased slowly from 22 °C to 23 °C. This can save more chilled water consumption and hence the associated electricity. It can also save more electricity consumed by the AHU motors. Furthermore, those employees who felt cold before will have an improved working environment.

7.1.5 Enable Motion Detection Lighting Control

Motion detection lighting control will save a significant amount of energy in the lighting of office buildings. This could result in less electricity waste by lights when the office is not occupied and reduce the heat gain from light bulbs, which reduces the cooling load of the HVAC system.

The motion detection lighting control system can also be improved. Currently, all the sensors are interconnected, and when one sensor is activated, all the lights on the same floor will be lighted. But sometimes there might be only one person in a small area. So the sensors can be disconnected from each other, each detector controlling the lights in the small area. Hence when a particular cubicle has some people working there, only the corresponding lights are lit while other lights are turned off. This could save more electricity.

Motion detection lighting control can also be implemented in the other two office buildings, the engineering service building and administration building. This can be implemented easily since the implementation in GSB is successful. This strategy can also be implemented in the manufacturing building, especially in the mechanical rooms where no one works while the lights are turned on most of the time.

7.1.6 Invest in Water Evaporative Cooling on Rooftop and Roof Garden

In this thesis, we have seen that external heat gain such as thermal conduction and radiation contribute significant amount of heat gain to the GSB building and hence increase cooling load. From Liu's work, we can determine the percentage of heat gain and thus cooling load attributed to external heat source [17]. A water evaporative cooling system can be installed on the roof of the building. The system sprays water on the roof and when the water evaporates, it takes away heat from the building. According to some studies, this cooling method could reduce the cooling loads by as much as 25% [12]. Since there are already companies that specialize in water evaporative cooling equipment, it would be easy for MSD to implement this strategy.

A roof garden involves the growth of various plants on the top of the buildings.

These green plants and soil can effectively block the heat transfer between the outside environment and the building. One typical and fast way of creating a roof garden is to plant turf on the roof. The grass and soil could effectively reduce heat gain from the solar radiation. Furthermore, the roof garden could increase the lifetime of the roof, provide and reduce runoff, and reduce air pollution and dust. According to previous studies, a roof garden could reduce HVAC cooling load by 10% to 25% depending on the architecture of the building.

Since the water evaporative cooling and roof garden are external building insulation techniques, they do not affect the interior environment of the building. These two strategies could also be studied and applied to manufacturing buildings.

7.2 FUTURE WORK

In this section, some suggestions for future work are presented. These areas can be the focus for future research and applications to reduce energy consumption in the company.

7.2.1 Reduce Air Change Per Hour during non-production

The ventilation requirement for the white zone is 15 air changes per hour (ACH=15). During non-production period, this air exchange rate can be brought down to around 10 air changes per hour, while still letting white zone maintain a higher relative pressure to the gray zone. Reducing the air exchange rate would result in significant energy savings in various parts of the HVAC system.

7.2.2 Validate and Modify AHU-Dehumidifier Models with Actual Data

The theoretical models need to be tested with the actual data obtained from the AHU-dehumidifier system. The details of Section 7.2.1 and 7.2.2 can be found in

Zhang's thesis [18].

7.2.3 Measure GSB Energy Consumptions Regularly

From the previous discussion in this thesis we can see that there are not enough systematic measurements of energy consumptions in the office building. Currently there are only two installed power meters measuring the total electricity consumed in GSB. We cannot differentiate the electricity consumed by the AHUs, lighting and other equipment. Chilled water flow meters could also be installed to measure the chilled water consumption in GSB. Hence more accurate electricity savings by reduced consumption of chilled water can be calculated. If we can monitor the electricity consumptions of each of the subgroups, better saving strategy could be formulated and implemented.

7.2.4 Equipment Power Management

Office equipment such as computers, printers, copiers, and displays also consume significant amount of electricity. These equipment usually have three operating states and corresponding energy consumptions states. The ON state consumes rated power, the SLEEP state consumes much less than ON state, and the OFF state consumes no energy. When employees leave the office in the afternoon, they might not turn off the computers and monitors. And during the day time, employees have meetings and site work. During these hours, they might leave the computers on and consume significant amount of electricity.

Future work could explore the potential savings from more refined equipment power management. Software could be developed to switch office equipment into sleep state if they are not actively operating for a specific delay time. Simulations could be developed to find the optimal settings of the system to maximize electricity savings.

7.2.5 Photovoltaic Window

Studies could be done to investigate Photovoltaic (PV) windows that consist of a double glazed window with semi-transparent solar cells. These windows provide natural light transmission as well as electricity production. Study could focus on the cooling load reduction due to blocked solar radiation. The natural lighting would also increase compared to traditional curtains. The electricity generated could be used in indoor lighting. Calculations or simulations could be carried out to find the optimum solar cell transmittance and window to wall ratio to achieve maximum energy savings. The cost and savings of the PV windows should be analyzed.

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APPENDIX A: GSB COMFORT LEVEL SURVEY

This survey would take about 10 minutes to complete. The objective of this survey is to find out the comfort level of the office temperature and lighting in GSB. We would like to optimize the energy consumption in GSB without compromising the comfort level of our employees. Your anonymous and candid response would do us great help to improve the indoor environment of GSB while reducing wasteful energy consumption. Please answer the following questions **based on your experience since January 2009.**

1. How do you feel the current office temperature in GSB?
   A. Too cold (go to 2)
   B. A bit cold but acceptable (go to 2)
   C. Just nice (go to 4)
   D. A bit hot but acceptable (go to 3)
   E. Too hot (go to 3)
2. Do you turn up the air-conditioning temperature?
   A. Yes B. No (go to the qn below)

If no, why?

   A. I just wear jacket
   B. I don't know how to adjust
   C. I don't know where the controller is
   D. The controller does not work
   E. Other reason, please specify

3. Do you turn down the air-conditioning temperature?
   A. Yes B. No (go to the qn below)

If no, why?

   A. I don't know how to adjust
   B. I don't know where the controller is
   C. The controller does not work
   D. Other reason, please specify

4. Please enter the percentage of the time you arrive at GSB in the morning during workdays in the following time slots:
   A. Before 7a.m. (if not 0, go to 5, otherwise go to 6)
   B. Between 7a.m. to 9a.m.
   C. After 9a.m.

5. What is the earliest time you arrive at your office in the morning?
   A. 6:45a.m.
   B. 6:30a.m.
   C. 6:15a.m.
   D. 6:00a.m.
6. Please enter the percentage of the time you leave GSB in the afternoon during workdays in the following time slots:
   A. Before 6pm
   B. Between 6pm to 8pm
   C. After 8pm (if not 0, go to 7, otherwise go to 8)
7. What is the latest time you leave your office in the afternoon?
   A. 8:15pm
   B. 8:30pm
   C. 8:45pm
   D. 9:00pm
8. Have you ever come to work on weekends since 2009?
   A. Yes (go to 9)
   B. No (go to 10)
9. How many times did you come to office on Saturdays and Sundays since 2009?
   A. 1-2
   B. 3-6
   C. >7

Please only answer question 10 to 11 if you have ever left office after 7 p.m. **since June 2009**

10. Have you noticed that the air-con is switched off at 7 p.m.?
    A. Yes (if yes, go to the next qn)
    B. No

How long does it take before you feel uncomfortable with the indoor environment?

A. Immediately
B. 15 minutes
C. 30 minutes
D. 45 minutes
E. 1 hour

11. Have you noticed that the lighting in GSB level 2 and 3 has been controlled by motion detector after 7pm?

   A. Yes (if yes, go to the next qn)

   B. No

How does the motion detection light control affect your work?

   C. No effect at all

   D.

12. Do you have any other suggestion about the air-con operation in GSB?

APPENDIX B: GSB EUI CALCULATION

GSB Energy Consumption Based on 2008 Data

1. Electricity From MCC

Date/Time	PM-US1-6A Real Energy	PM-US1-7B Real Energy	6A+7B Real Energy
Jul' 08	27,796	34,340	62,135
Aug' 08	24,887	33,165	58,052
Sept' 08	23,635	32,456	56,092
Oct '08	24,979	32,384	57,363
Nov '08	24,404	28,622	53,027
Dec '08	24,517	28,703	53,220
Total Jul-Dec 08	150,218	189,670	339,888
Annual KWh	**726,681**		

2. Chilled Water

Chilled Water Electricity

Date/Time	CHW usage (kWh equivalent)
Jul' 08	109,954
Aug' 08	112,241
Sept '08	108,752
Oct '08	112,119
Nov '08	103,460
Dec '08	107,937
Total Jul-Dec 08	654,463
Annual KWH	**1,308,925**

3. Compressed Air

Date/Time	Total electricity used for compressed air KWh	GSB Usage as % of total	GSB Usage KWh
Jul' 08	196,093	5.09%	9,988
Aug' 08	216,496	5.09%	11,027
Sept '08	207,400	5.09%	10,564
Oct '08	218,777	5.09%	11,143
Nov '08	184,588	5.09%	9,402
Dec '08	216,496	5.09%	11,027
Total Jul-Dec 08	1,239,850	5.09%	63,150
Annual KWH	**126,301**		
Total Energy Consumption KWh	**2,161,906**		

GSB Floor Area (m2)	
1ST FLOOR	1,742
2ND FLOOR	1,629
3RD FLOOR	1,629
LOWER ROOF	671
Total	**5,670**

Summary of Energy Consumption in KWH	***Consumption***	***% of Total***
Electricity	**726,681**	**33.61%**
Chilled Water (CHW Electricity)	**1,308,925**	**60.54%**
Compressed Air	**126,301**	**5.84%**
Total Energy Consumption (KWH equivalent)	**2,161,906**	**100.00%**
Total floor area (m^2)	**5,670**	
EUI ($kwh/m^2/year$)	**381**	
EUI ($kwh/m^2/year$) From ESU Website	**358**	

APPENDIX C: PF2 EUI CALCULATION

PF2 Energy Consumption Based on 2008 Data

1. Electricity KWH

Date/ Time	PM-US3-2A	PM-US3-5B	Total
Jan' 08	195,996	6,986	202,982
Feb' 08	201,601	6,937	208,538
Mar' 08	209,598	7,429	217,027
Apr' 08	199,840	7,405	207,245
May' 08	206,250	6,770	213,020
Jun' 08	165,646	5,846	171,493
Jul' 08	172,517	6,041	178,558
Aug' 08	179,579	6,726	186,306
Sept '08	172,980	6,183	179,163
Oct '08	147,939	6,945	154,884
Nov '08	157,216	5,695	162,911
Dec '08	184,819	6,662	191,481
Annual Total	**2,345,367**	**85,120**	**2,430,487**

2. Chilled Water

Chilled water electricity

Date/Time	CHW electricity (kWh)
Jul' 08	130,231
Aug' 08	132,939
Sept '08	128,806
Oct '08	132,795
Nov '08	122,539
Dec '08	127,841
Total Jul-Dec 08	775,151
Annual	**1,550,301**

3. Steam Generation

Boiler Electricity

Date/Time	KWH
Jul' 08	8,861
Aug' 08	8,179
Sept '08	8,009
Oct '08	8,003
Nov '08	8,046
Dec '08	7,831
Total Jul-Dec 08	48,929
Annual	**97,858**

Natural Gas

Date/Time	KWH Equivalent (converted from mmBTU)	NG (mmBTU)
Jul' 08	725,687	2,476
Aug' 08	688,411	2,349
Sept '08	710,671	2,425
Oct '08	728,363	2,485
Nov '08	635,664	2,169
Dec '08	731,394	2,496
Total Jul-Dec 08	4,220,190	14,400
Annual	**8,440,380**	**28,800**

4. Compressed Air

Date/Time	Total electricity used for compressed air KWh	PF2 Usage as % of total	PF2 Usage KWh
Jul' 08	210,885	13.58%	28,643
Aug' 08	216,496	13.58%	29,405
Sept '08	207,400	13.58%	28,170
Oct '08	218,777	13.58%	29,715
Nov '08	184,588	13.58%	25,071
Dec '08	191,247	13.58%	25,976
Total Jul-Dec 08	1,229,393	13.58%	166,980
Annual	**333,961**		

5. PUW	
Date/Time	**PUW Electricity (kWh)**
Jul' 08	16,702
Aug' 08	16,702
Sept '08	16,163
Oct '08	16,702
Nov '08	16,163
Dec '08	16,702
Total Jul-Dec 08	99,134
Annual	**198,268**

PF2 Floor Area (m^2)	**White**	**Gray**	**Black**	**Total**
Floor 1	2,123	380	541	3,044
Floor 2	849	65	2,130	3,044
Floor 3	-	-	57	57
Total	2,972	445	2,728	6,145

Summary of Energy Consumption in KWH	***White***		***Gray***		***Black***	
	Consumption	***% of Total***	***Consumption***	***% of Total***	***Consumption***	***% of Total***
Electricity (HVAC)	**2,012,481**	**16.72%**	**131,706**	**19.40%**	**201,180**	**60.20%**
Electricity (Process Equipment)	**85,120**	**0.71%**	**-**	**0.00%**	**-**	**0.00%**
Chilled Water	**1,330,262**	**11.05%**	**87,059**	**12.82%**	**132,981**	**39.80%**
Steam Generation	**8,111,326**	**67.38%**	**426,912**	**62.87%**	**-**	**0.00%**
Compressed Air	**300,565**	**2.50%**	**33,396**	**4.92%**	**-**	**0.00%**
PUW	**198,268**	**1.65%**	**-**	**0.00%**	**-**	**0.00%**
Total (KWH/year)	**12,038,021**	**100.00%**	**679,073**	**100.00%**	**334,161**	**100.00%**
Floor Area (m2)	**2,972**		**445**		**2,728**	
EUI (KWH/m2/year)	**4,050**		**1,526**		**122**	
Total PF2 Energy Consumption (KWH equivalent/year)	**13,051,255**					

Summary of Energy Consumption (Separate Electricity (KWH) and Fuel (mmBTU))	White		Gray		Black	
Electrical (KWH/year)	Consumption	% of Total	Consumption	% of Total	Consumption	% of Total
Electricity (HVAC)	2,012,481	50.07%	131,706	51.24%	201,180	60.20%
Electricity (Process Equipment)	85,120	2.12%	-	0.00%	-	0.00%
Chilled Water	1,330,262	33.09%	87,059	33.87%	132,981	39.80%
Steam Generation (Boiler Electricity)	92,965	2.31%	4,893	1.90%	-	0.00%
Compressed Air	300,565	7.48%	33,396	12.99%	-	0.00%
PUW	198,268	4.93%	-	0.00%	-	0.00%
Total (KWH/year)	4,019,660	100.00%	257,054	100.00%	334,161	100.00%
Total PF2 Electricity Consumption (KWH/year)	4,610,875					
Fuel (mmBTU/year)						
Steam Generation (NG)	27,360		1,440		-	
Total (mmBTU/year)	27,360		1,440		-	
Total PF2 Fuel Consumption (mmBTU/year)	28,800					

Assumptions Made to breakdown Energy Consumption by Area Types	White (%)	Gray (%)	Black (%)
Electricity (HVAC)	85.81%	5.62%	8.58%
Electricity (Process)	100.00%	0.00%	0.00%
Chilled water: assume energy consumption ratio follows that of the AHU/FCU power usage	85.81%	5.62%	8.58%
Steam is all used in production area. Steam is used in generating hot water for room temperature control (80%) and dehuminication (20%).	95.00%	5.00%	0.00%
Compressed air is mainly used to support BAS (Building Automation System) control & instrumentation. They are mainly used in white area for process equipment and HVAC control. Only 10% in gray area.	90.00%	10.00%	0.00%
PUW	100.00%	0.00%	0.00%

APPENDIX D: GSB ELECTRICAL EQUIPMENT LIST

GSB Electrical Office Equipment List					
Lights					
Floor 1					
Type of Lights	Units	Rated power(W)	Total Rated power(W)	Operation Hours(h/day)	Total consumption(kWh/day)
4 feet Fluorescent lights 1	72	37	2664	12	32
4 feet Fluorescent lights 2	126	37	4662	4	19
Compact Fluorescent lights 1	50	19	950	4	4
Compact Fluorescent lights 2	230	19	4370	24	105
2 feet Fluorescent lights	16	19	304	24	7
Power Subtotal(W)			**12950**	Floor Subtotal(kWh/day)	**167**
Floor 2					
Type of Lights	Units	Rated power(W)	Total rated power(W)	Operation Hours(h/day)	Total consumption(kWh/day)
4 feet Fluorescent lights	309	37	11433	12	137
Compact Fluorescent lights	124	19	2356	24	57
2 feet Fluorescent lights	5	19	95	24	2
Power Subtotal(W)			**13884**	Floor Subtotal(kWh/day)	**196**
Floor 3					
Type of Lights	Units	Rated power(W)	Total rated power(W)	Operation Hours(h/day)	Total consumption(kWh/day)
4 feet Fluorescent lights	419	37	15503	12	186
Compact Fluorescent lights	60	19	1140	24	27
2 feet Fluorescent lights	4	19	76	24	2
Power Subtotal(W)			**16719**	Floor Subtotal(kWh/day)	**215**
Floor 4					
Type of Lights	Units	Rated power(W)	Total rated power(W)	Operation Hours(h/day)	Total consumption(kWh/day)
4 feet Fluorescent lights	20	37	740	12	9
Compact Fluorescent lights	0	19	0	24	0

2 feet Fluorescent lights	0	19	0	24	0
Power Subtotal(W)			**740**	Floor Subtotal(kWh/day)	**9**
Lights Power Sub Total (W)			**44293**	Lights Consumption subtotal(kWh)	**587**
Items	Units	Rated power(W)	Total rated power(W)	Operation Hours(h/day)	Total consumption(kWh/day)
			Pantry		
Tea Maker	4	300	1200	24	29
Refrigerator	3	250	750	24	18
Power Subtotal(W)			**1950**	Consumption Subtotal(kWh/day)	**47**
			Copier Room		
Color Printer	2	572	1144	2	2
Copier	2	1166	2332	2	5
Paper Crusher	2	750	1500	0.2	0.3
Power Subtotal(W)			**4976**	Consumption Subtotal(kWh/day)	**7**
			Computer		
Desk Computer	34	150	5138	8	41
Laptop	103	90	9248	8	74
Power Subtotal(W)			**14385**	Consumption Subtotal(kWh/day)	**115**
			Kitchen		
2-door tall Refrigerator 0 °C	4	515	2060	24	49
2-door tall Refrigerator -7 °C	1	699	699	24	17
2-door low Refrigerator	2	120	240	24	6
3-door tall Refrigerator 0 °C	1	539	539	24	13
3-door tall Refrigerator -7 °C	1	768	768	24	18
Soup Pot	2	440	880	4	4
Ice Maker	2	1150	2300	24	55
Dish Washer	1	2350	2350	4	9
Power Subtotal(W)			**9835**	Consumption Subtotal(kWh/day)	**171**
			Canteen		
42' LCD TV	4	70	280	12	3
56' LCD TV	2	450	900	12	11
Vending Machine 5 °C	5	200	1000	24	24
Vending Machine 24 °C	1	100	100	24	2

Water Boiler	1	500	500	24	12
Power Subtotal(W)			**2780**	Consumption Subtotal(kWh/day)	**53**