Improving Energy Efficiency in a Pharmaceutical Manufacturing Environment – Production Facility

by

Endong Zhang

Bachelor of Engineering in Bioengineering (2008)
National University of Singapore

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING IN MANUFACTURING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SEPTEMBER 2009

Signature of Author ....
Department of Mechanical Engineering
Aug 18, 2009

Certified by ....
Duane S. Boning
Professor of Electrical Engineering and Computer Science
Thesis Supervisor

Accepted by ....
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Chairman, Committee on Graduate Students

Improving Energy Efficiency in a Pharmaceutical Manufacturing Environment – Production Facility

by

Endong Zhang

Submitted to the Department of Mechanical Engineering
on August 18, 2009 in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering in
Manufacturing

ABSTRACT

The manufacturing plant of a pharmaceutical company in Singapore had low energy efficiency in both its office buildings and production facilities. Heating, Ventilation and Air-Conditioning (HVAC) system was identified to be the major energy consumer in the plant. An HVAC specific energy management tool was developed to monitor the energy efficiency and calculate the heat gains and cooling loads. In the office building, the HVAC operation schedule was revised, and motion detection lighting control was installed and configured to save electricity. In production facilities, house vacuum, process vacuum and dust collector were shut down during non-production time in Pharmaceutical Facility 2 (PF2). Statistical analysis using measured data was performed to verify the projected energy savings. Dehumidifier was disabled in Pharmaceutical Facility 1 (PF1) to relax the relative humidity from around 22% to 50%, while still maintaining it within the upper specification of 55%. Theoretical AHU-Dehumidifier models were built to find the optimum system settings with minimum energy consumption.

With the implemented strategies, the annual energy consumption would be reduced by 6.68%, 6.58% and 2.32% in the office building, PF1 and PF2 respectively. The AHU-Dehumidifier models suggested a pre-cooling off-coil temperature of 15.5° C and a post-cooling off-coil temperature of 21 ° C in face of the current humidity requirement to achieve minimum energy consumption.

Keywords: energy efficiency, EUI, HVAC, dehumidification, pharmaceutical

Thesis Supervisor: Duane S. Boning
Title: Professor of Electrical Engineering and Computer Science

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest appreciation to our thesis supervisor, Prof. Duane Boning, for his invaluable guidance and encouragement throughout the project.

Kind thanks also goes to AFT[1] Singapore for sponsoring this internship. Specifically, I want to thank Mr. Lim Siang Sim, our corporate supervisor, for giving me valuable suggestions and feedback. Many thanks also go to all the staff at AFT Singapore, especially Mr. Steven Huang, for his strong support in the project.

Great appreciation goes to all the professors in the M.Eng Manufacturing program, especially Prof. David Hardt, Dr. Brian Anthony, Prof. Stephen Graves, Prof Jung Hoon Chun, and Prof. Stanley Gershwin for making this program a rewarding experience.

I would also like to take this opportunity to offer my heartfelt gratitude to Ms. Jennifer Craig for reviewing this thesis and providing valuable advices on the linguistic aspect.

Last but not least, I would like to thank my team-mates, Mr. Wu Li and Mr. Haoyu Liu for accompanying me on this journey of learning and discovery. Without them, this work would not be possible.

---

[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.

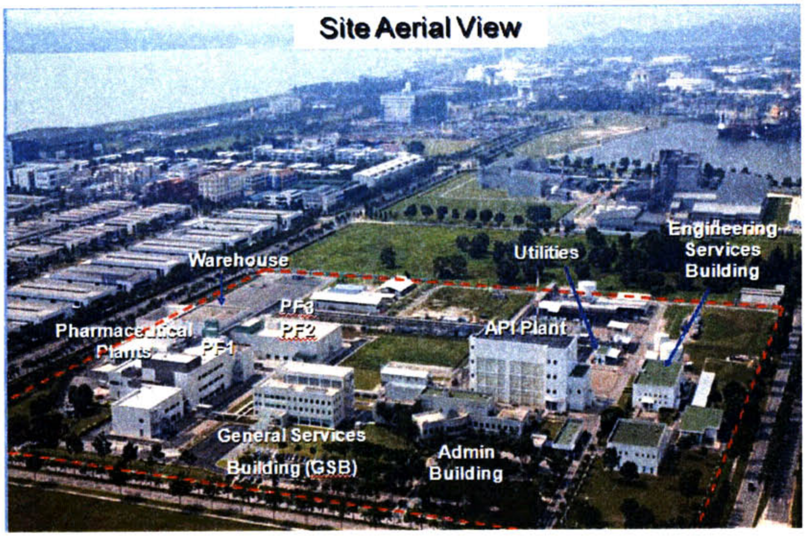


Figure 1: Site Aerial View [2]

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].

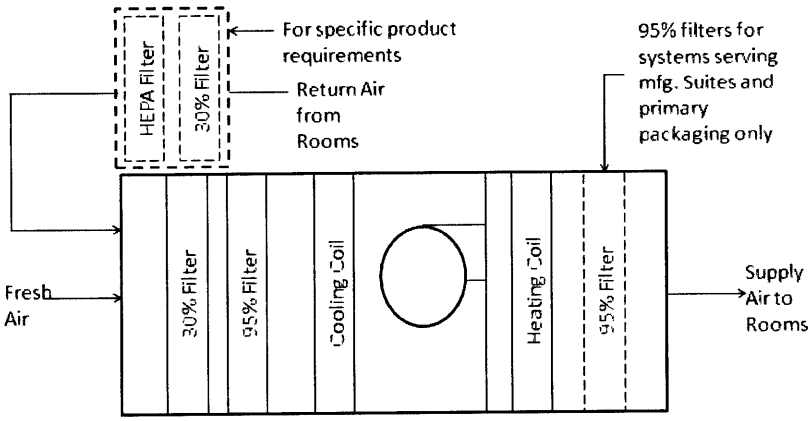


Figure 2: Filters in a Typical Air Handling Unit Diagram

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 practiced teamwork and leadership. Mr. Haoyu Liu led the part of the project which develops a general energy management tool to analyze energy consumption pattern and calculate cooling load of the HVAC system in both the office building and the production facilities. Mr. Wu Li led the team in the office building energy saving. He explored various energy saving opportunities and chose to focus on the HVAC rescheduling and the motion detection lighting control to reduce energy consumption in GSB. My work focused on reducing energy consumption in the production facilities. In PF2, shutting down house vacuum (HV), process vacuum (PV) and dust collector (DC) during non-production hours was studied and implemented. Dehumidifier disabling was carried out in PF1 to reduce wasteful energy usage. An AHU-DH model was also developed in attempt to optimize the system settings and achieve minimum energy consumption. The focus of this thesis is on the energy saving strategies for the production facilities. The methodology and results from Liu's and Li's work are briefly summarized.

In Chapter 2, historical data are used to calculate the EUI of the buildings in the company. Based on the energy performance of each building and the corresponding industrial benchmark, the energy efficiency problem faced by the company is defined and stated. 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 works on the HVAC energy saving strategies. Chapter 4 first summarizes Liu's and Li's works in the development of the energy management tool and the office building energy saving, and proceeds to describe the two energy saving methods in the production facility as well as the AHU-Dehumidifier modeling. The results and discussion for the implemented strategies and the models are presented in Chapter 5, which is sectioned and sequenced in the same way as Chapter 4, i.e., the results and discussion of Section 4.2 are presented in Section 5.2. Chapter 6 makes a project-wise conclusion based on the methods and results. Finally, Chapter 7 gives recommendations for Company AFT and proposes some potential future work.

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.

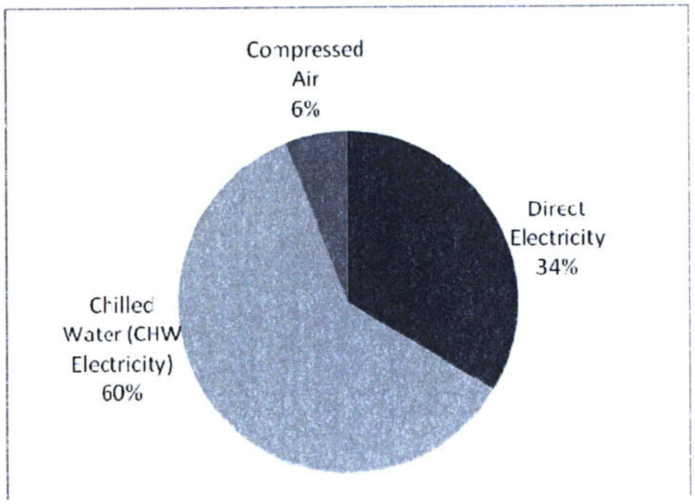


Figure 3: GSB Energy Consumption Structure

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.

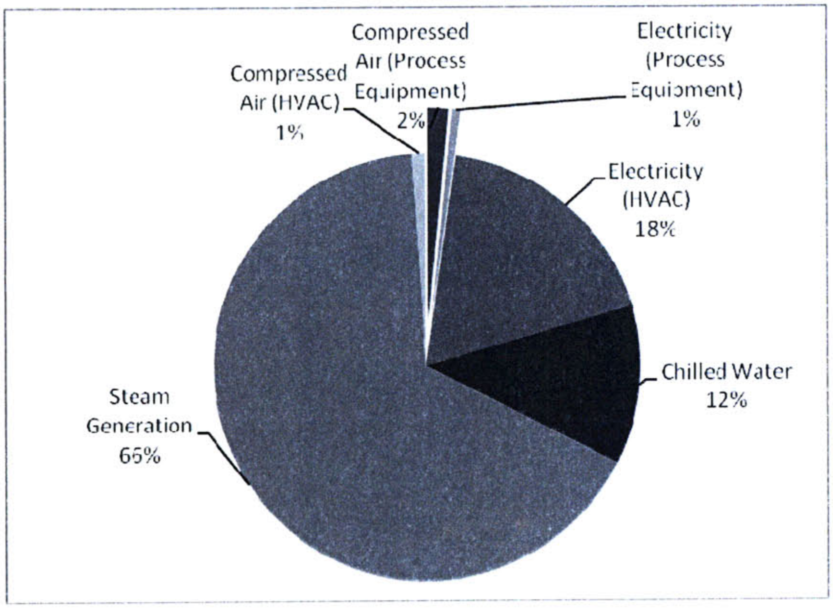


Figure 4: PF2 Energy Consumption by Usage

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.

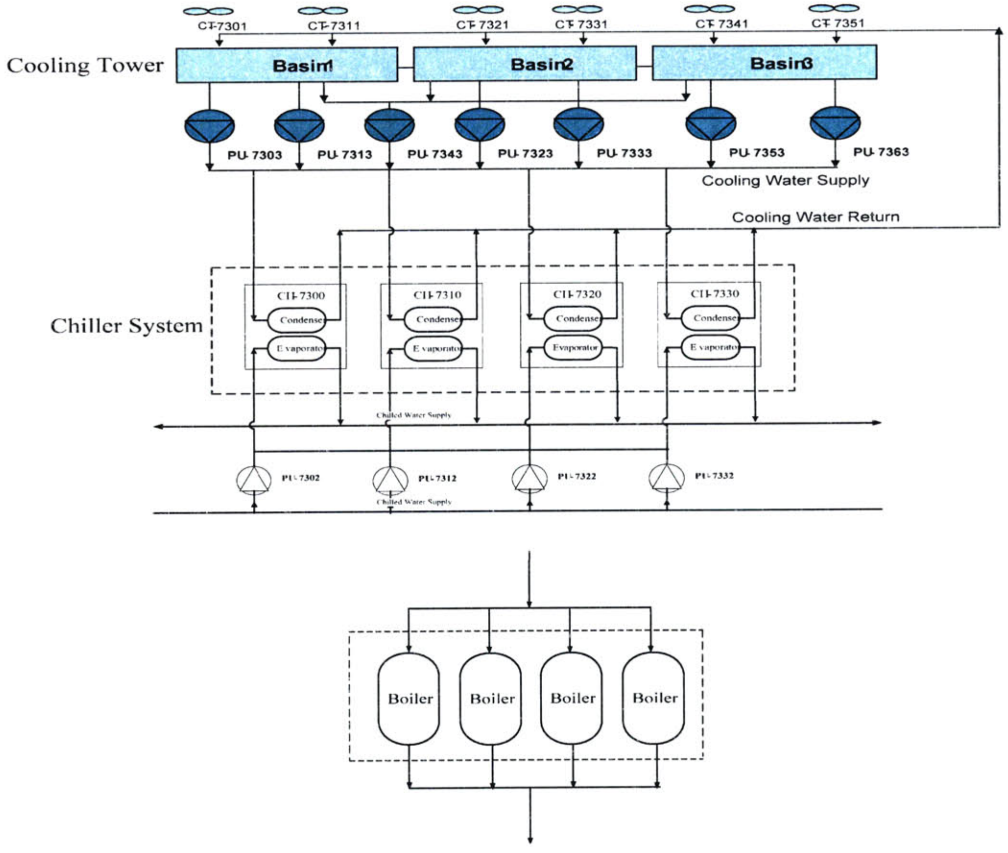
An HVAC system functions to provide an environment in which some control factors are maintained within desired ranges. Examples of some standard parameters are

- Dry bulb temperature of 23 °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.

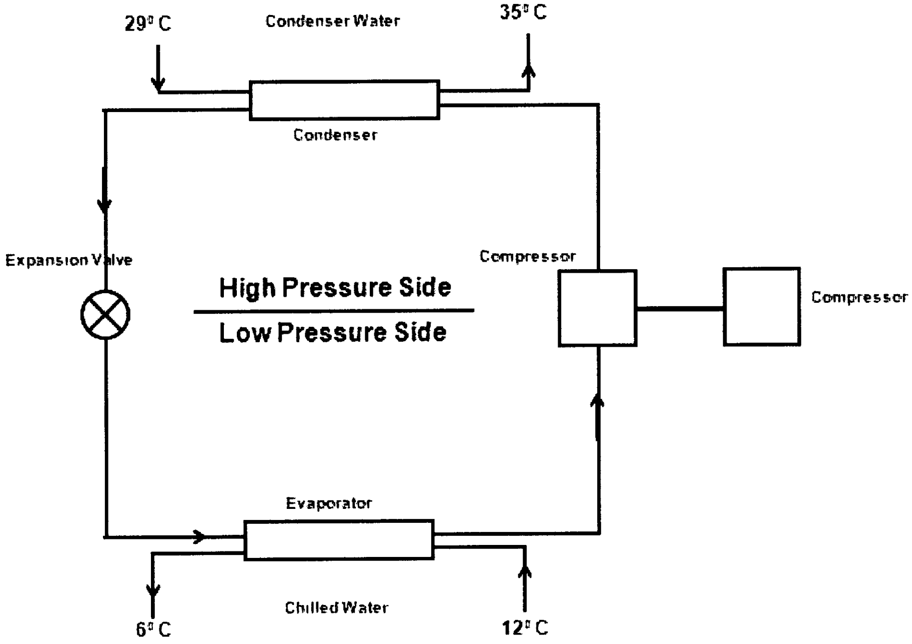


Figure 6: Water Chiller Cooling Process

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.

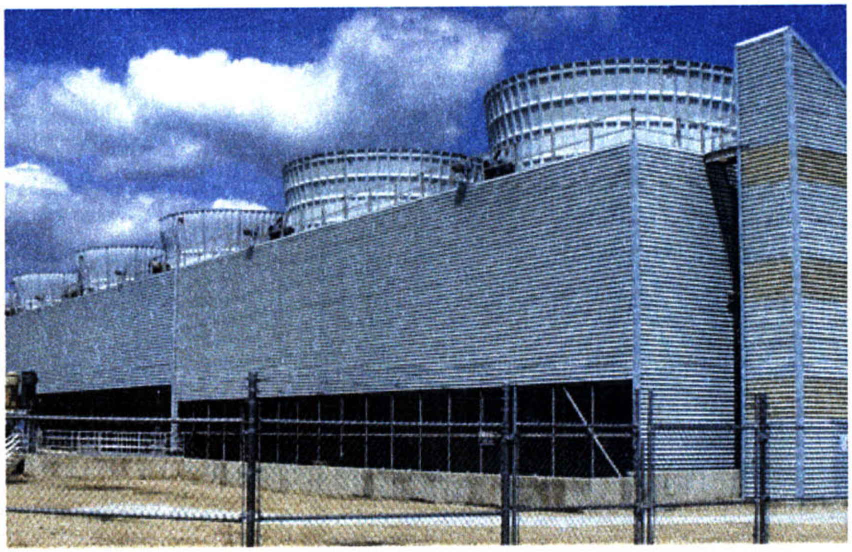


Figure 7: Cooling Tower [2]

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.

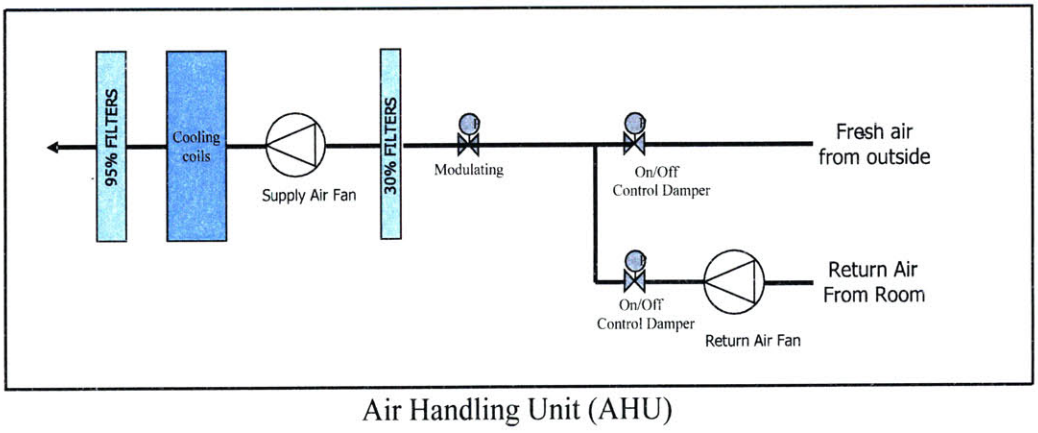


Figure 9: Schematic Diagram of AHU [7]

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 savings [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.

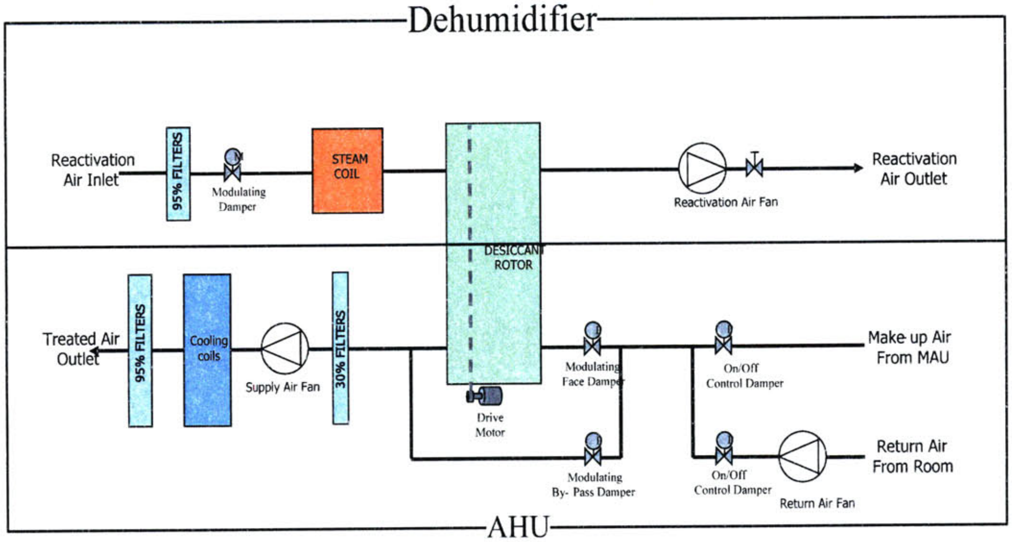


Figure 10: AHU with Dehumidifier [8]

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 ºC to 25.5 ºC. Overcooling in Singapore is sometimes observed. By raising the set point temperature by 1 ºC, 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 PF. In Section 4.1, the energy management tool for the office building and the production facility is introduced. Section 4.2 presents the energy saving strategies that are implemented in GSB. More details about these two sections can be found in Mr. Haoyu Liu's and Mr. Wu Li's theses. Section 4.3 describes the two energy saving strategies which are implemented in PF, including the shutdown of vacuum cleaning system during non-production time and the disabling of dehumidifier for humidity-insensitive products. These are presented in Section 4.3.1 and Section 4.3.2 respectively. Lastly, the AHU-Dehumidifier modeling method is described in Section 4.3.3 in details.

This chapter only describes the methodologies, while the results and discussion are presented in Chapter 5 in the corresponding sections and subsections. For example, the discussion for Section 4.3.3 is presented in Section 5.3.3.

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 helps to understand and 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 extremely 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 can be found in Mr. Haoyu Liu's thesis [18].

4.2 GSB Energy Saving

The two strategies which are implemented in the office building are the rescheduling of HVAC operation hours and the installation and configuration of motion detection lighting control.

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 addition to HVAC rescheduling, motion detection lighting control is installed and configured in GSB to switch off the lights when the office is not occupied. Detailed description can be found in Mr. Wu Li's thesis [17].

4.3 PF Energy Saving

The energy saving methods that have been implemented in PF include shutting down house vacuum (HV), process vacuum (PV), dust collector (DC) during non-production time and disabling dehumidifier. In addition, the AHU-Dehumidifier system is modeled using Microsoft Excel.

4.3.1 Shutting Down HV, PV and DC during Non-production Time

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 equipments will turn them off when there is no production activity in the pharmaceutical facilities. Electricity savings from this measure are estimated. No implications on the building environment and product quality are expected.

Calculation, Data Collection and Statistical Analysis

The production activity in PF2 from June to December 2009 is not continuous, leaving substantial idle times. During such non-production days, the facility's indoor environment requirement can be relaxed, while still maintaining at the level where strict environmental parameters can be quickly restored. Under such circumstance, HV, PV and DC can be shut down.

The operating powers of the equipment are obtained from the BAS computer system. The energy savings by shutting down these machines is estimated by:

$$\text{Annual Energy Savings} = \text{Sum of Operating Powers} \times \text{Number of Idle Hours}$$

In order to verify the calculation, ideally the actual power measurement for the equipment should be performed. Due to technical difficulty, such measurement is impossible to carry out. An alternative approach is adopted here.

In fact, the site attempted to shut down HV, PV and DC last year, when PF1 and PF2 were not in operation in June 2008. The electricity consumption data for three weeks before and after the action is collected. The difference is assumed to be solely attributed to the shutting down of HV, PV and DC. Table 6 shows the shutdown schedule for PF2.

Table 5: HV PV and DC Shutdown Routine in PF2

Day	*Shutdown Time*	*No. of Shutdown Hours per day*
Weekdays	Daily 6.30pm to 6.30am	12
Weekends	Weekly Fri 6.30pm to Mon 6.30am	24

Assuming the daily electricity consumptions on weekdays, on weekends, before and after the shutdown are all normally distributed, as shown in Table 7, Welch's t-tests are carried out to confirm the difference in mean electricity consumptions before and after the shutdown, as well as the agreement between the measured electricity savings and the projected savings calculated with the operating powers from BAS.

Table 6: Four Normally Distributed Populations of Daily Electricity Consumption

No.	*Population*	*Sample Size*
1	Weekday, before shutdown, WD_before ~ $N(\mu_1, \sigma_1)$	14
2	Weekend, before shutdown, WE_before ~ $N(\mu_2, \sigma_2)$	6
3	Weekday, after shutdown, WD_after ~ $N(\mu_3, \sigma_3)$	14
4	Weekend, after shutdown, WE_after ~ $N(\mu_4, \sigma_4)$	6

Two-sample one-tail t-tests are used to verify the mean shift before and after the shutdown. The electricity consumption in kWh in a 24-hour period is taken as one sample point. The null hypothesis and the alternative hypothesis are:

Test 1: Weekday before and after shutdown

Ho: $\mu_1 = \mu_3$; *H1:* $\mu_1 > \mu_3$

Test 2: Weekend before and after shutdown

Ho: $\mu_2 = \mu_4$; *H1:* $\mu_2 > \mu_4$

To assess the agreement between the measured electricity savings and the calculated savings, R-Square value is computed. The difference between the daily electricity consumption before and after the shutdown on the same day of the week is taken as one sample point. This would eliminate the possible noise due to the different plant activity on different days of the week. This difference in actual energy consumption is plotted together with the calculated savings.

Let x = calculated daily savings, y = actual daily savings

$$r^2 = \frac{[\sum(x-\bar{x})(y-\bar{y})]^2}{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}$$

$$\begin{aligned} \textit{where } \bar{x} &= \text{average savings from actual measurement} \\ \bar{y} &= \text{average savings from calculation} \end{aligned}$$

The results of the statistical analysis are presented in Chapter 5 Section 5.3.1.

Implementation

Implementation plans are important in converting the potential savings to actual benefits. This can involve developing operating protocols for the technicians and maintenance team. An example is shown in Appendix A.

4.3.2 Disabling Dehumidifier for RH Insensitive Products

One dehumidifier (S05N01) is installed on one of the AHUs in PF1 (AHS05N01). The dehumidifier unit is 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 has been disabled since July 2009.

Using Psychrometric Chart to Predict the RH of Supply Air from Design Specifications

Psychrometric charts, which are graphical equations of state that represent the interrelation of air temperature and moisture content at given pressures, are used to find out the air properties. Figure 11 shows a psychrometric chart under standard atmospheric pressure. Dry bulb temperature, wet bulb temperature, moisture content (humidity ratio), relative humidity, vapor pressure and specific enthalpy can be obtained from the chart.

Design specifications of the AHU-Dehumidifier system are reviewed. The make-up air parameters are particularly important because it determines the final humidity ratio of the supply air with dehumidifier disabled. With this information, the RH of the supply air is predicted. Dehumidifier can be disabled if the predicted RH is within specification. This is to provide a theoretical support for the decision of disabling dehumidifier.

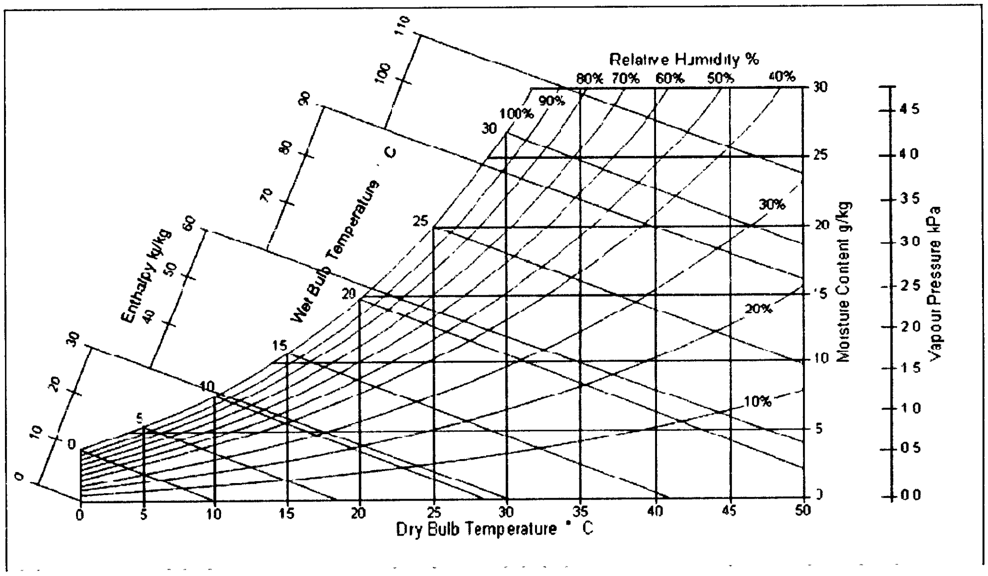


Figure 11: Psychrometric Chart at Standard Atmospheric Pressure [6]

Disabling Dehumidifier

Dehumidifier is disabled by closing the steam valve in the reactivation air passage, turning off the reactivation air fan and the desiccant rotor motor, closing the face damper and fully opening the bypass damper in the supply air passage, as shown in Figure 12.

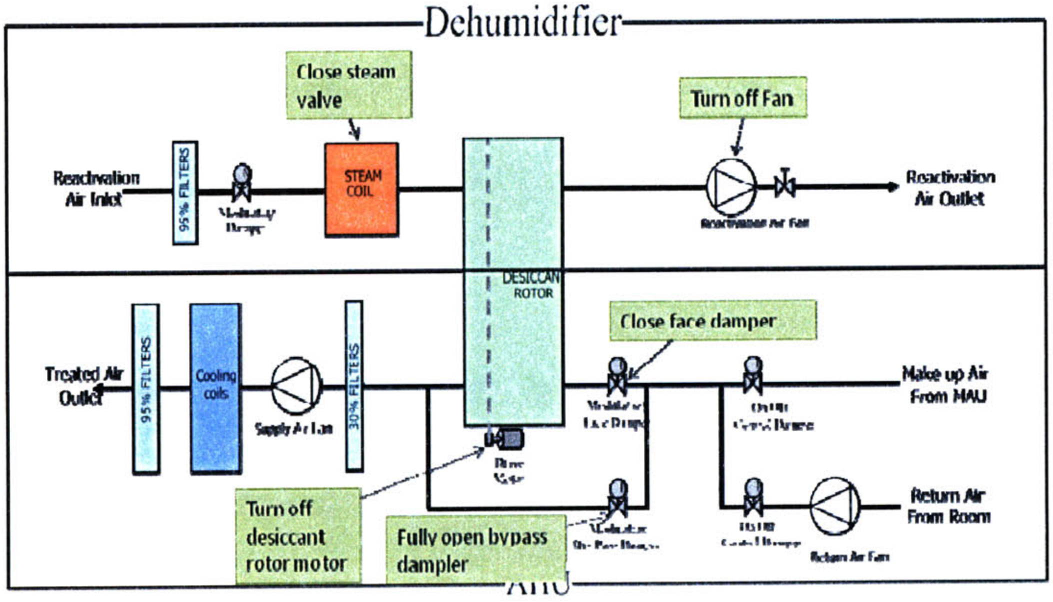


Figure 12: Disabling the Dehumidifier

After disabling the dehumidifier, there is no reactivation air flow. The supply air stream fully bypasses the desiccant rotor.

Examining the Supply Air RH after Disabling Dehumidifier

Measured air temperature and relative humidity are obtained from a BAS snapshot. A psychrometric chart is used to find out the supply air RH. This is to verify that with the dehumidifier disabled, the supply air RH will still meet the requirement using solely the cooling-based dehumidification.

Energy and Cost Savings

Figure 13 shows where the energy savings come from after the dehumidifier is disabled. Three areas of energy and cost savings can be realized, including the direct electricity savings from the reactivation air fan and the desiccant rotor motor, the savings of steam consumption for the reactivation air heating, and the saving of chilled water consumption in the post-cooling coil. The savings from the three areas are estimated.

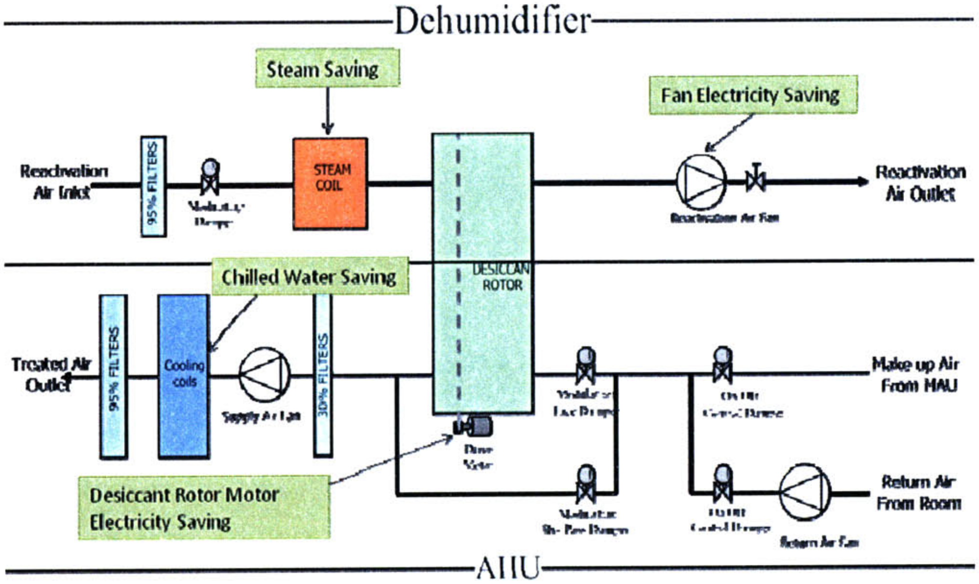


Figure 13: Energy Savings after Disabling Dehumidifier

Direct Electricity Savings

The rated powers of the reactivation air fan and desiccant wheel motor are noted. Assuming the power factor is 0.8 and the unit electricity cost is $0.213/kWh, the electricity savings and cost savings are estimated by:

$$\mathit{Electricity\ Savings} = \mathit{Rated\ Power} \times \mathit{Power\ factor} \times \mathit{Duration\ of\ Shutdown}$$

$$\mathit{Cost\ Savings} = \mathit{Unit\ Electricity\ Cost} \times \mathit{Electricity\ Savings}$$

Savings of Steam Consumption

Direct steam consumption measurement in this single AHU-Dehumidifier system is difficult to carry out. Instead, steam consumption in PF1 was monitored hourly for seven days before and after disabling the dehumidifier in July and August 2009. Assuming all other steam users in PF1 maintained the same consumption levels in these 14 days, the difference of steam consumption before and after disabling the dehumidifier can be solely attributed to the closing of the steam coil in this AHU-Dehumidifier system. Multiple seven-day sets of measurement data are used so that the sample size (there are 24*7 = 168 samples drawn from the each population) is large enough to even out the fluctuation of steam consumption which may affect the result. Two sample t-test is carried out to verify the difference and estimate the average savings.

As steam is generated by burning natural gas, the steam savings are converted to the savings in the natural gas consumption. From the site's historical data, the natural gas consumption for producing each kg of steam is found to be 0.003234 mmBTU. Unit cost of natural gas is assumed to be $12/mmBTU. Therefore,

$$Natural\ Gas\ Savings\ in\ mmBTU = Steam\ Savings\ in\ kg \times 0.003234\ mmBTU/kg$$

$$Cost\ Savings = \$12/mmBTU \times Natural\ Gas\ Savings\ in\ mmBTU$$

Savings of Chilled Water Consumption

After disabling the dehumidifier, the supply air stream fully bypasses the desiccant and thus is not heated up by the desiccant rotor. This exerts less cooling load for the downstream post-cooling chilled water coil: i.e. less energy from the air is to be extracted by the chilled water to reach the same off-coil set-point temperature.

The savings of chilled water consumption in the post-cooling coil cannot be measured directly from the system. Instead, the temperature and relative humidity of the air in the upstream and downstream of the post-cooling coil is obtained from the BAS snapshot before and after disabling the dehumidifier. The cooling load of the chilled water is then calculated theoretically. The difference in cooling load is then translated to the chiller electricity savings.

The process for moist air cooling is illustrated in Figure 14. Under constant pressure, air at a particular temperature and RH has a fixed specific enthalpy and humidity ratio. With known mass flow rate, temperature and RH, the difference in energy content, which must be extracted by the chilled water cooling coil, can be calculated.

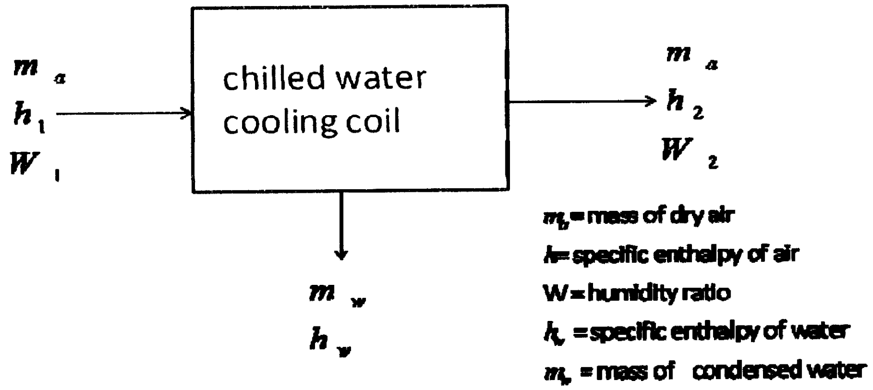


Figure 14: Moist Air Cooling

From material and energy balance, we have:

$$m_a h_1 = m_a h_2 + q + m_w h_w$$
$$m_a W_1 = m_a W_2 + m_w$$

Thus:

$$m_w = m_a(W_1 - W_2)$$
$$q = m_a[(h_1 - h_2) - (W_1 - W_2)h_w]$$

Here q represents the cooling load in the post-cooling coil. The difference in the cooling load before and after disabling the dehumidifier is converted to electricity savings using the site's chiller efficiency, which is known to be 0.861 kW/RT. (RT = refrigeration ton , a measure of cooling capacity; 1 RT = 3.517 kW.)

Therefore:

$$Power\ Savings\ in\ kW = 0.861\ (\Delta q),$$

$$where\ \Delta q = Reduction\ in\ Cooling\ Load\ in\ RT$$

The electricity and cost savings are then obtained with the duration of shutdown and the unit cost of electricity of \$0.213/kWh.

4.3.3 Modeling the AHU and Dehumidifier System

To further study and fine tune the system, a theoretical model of the AHU and dehumidifier is built in Microsoft Excel. The basic idea is to characterize the moist air at each stage along the process of cooling, heating and dehumidification in the AHU-Dehumidifier system. To do this, the state of the air must be expressed exactly using psychrometric equations. Appendix B is a list of some psychrometric equations used in the model.

Basically, when temperature and RH are known, the humidity ratio W and the specific enthalpy h can be calculated. Reversely, in the case when temperature and W are known, RH and h can be calculated. Appendix C is an example of the calculated properties of fresh air.

Two types of cooling/dehumidification models are built. Type I has only the pre-cooling coil, the post-cooling coil and the hot water reheating loop. This applies to the case when the dehumidifier is disabled. Type II has the pre-cooling coil, the dehumidifier, the post-cooling coil and the hot water reheating loop. This applies to the AHU-Dehumidifier couple.

Using this model, the power consumption in each piece of equipment can be calculated. By setting different equipment parameters such as the pre-cooling set-point temperature, the post-cooling set-point temperature and the percentage of air passing through dehumidifier, the operating point with minimum energy consumption can be found.

The following sections detail the modeling methods.

Modeling Various Air Treatments and Energy Consumption

In the AHU-Dehumidifier system, the air treatment can be classified into five types: mixing, cooling, heating, desiccant passing and room passing. The following sections describe how these treatments are modeled.

Mixing

Figure 15 shows the mixing of two air streams. The governing relationships are:

Energy Balance: $m_{a1}h_1 + m_{a2}h_2 = m_{a3}h_3$
Air Mass Balance: $m_{a1} + m_{a2} = m_{a3}$
Water Mass Balance: $m_{a1}W_1 + m_{a2}W_2 = m_{a3}W_3$

Thus: $\frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1} = \frac{m_{a1}}{m_{a2}} = k$

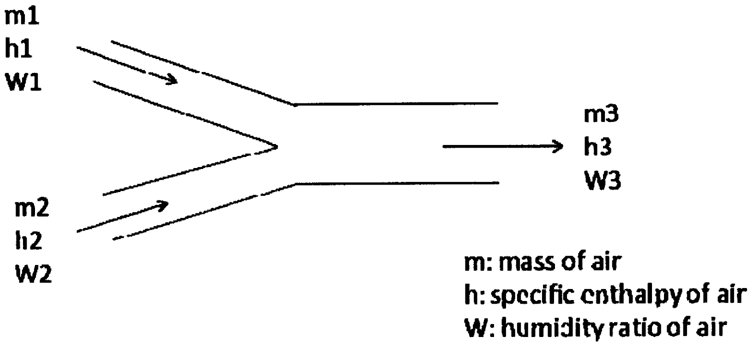


Figure 15: Mixing of Two Air Streams

With known mass flow rate, specific enthalpy and humidity ratio in the two mixing air streams, the resultant air properties can be calculated.

Cooling

The relationship and the energy difference are described previously in Figure 14 and the equations that follow.

Energy change is: $q_{cooling} = m_a[(h_1 - h_2) - (W_1 - W_2)h_w]$

Heating

During heating, there is no change in humidity ratio, thus the energy change is simply:

$$q_{heating} = m_a(h_2 - h_1)$$

Desiccant Passing

The temperature of supply air after passing the desiccant is found by mixing the reactivation air and the supply air at the inlet of the desiccant. The humidity ratio of the air after passing the desiccant is assumed to be 16.1% of that before passing the desiccant, i.e. the desiccant removes 83.9% of the moisture content. This is obtained from the design specifications of the dehumidifier.

Room Passing

When the supply air passes through the rooms, its temperature and humidity tend to reach equilibrium with the room air. The temperature of the return air is assumed to be 22.8° C and the humidity ratio is assumed to be equal to that specified by the room requirement.

With air properties specified and calculated at all the stages of the system, the model can calculate the cooling/heating loads in the pre-cooling coil, post-cooling coil, and reheating loop. The energy consumption rate from these devices is calculated given the chiller efficiency (the power that chiller consumes to generate 1 RT of cooling capacity, measured in kW/RT) and the hot water loop efficiency (the amount of natural gas required to generate the hot water that can provide 1 kW of heating capacity). Other energy consumptions such as the steam consumption and the motor and fan electricity consumption are zero when the dehumidifier is shut down, and assumed to be constant when the dehumidifier is in operation. Steam consumption rate is assumed to be 142.8 kg/hr and electricity power is assumed to be 3.89 kW. These are based on the results from the previous section discussing the steam and electricity savings. Finally, the total power consumption is calculated.

P(Type I Total) = P(Pre-Cooling Coil) + P(Post-Cooling Coil)
+ P(Reheat Loop)

P(Type II Total) = P(Pre-Cooling Coil) + P(Post-Cooling Coil)
+ P(Reheat Loop) + P(Steam Coil) + P(Motor Electricity)

where P(X) = power consumption in X.

Total cost rate to operate the system is calculated by:

Type I Total Energy Cost Rate
=(Unit Electricity Cost)× [P(Pre-Cooling Coil) + P(Post-Cooling Coil)]
+(Unit NG Cost)× P(Reheat Loop)

Type II Total Energy Cost Rate
= (Unit Electricity Cost)×[P(Pre-Cooling Coil) + P(Post-Cooling Coil) + P(Motor Electricity)]
+ (Unit NG Cost)×[P(Reheat Loop) + P(Steam Coil)]

Setting the Parameters and Constraints

The weather data of Singapore in 2008 is collected, which includes dry-bulb temperature, wet-bulb temperature, dew-point temperature and relative humidity. From this information, the average fresh air temperature is estimated to be 29° C and the average RH is 80%.

Other initial system parameters are as shown in Table 8. These figures are obtained from the site's historical data and the system's current set points. Hot water loop efficiency and total room volume under service are not available. They are estimated by the author to complete the model. All the system parameters can be changed by the model user.

Table 7: Initial System Parameters According to the Site's Data and Design Specifications

Parameter	*Value*	*Unit*
Chiller Efficiency	0.861	kW/RT
Hot Water Loop Efficiency*	0.005	(mmBTU NG/hr)/kW heat load
Unit Electricity Cost	0.213	$/kWh
Unit NG Cost	12	$/mmBTU
Room Volume under Service*	600	Cubic meters
Pre-cooling Off-coil Temperature	11.8	° C
Pre-cooling Off-coil Temperature	15	° C
Reheat Loop Temperature	21.1	° C

*The figure is estimated by the author to complete the modeling. The actual figure for the site is not available and may need future research to find out.

Table 9 shows the current room requirements used to test the supply air. The model ensures that the supply air's temperature, RH, air change rate and percentage of fresh air are all bounded by the corresponding upper and lower specification limits before yielding the output to the user. The model user is able to modify these figures when the production environment requirements change. For example, when the humidity sensitive product is to be manufactured, the RH should be set to 27%.

Table 8: Current Room Requirements

Parameter	*Upper Specification*	*Set point*	*Lower Specification*	*Unit*
Temperature	22.2	21.1	20	° C
Relative humidity	55.00%	50.00%	N.A.	
Air change rate	N.A.		15	times per hour
Percentage of fresh air	N.A.		10.00%	

To avoid logical errors, the system configuration check is also performed. These tests are summarized in Table 10. Basically, the off-coil set-point temperature of cooling coils should not be higher than the temperature of the upstream air, and the set-point temperature of reheat loop should not be lower than the temperature of the upstream air. If the set-point temperatures violate these rules, there will be a logical error and the power consumption in that device will become negative. In addition, since condensation in the post-cooling coil is deemed to be undesirable by the company, one more test checks whether the set-point temperature of post-cooling coil is higher than the dew-point temperature at that stage. If not, condensation will occur at the post-cooling coil and a warning is generated. However, it will not be recognized as a logic error, thus the output is still returned.

Table 9: System Configuration Check

Item	*What to Check*
Pre-cooling Coil	Set-point temperature cannot be higher than upstream air temperature
Post-cooling Coil	Set-point temperature cannot be higher than upstream air temperature
Reheat Loop	Set-point temperature cannot be lower than upstream air temperature
Condensation at Post-cooling	Set-point temperature cannot be lower than the dew-point temperature

Modeling Assumptions

The critical assumptions are as follows:

1. The AHU-Dehumidifier system operates at atmospheric pressure.
2. Motor power and steam consumption rate are constant once they are in operation, because there are no inbuilt feedback systems to control the power consumptions.
3. Dehumidifier's ability to remove moisture is constant with different air flow rate.
4. Total mass flow rate of air is constant and there is no air leakage.
5. Any heat loss is ignored.

Developing User Interface

A simple user interface is built in Microsoft Excel. In a simulation, the user is prompted to enter system parameters such as chiller efficiency, unit cost of electricity and natural gas, the total volume of rooms under service, room requirements such as temperature, RH and percentage of fresh air, as well as the various set-points of each piece of equipment, such as the off-coil temperature and percentage of air passing through the desiccant. This information is linked to the spreadsheet which performs the calculations and returns the results of air parameters at different stages and the cooling/heating loads in each piece of equipment. The spreadsheet will check the supply air parameters to ensure they are within the specification limits. At the same time, the spreadsheet examines whether there are system errors in the cooling coils and the reheat coil. If the input system settings result in out-of-specification supply air or configuration error, the user would be prompted to check and re-input the settings, otherwise the cooling/heating loads or the power consumptions in each piece of equipment, as well as the energy cost rate of the system will be calculated and returned.

5. RESULTS AND DISCUSSION

This chapter presents the results and discussion of the methodologies described in Chapter 4. Section 5.1 and Section 5.2 summarize the results of the energy management tool and the office building energy saving respectively. Detailed analysis can be found in Liu's [18] and Li's [17] theses. Section 5.3 details the analysis of the PF energy saving methods. The section numbering is in accordance with Chapter 4. For example, Section 5.3.1 presents the findings from Section 4.3.1.

5.1 Developing Energy Management Tool

The EUI of GSB and PF2 is 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, please refer to Mr. Haoyu Liu's thesis [18].

5.2 GSB Energy Saving

With the newly implemented HVAC operating schedule, The AHU motor energy consumption is reduced by 2% on weekdays and 74% on weekends, which gives an overall reduction of about 16.5% annually. Newly installed motion detection lighting control would further save over 50,000 kWh of electricity annually. For detailed analysis and discussion, please refer to Mr. Wu Li's thesis [17].

5.3 PF Energy Saving

5.3.1 Shutting Down HV, PV and DC during Non-production Time

Projected Savings in 2009

Table 11 shows the DC, HV and PV equipment list in PF2, with the operating power of each piece of equipment noted. With this and the production schedule for the year, the daily and annual energy savings can be calculated. Cost savings can be derived assuming a fixed average electricity unit cost of $0.241/day.

Table 10: Calculation of Electricity and Cost Savings with HV, PV and DC Shutdown

PF2 Equipment	*Operating Power (kW)*	*Energy Savings, (kWh/day)*	*Cost Savings*, $/day*	*Cost Savings on weekend days**, $*	*Cost Savings on non-production days, $*
Dust Collector DC-2019	23.04	552.96	$118.33	$7,100.01	$8,182.76
Dust Collector DC-2020	15.36	368.64	$78.99	$4,733.34	$5,455.17
Dust Collector DC-2021	22.65	543.6	$116.33	$6,979.82	$8,044.25
Process Vacuum DC-2030	20.24	485.76	$103.95	$6,237.16	$7,188.33
House Vacuum DC-2027	20.06	481.44	$103.03	$6,181.69	$7,124.40
Sum	101.35	2432.4	$520.53	$31,232.02	$35,994.90

Total Cost Savings: $67,227

*Assume unit electricity cost of $0.241/kWh

**There are 60 weekend days from June to December

From the calculation, the potential cost savings from June to December 2009 could be as high as $67,227. The electricity savings are 278,950 kWh.

Measurement Data from 2008 and Statistical Analysis

To evaluate the actual electricity savings, the measurement data from 2008 is used. The hypothesis testing results shown in Table 12 and Table 13 confirm the mean shift.

Table 11: Two-Sample T-Test and CI: WD_before, WD_after

Variable	*Sample size, N*	*Mean*	*StDev*	*SE Mean*
WD_after	14	5413	111	30
WD_before	14	6809	110	29

Difference = mu (WD_After) - mu (WD_Before)
Estimate for difference: -1395.8
99% upper bound for difference: -1292.0
T-Test of difference = 0 (vs <): T-Value = -33.42 P-Value = 0.000 DF = 25

Table 12: Two-Sample T-Test and CI: WE_After, WE_Before

Variable	*Sample size, N*	*Mean*	*StDev*	*SE Mean*
WE_after	6	4358.3	33.2	14
WE_before	6	6621	150	61

Difference = mu (WE_After) - mu (WE_Before)
Estimate for difference: -2262.4
99% upper bound for difference: -2050.7
T-Test of difference = 0 (vs <): T-Value = -35.96 P-Value = 0.000 DF = 5

The two tests both yield P-Value less than 0.0005, therefore we are almost 100% confident that the electricity saving is realized with shutdown of HV, PV and DC.

Next, the measured power savings are compared with the calculated savings. From Table 6 and Table 11, the daily electricity savings are calculated as shown below.

Weekday Daily Savings: 101.35 kW × *12 hours = 1216.2 kWh*

Weekend Daily Savings: 101.35 kW ×*24 hours = 2432.4 kWh*

These values are plotted together with the measured data in Figure 16.

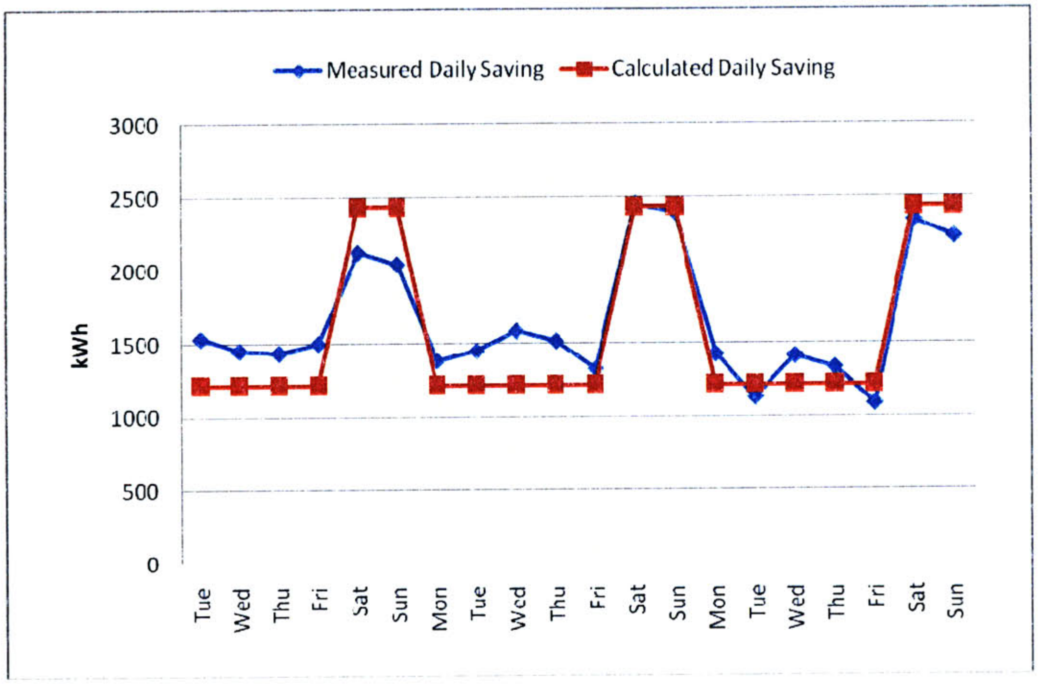


Figure 16: Measured Savings and Calculated Savings

The R-Square is calculated to be 0.891, indicating satisfactory fit between the measurement and the calculation. Therefore, the way of using operating power to calculate the potential energy savings can be accepted. The projected electricity savings figure of $67,227 from June to December 2009 is considered valid.

Limitation of the Method

In 2008, the electricity consumption of HV, PV and DC was not directly measured. It was obtained by subtracting the total daily consumption of PF2 after shutdown from the daily consumption before shutdown. This difference was a result of many activity changes in PF2, but is here assumed to be solely the effect of shutting down HV, PV and DC. In other words, the electricity consumption is assumed to be in a steady state, and other contributors to the variation of electricity usage are neglected. In such circumstance, if there are more data points available, the effect of non-shutdown related activity can be reduced, and a better estimate of the savings due to the shutdown may be obtained.

5.3.2 Disabling Dehumidifier for RH Insensitive Products

Processes of Cooling and Dehumidification

Figure 17 shows the layout of an AHU coupled with a dehumidifier. Figure 18 shows photos of some parts of the system. In PF1, AH-2001 and DH-2001 couple is installed in this way. Two air passages are present in this system: the supply air and the reactivation air, which run in opposite directions.

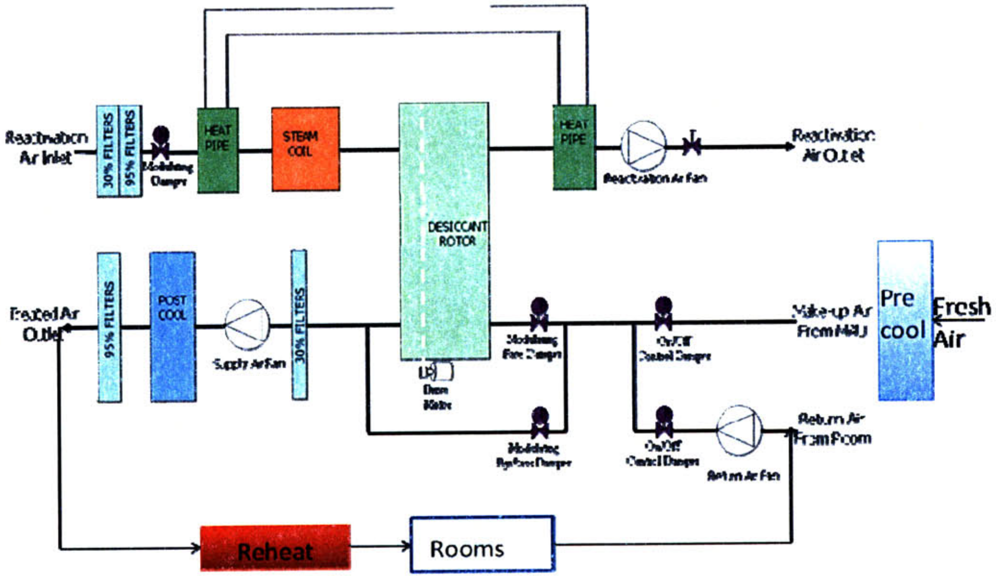


Figure 17: Schematic of AHU-Dehumidifier Couple

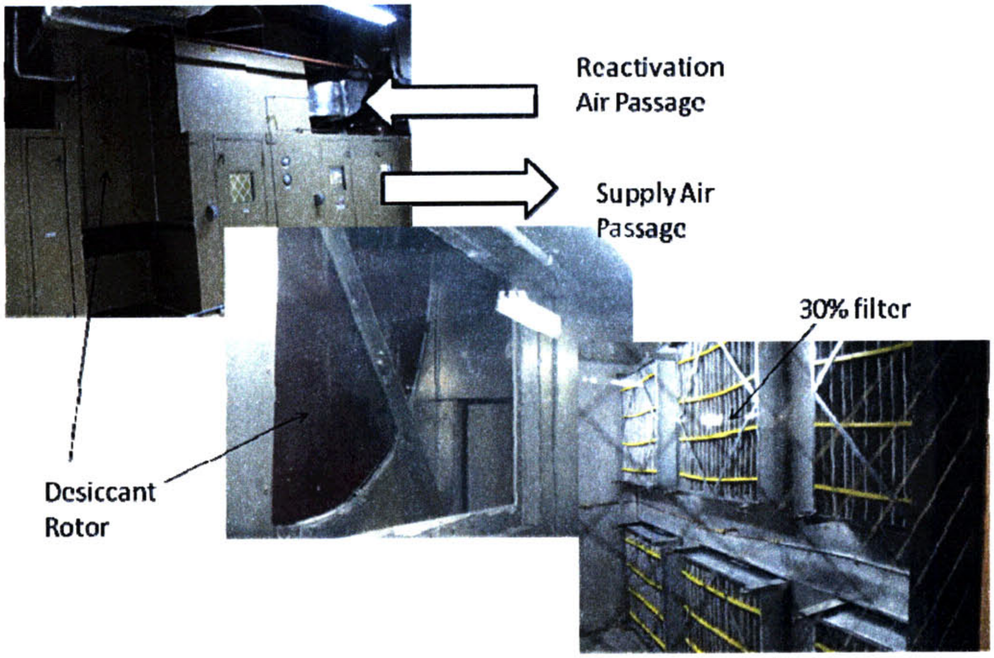


Figure 18: Some Parts of the AHU-Dehumidifier Couple

In Figure 17, the lower air passage is the supply air, which runs from the right to the left. It is a mixture of the return air and the make-up air. Depending on the source of the return air, it is sometimes treated by HEPA filters before joining this passage to remove particulates and avoid product cross contamination. Make-up air, as the name suggests, completes the composition of the supply air. It is essentially fresh outside air pre-treated by the upstream AHU. While it passes through the pre-cooling coil, apart from being cooled down, a portion of its moisture is also removed by condensation, as air at lower temperature has lower saturation vapor pressure. Usually, the ratio of return air to make-up air is about 80% to 20%.

The mixed air then either passes through the desiccant rotor or bypasses it. The portion of air passing through the desiccant will have its moisture further removed. However, the temperature would increase drastically due to the hot desiccant wheel. The two air passages merge after the dehumidifier. The ratio of air passing through desiccant is determined by the degree of opening of the face damper and the bypass damper. In this way, the desired humidity of the final air can be controlled. It can also be used to minimize the portion of air going through desiccant so as to have a mixed air downstream with lower temperature, which exerts less cooling load for the post-cooling coil.

The mixed air is filtered and cooled down by the post-cooling coil. Just before the treated air is fed into the respective rooms, it is reheated by the hot water system to around 21 °C.

The reactivation air serves to reactivate the desiccant. It is first filtered to avoid contamination in the desiccant wheel. The air is then heated up by the steam coil. With higher temperature, its saturation vapor pressure, or the moisture holding capacity, increases. After passing through the desiccant, the moisture content of the desiccant would be absorbed by the hot air. The reactivation air with higher moisture is finally released to the atmosphere. By constantly removing moisture in this way, the desiccant is prevented from saturation. Another noteworthy feature of the system is the heat pipe, which is installed as an energy saving measure: it transfers heat from the downstream air to upstream air, so that part of the heat from the reactivation air is recovered. This would lower the heating load of the steam coil.

Using Psychrometric Chart to Predict the RH of Supply Air from Design Specifications

Figure 19 shows the current design specifications of the AHU-Dehumidifier couple. The make-up air stream has temperature of 15.6° C and humidity ratio of 7.47 g moisture/kg dry air. Without dehumidifier, this humidity ratio will be maintained downstream, i.e. the supply air will also have the humidity ratio of 7.47 g moisture/kg dry air.

Figure 20 shows how to use the psychrometric chart to derive the state of the supply air. Looking for 15.6° C on the horizontal axis and 7.47 g moisture/kg dry air on the vertical axis, the state of the make-up air is marked on the chart. To maintain this humidity ratio and heat the air to 21.1° C, the state point would simply shift horizontally to the right until temperature is 21.1° C. The corresponding relative humidity is about 48%, which is smaller than 50% and would meet the room environment requirement. Therefore, even without the dehumidifier, the relative humidity of the supply air can be well controlled to 50% and below given the current system settings.

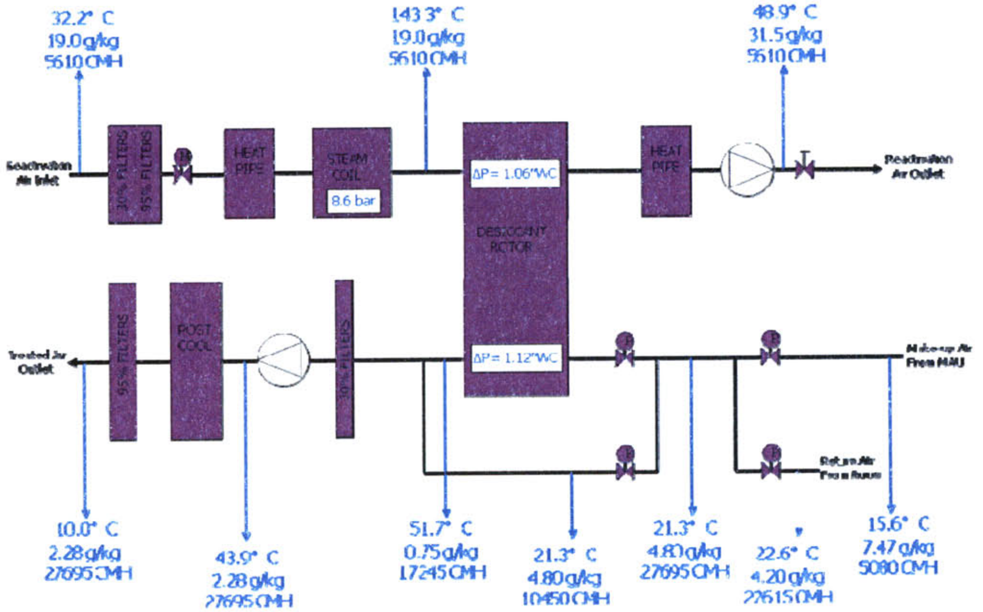


Figure 19: Design Specifications of AHU-Dehumidifier Couple with Dehumidifier [8]

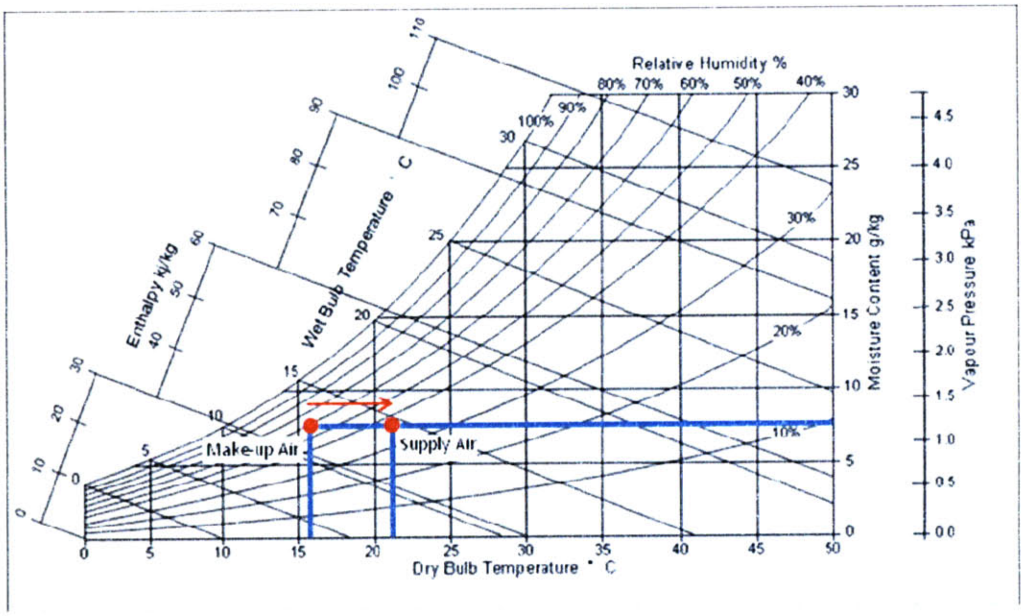
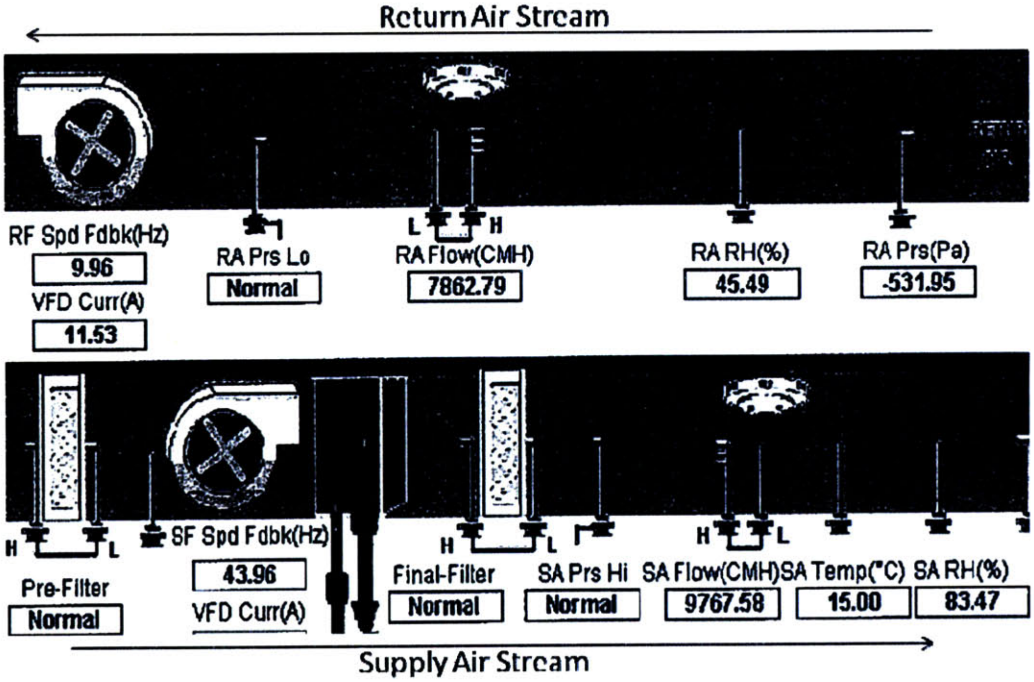


Figure 20: State of Make-up Air and Supply Air with Dehumidifier Disabled (from Design Specifications)

Examining the Supply Air RH after Disabling Dehumidifier

A snapshot of the AHU-Dehumidifier system parameters after the dehumidifier is disabled is obtained from the Building Automation System (BAS) and shown in Figure 21. The temperature and relative humidity of the supply air after the post-cooling coil is 15° C and 83.47% respectively. Similarly, the state of the supply air can be obtained from the psychrometric chart. Figure 22 shows that the relative humidity of the supply air at 21.1° C would be about 50%, which is satisfactory. It is also worthwhile to note that in Figure 21, the RH of return air is 45.49%, which is a stronger piece of evidence that the room relative humidity is kept below 50%.



RF Spd Fdbk(Hz) 9.96
VFD Curr(A) 11.53
RA Prs Lo Normal
RA Flow(CMH) 7862.79
RA RH(%) 45.49
RA Prs(Pa) -531.95
Pre-Filter Normal
SF Spd Fdbk(Hz) 43.96
VFD Curr(A)
Final-Filter Normal
SA Prs Hi Normal
SA Flow(CMH) 9767.58
SA Temp(°C) 15.00
SA RH(%) 83.47

Figure 21: Measurement of Air Temperature and Relative Humidity after Disabling Dehumidifier [2]

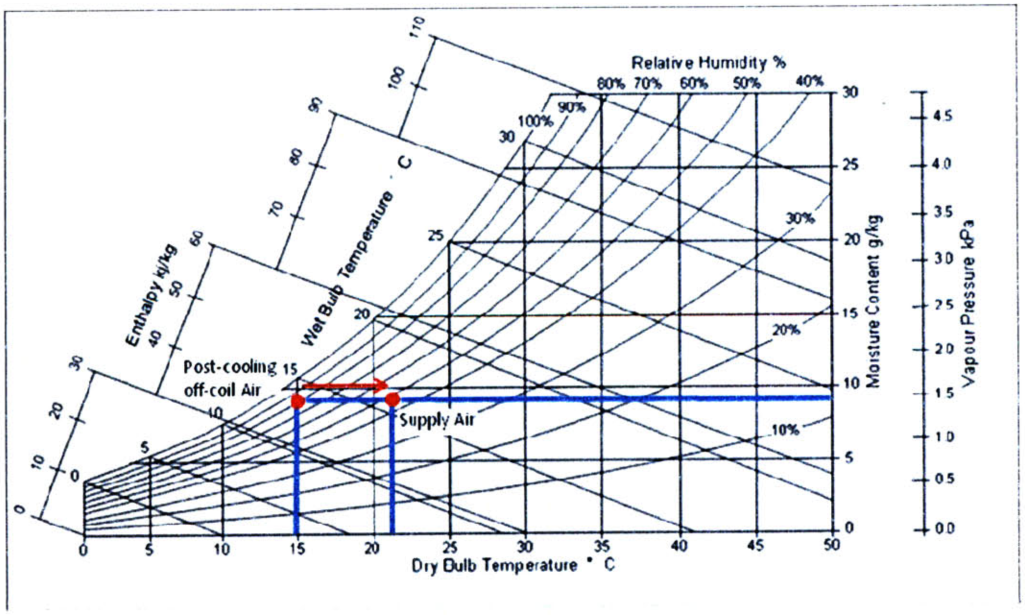


Figure 22: State of Post-cooling Off-coil Air and Supply Air with Dehumidifier Disabled (from Actual Measurement)

Energy Savings Calculation

Overall, the annual energy and cost savings is shown in Table 14. The bulk of cost savings come from reduction in steam and chilled water consumption.

Table 13: Summary of Annual Energy and Cost Savings by Disabling Dehumidifier

Direct Motor and Fan Electricity Savings		*Steam Consumption Savings*		*Chilled Water Consumption Savings*	
Electricity (kWh)	*Cost ($)*	*Natural Gas (mmBTU)*	*Cost ($)*	*Electricity (kWh)*	*Cost ($)*
27,261	5,807	4,046	48,546	143,305	30,524
Total Energy Savings: 170,566 kWh of Electricity, 4046 mmBTU of Natural Gas Total Cost Savings: $84,877					

The results for each area of energy saving are discussed below.

Direct Electricity Saving

The rated powers of the desiccant wheel motor and the reactivation fan are found to be 0.19 kW and 3.70 kW. The result is shown in Table 15.

Table 14: Direct Electricity Saving

		Savings/Day		*Savings/Year*	
	Rated Power (kW)	*Electricity (kWh)*	*Cost ($)*	*Electricity (kWh)*	*Cost ($)*
Desiccant Wheel Motor	0.19	3.65	0.78	1,332	284
Reactivation Air Fan	3.70	71.04	15.13	25,930	5,523
Total	3.89	74.69	15.91	27,261	5,807

Saving of Steam Consumption

The result of the two-sample t-test for the steam consumption before and after disabling the dehumidifier is shown in Table 16.

Table 15: Two-Sample T-Test and CI: Steam_After, Steam_Before

Variable	*Sample size, N*	*Mean*	*StDev*	*SE Mean*
Steam_After	168	2399	163	13
Steam_Before	168	2541	150	12

Difference = mu (Steam_After,) - mu (Steam_Before)
Estimate for difference: -142.8
90% upper bound for difference: -120.9
T-Test of difference = 0 (vs <): T-Value = -8.36 P-Value = 0.000 DF = 331

With a p-value of less than 0.0005, we are almost 100% confident to say that there is a mean shift in the steam consumption in PF1 after the dehumidifier is disabled. The reduction in steam consumption is estimated to be 142.8 kg/hr. Therefore,

Natural Gas Savings = 0.003234 mmBTU/kg × 142.8 kg/hr = 0.462 mmBTU/hr

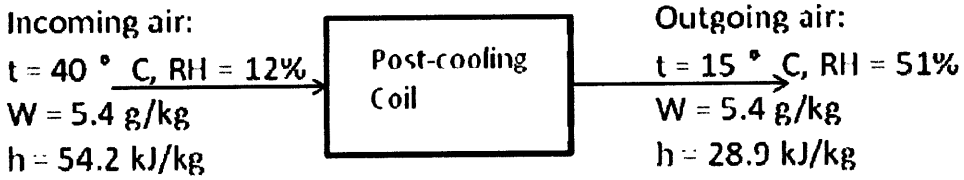
Annual NG Savings = 0.462 mmBTU/hr × 24 hr/day × 365 days/year

= 4046 mmBTU

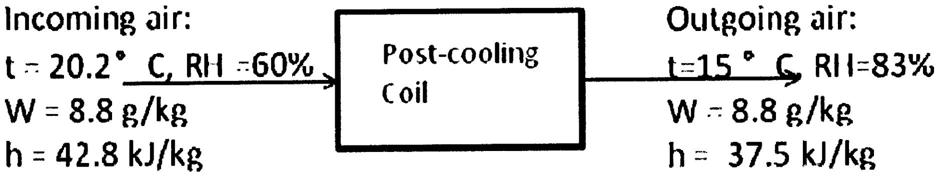
Annual Cost Savings = 4046 mmBTU ×S$12/mmBTU = S$48,546

Saving of Chilled Water Consumption

The measurement of the air temperature and RH before and after disabling the dehumidifier is obtained from the BAS snapshot. The corresponding specific enthalpy of the air is obtained from the psychrometric chart. These results are shown in Figure 23.



Before Disabling Dehumidifier



After Disabling Dehumidifier

Figure 23: BAS Measurement of Parameters of Air Upstream and Downstream of the Post-cooling Coil before and after the Dehumidifier is Disabled

It can be seen that in both cases, there is no change in the humidity ratio (*W*) upstream and downstream of the post-cooling coil. This is reasonable because according to the design specifications, the post-cooling coil is not supposed to have condensation: the off-coil set-point temperature of the post-cooling coil (15° C) is higher than that of the pre-cooling coil (10° C -12° C). Therefore, the air which has been through the pre-cooling process would not reach 100% RH when it comes out of the post-cooling coil at 15° C, and no condensation would occur. In the case when there is dehumidifier, the humidity ratio is even lower when the air reaches the post-cooling coil, thus it is even more impossible to have condensation there.

Also, from the BAS information, the mass flow rate is estimated to be constantly 12,000 kg/hr. Cooling load before and after disabling dehumidifier can be calculated:

$$
\begin{aligned}
q_{before} &= m_a[(h_1 - h_2) - (W_1 - W_2)h_w] \\
&= (12000 kg / hr)(54.2 - 28.9) kJ / kg \\
&= 303600 kJ / hr \\
&= 84.3 kW \\
&= 24.0 RT
\end{aligned}
$$

$$
\begin{aligned}
q_{after} &= m_a[(h_1 - h_2) - (W_1 - W_2)h_w] \\
&= (12000 kg / hr)(42.8 - 37.5) kJ / kg \\
&= 63600 kJ / hr \\
&= 17.7 kW \\
&= 5.0 RT
\end{aligned}
$$

Δ q = 24.0 RT – 5.0 RT = 19. 0 RT

With chiller efficiency of 0.861 kW/RT, power savings is calculated:

Power Savings = 0.861 kW/RT × 19.0 RT =16.4 kW

Annual energy and cost savings is calculated:

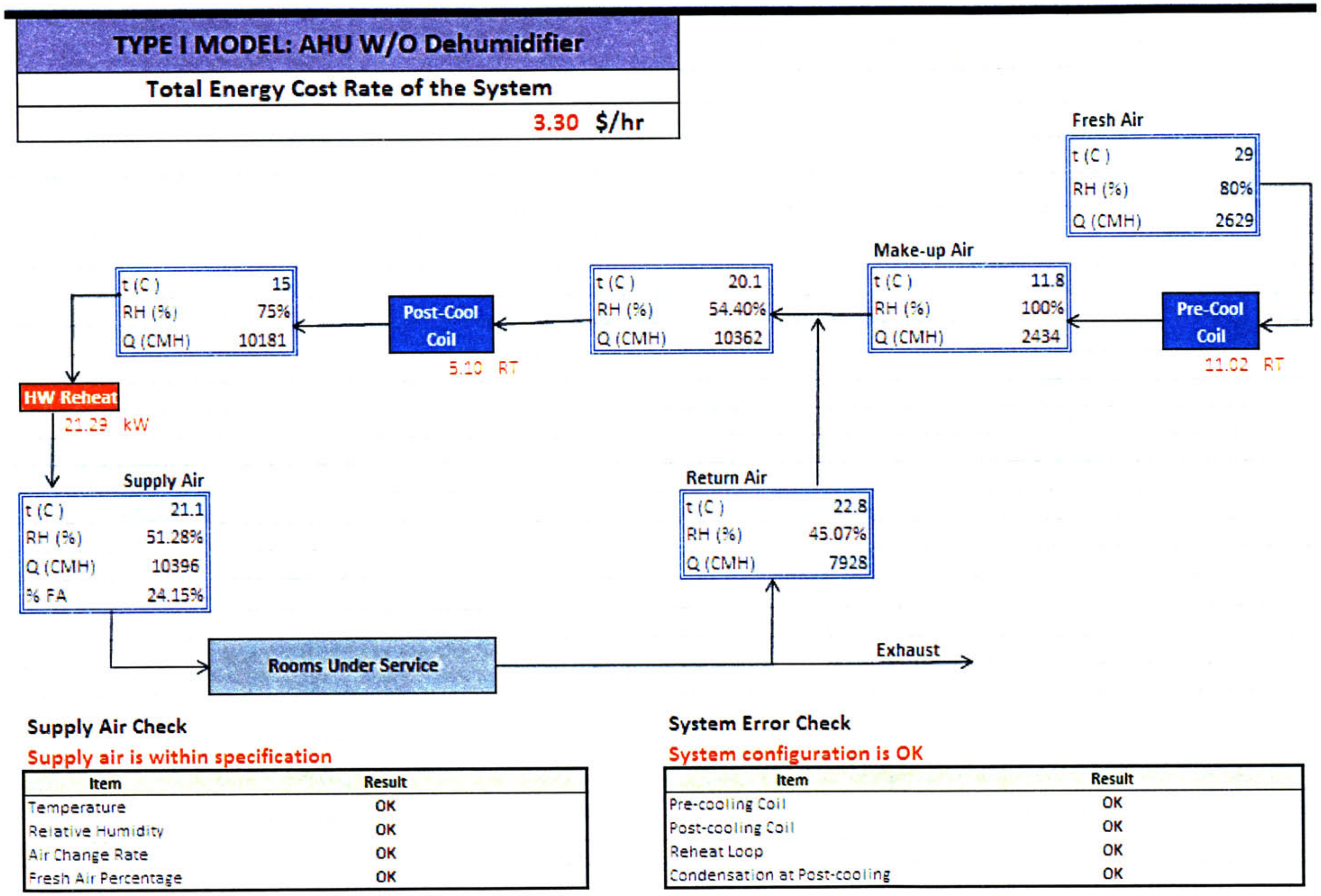
*Annual Electricity Savings = 16.4 kW * 24 hr/day × 365 days = 143,305 kWh*

Annual Cost Savings = 143,305 kWh × S$0.213/kWh = S$30,524

5.3.3 Modeling the AHU and Dehumidifier System

Simulation with Current System Settings

Figure 24 and Figure 25 show the Type I model and the Type II model respectively, with the current system settings and room requirements inputted. Essentially, Type II shows the system status before the dehumidifier is disabled and Type I shows the current system status.



TYPE I MODEL: AHU W/O Dehumidifier

Total Energy Cost Rate of the System

3.30 $/hr

Fresh Air

t (C)	29
RH (%)	80%
Q (CMH)	2629

Make-up Air

t (C)	11.8
RH (%)	100%
Q (CMH)	2434

t (C)	20.1
RH (%)	54.40%
Q (CMH)	10362

t (C)	15
RH (%)	75%
Q (CMH)	10181

Supply Air

t (C)	21.1
RH (%)	51.28%
Q (CMH)	10396
% FA	24.15%

Return Air

t (C)	22.8
RH (%)	45.07%
Q (CMH)	7928

Supply Air Check

Supply air is within specification

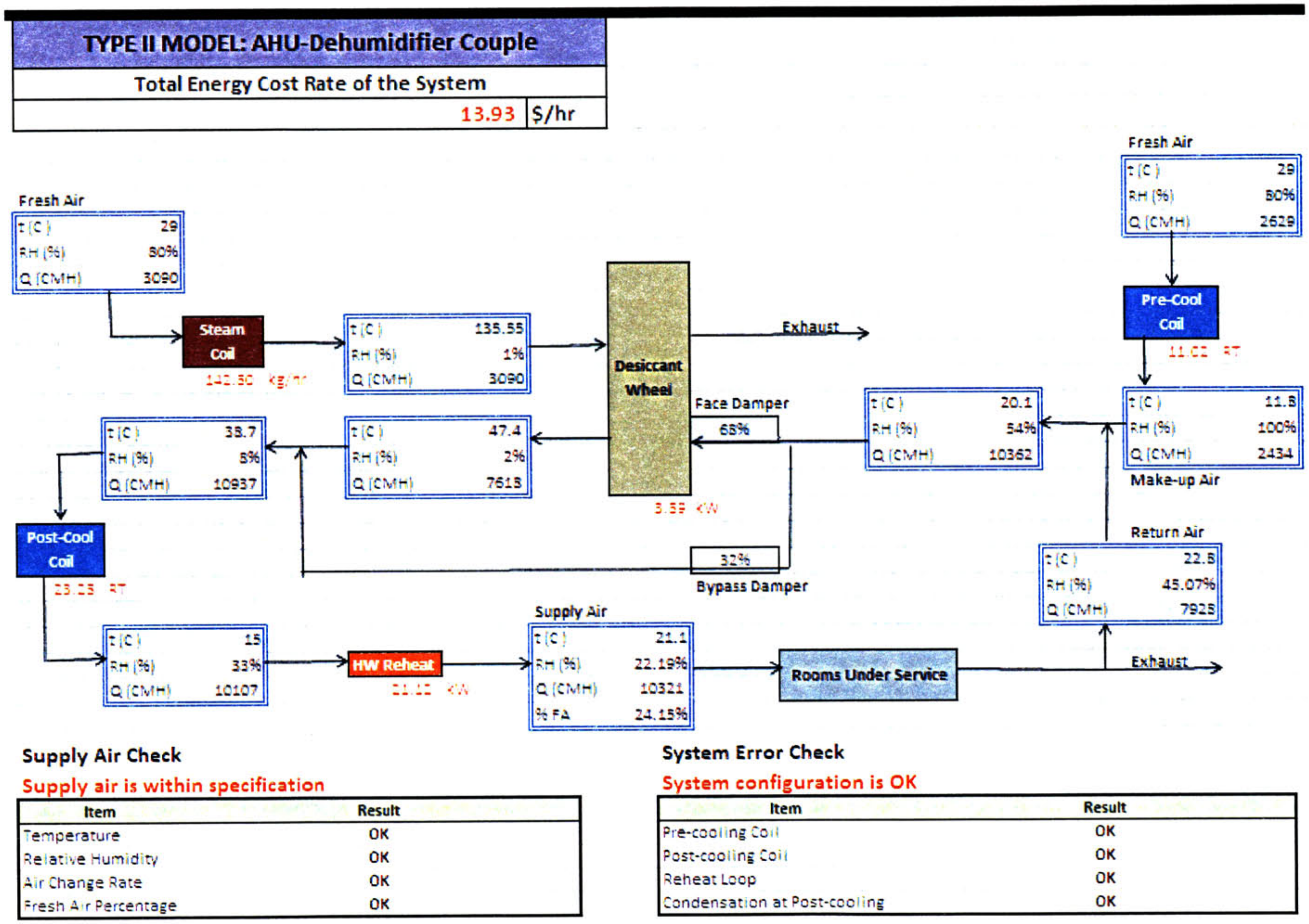
Item	Result
Temperature	OK
Relative Humidity	OK
Air Change Rate	OK
Fresh Air Percentage	OK

System Error Check

System configuration is OK

Item	Result
Pre-cooling Coil	OK
Post-cooling Coil	OK
Reheat Loop	OK
Condensation at Post-cooling	OK

Figure 24: Type I Model



TYPE II MODEL: AHU-Dehumidifier Couple

Total Energy Cost Rate of the System	
13.93	$/hr

Supply Air Check

Supply air is within specification

Item	Result
Temperature	OK
Relative Humidity	OK
Air Change Rate	OK
Fresh Air Percentage	OK

System Error Check

System configuration is OK

Item	Result
Pre-cooling Coil	OK
Post-cooling Coil	OK
Reheat Loop	OK
Condensation at Post-cooling	OK

Figure 25: Type II Model

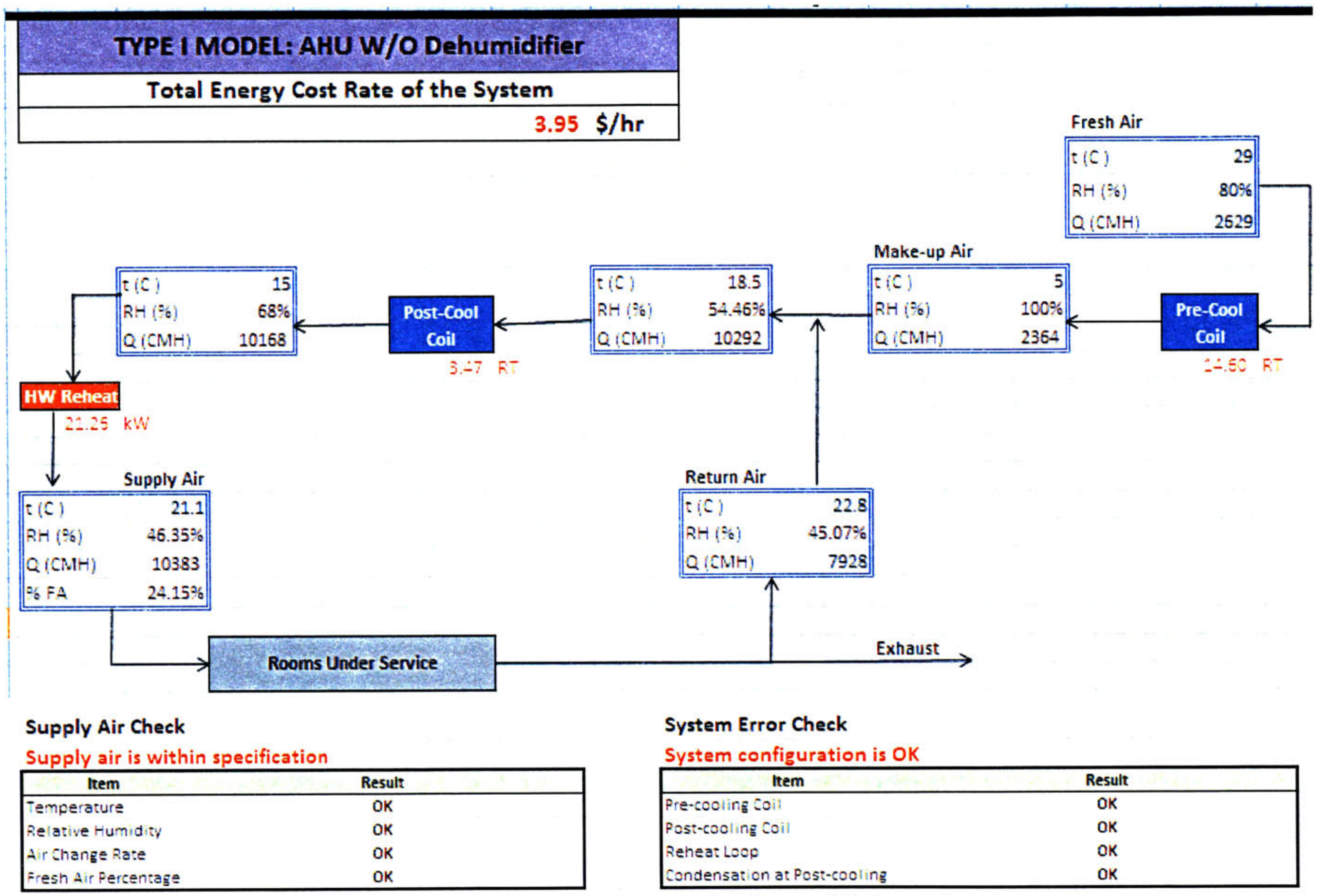
The cooling/heating loads and power consumptions are displayed under the equipment cells. The cost of operating the Type I system is $3.30/hour and the Type II system is $13.93/hour. The cost savings by disabling the dehumidifier is about $10.6/hour, which is consistent with the previous calculation. Besides the addition of steam coil and the motor electricity in the Type II system, the primary difference between the two systems occurs at the post-cooling coil: the air is heated up when it passes through the desiccant rotor, adding extra cooling load to the post-cooling coil.

The supply air RH is about 51% in Type I and about 22% in Type II. As the current upper specification limit for RH is 55%, Type I system is satisfactory. Therefore, dehumidifier can be disabled to realize energy and cost savings.

However, if a humidity sensitive product is being manufactured, the Type I system cannot be used because the minimum supply air RH it can provide is about 46%, which is still much higher than the required 27%. This is shown in Figure 26: as the chilled water temperature is about 5° C, the lower limit of the temperature of the off-coil air is 5° C. Setting the make-up air to 5° C, Type I system is then operating at the state with the most reduction of moisture at the pre-cooling coil. The resultant supply air RH is 46%.

Figure 27 shows the state of Type II system with maximum dehumidification: setting the make-up air to 5° C and face damper to 100%. The resultant supply air RH is about 7.5%. This is the minimum supply air RH that the Type II system can provide.

Therefore, in the case when humidity sensitive product is being manufactured, Type II system has to be used, i.e., the dehumidifier must be enabled.



TYPE I MODEL: AHU W/O Dehumidifier

Total Energy Cost Rate of the System

3.95 $/hr

Fresh Air

t (C)	29
RH (%)	80%
Q (CMH)	2629

Make-up Air

t (C)	5
RH (%)	100%
Q (CMH)	2364

t (C)	18.5
RH (%)	54.46%
Q (CMH)	10292

t (C)	15
RH (%)	68%
Q (CMH)	10168

Supply Air

t (C)	21.1
RH (%)	46.35%
Q (CMH)	10383
% FA	24.15%

Return Air

t (C)	22.8
RH (%)	45.07%
Q (CMH)	7928

Supply Air Check

Supply air is within specification

Item	Result
Temperature	OK
Relative Humidity	OK
Air Change Rate	OK
Fresh Air Percentage	OK

System Error Check

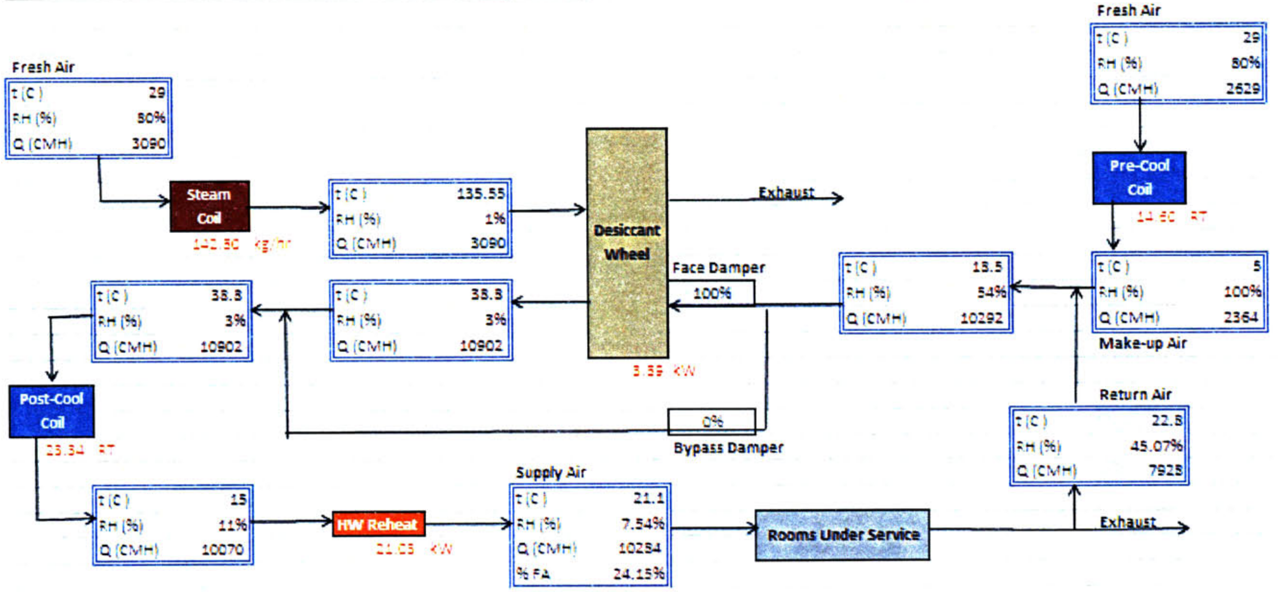
System configuration is OK

Item	Result
Pre-cooling Coil	OK
Post-cooling Coil	OK
Reheat Loop	OK
Condensation at Post-cooling	OK

Figure 26: Minimum Achievable Supply Air RH with Type I System

TYPE II MODEL: AHU-Dehumidifier Couple

Total Energy Cost Rate of the System	
14.59	$/hr



Fresh Air
t (C) 29
RH (%) 80%
Q (CMH) 3090

Steam Coil
142.50 kg/hr

t (C) 135.55
RH (%) 1%
Q (CMH) 3090

Desiccant Wheel
3.55 KW

Exhaust

Face Damper
100%

Bypass Damper
0%

t (C) 38.3
RH (%) 3%
Q (CMH) 10802

t (C) 38.3
RH (%) 3%
Q (CMH) 10802

Post-Cool Coil
23.34 RT

t (C) 15
RH (%) 11%
Q (CMH) 10070

HW Reheat
21.05 KW

Supply Air
t (C) 21.1
RH (%) 7.54%
Q (CMH) 10284
% FA 24.15%

Rooms Under Service

Exhaust

Fresh Air
t (C) 29
RH (%) 80%
Q (CMH) 2629

Pre-Cool Coil
14.50 RT

t (C) 5
RH (%) 100%
Q (CMH) 2364

Make-up Air

t (C) 18.5
RH (%) 54%
Q (CMH) 10292

Return Air
t (C) 22.8
RH (%) 45.07%
Q (CMH) 7928

Supply Air Check

Supply air is within specification

Item	Result
Temperature	OK
Relative Humidity	OK
Air Change Rate	OK
Fresh Air Percentage	OK

System Error Check

System configuration is OK

Item	Result
Pre-cooling Coil	OK
Post-cooling Coil	OK
Reheat Loop	OK
Condensation at Post-cooling	OK

Figure 27: Minimum Achievable Supply Air RH with Type II System

Optimization of System Settings

To minimize energy consumption, the post-cooling off-coil temperature should be set as close to the required supply air temperature as possible, to minimize the cooling load of itself as well as the heating load of the downstream reheat loop. The current off-coil set-point temperature for the post cooling coil is 15° C, which results in higher than necessary energy consumption in the post-cooling coil and the reheat loop.

The following sections describe the optimized system settings, which may further reduce the energy consumption and operating cost. However, no numbers of savings are presented because the models have yet to be validated. Nevertheless, the models help the energy managers to examine the system and provide directions for future work.

50% Supply Air RH

When no humidity sensitive drug is under production, the minimum energy consumption occurs in the Type I system with the settings shown in Figure 28.

With the current requirements, the post-cooling coil in the Type I system is even not necessary as its upstream air would always be below 21.1° C. This is because that the 50% RH requirement would dictate the highest pre-cooling off-coil temperature of 15.5° C, which results in the highest possible post-cooling coil incoming air temperature of about 21.0° C. This air stream also needs very small amount of reheating before it can be supplied to the room.

The minimum energy cost rate is \$1.62/hr, which is primarily spent on the pre-cooling process with cooling load of 8.70 RT. This cost rate is smaller than the current cost rate of \$3.95/hr. Therefore, by setting a higher post-cooling off coil temperature, further energy and cost savings can be realized.

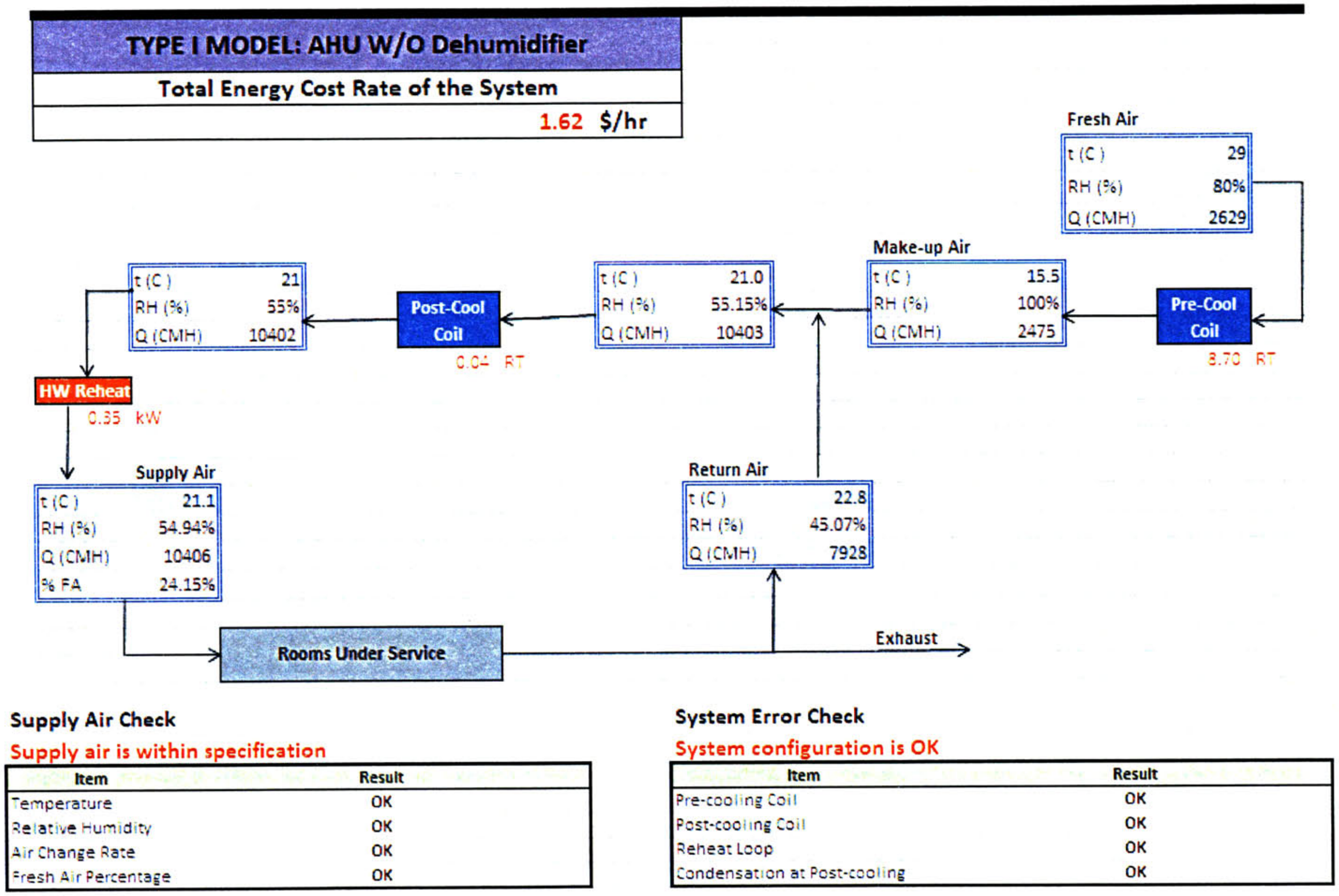
Note that if the Type II system is used, the minimum energy cost rate of $9.27/hr occurs when pre-cooling coil is bypassed/disabled (this is done by setting the make-up air temperature to 29° C, the same as the fresh air temperature), and the percentage of air passing through the dehumidifier is set to be 25%. This is more energy and cost consuming than the Type I system.

27% Supply Air RH

When a humidity sensitive drug is under production, the minimum energy consumption occurs in the Type II system with the settings shown in Figure 29. In this case, the Type I system cannot satisfy the requirements as discussed earlier.

The make-up air temperature is set to be 29° C, meaning there is no pre-cooling process and all the dehumidification is carried out at the dehumidifier. The face damper is set to 74%, any lower than which the supply air RH would rise above 27%. The post-cooling off-coil temperature is set to be 21.1° C to minimize its cooling load and eliminate the need of using the reheat loop. These settings result in a cost rate of about $10.24/hour. Besides the constant consumption rate from the steam coil and the motor electricity, this energy cost is attributed to the post-cooling coil, as the pre-cooling and reheating process have been precluded.

It can be seen that once the Type II system is used, the power consumption and cost rate would increase significantly due to the steam coil and motor electricity consumptions. As discussed earlier, the minimum supply air RH that the Type I system can provide is about 46%, thus once the RH specification is below 46%, the Type II system must be used (i.e., dehumidifier enabled) and the minimum power consumption would increase significantly.



Supply Air Check

Supply air is within specification

Item	Result
Temperature	OK
Relative Humidity	OK
Air Change Rate	OK
Fresh Air Percentage	OK

System Error Check

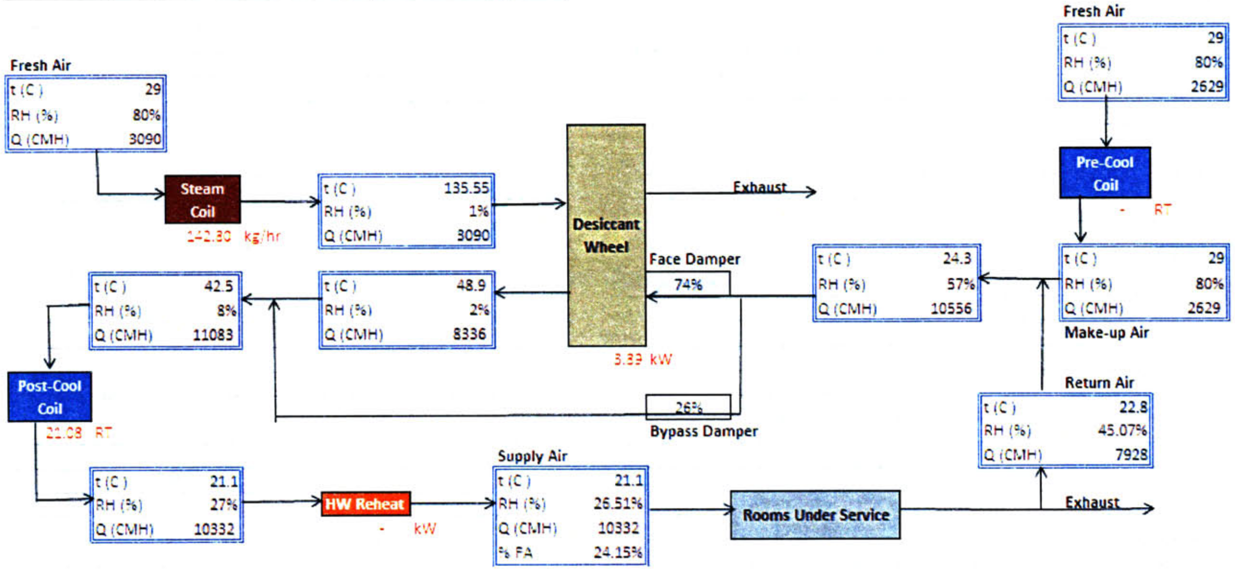
System configuration is OK

Item	Result
Pre-cooling Coil	OK
Post-cooling Coil	OK
Reheat Loop	OK
Condensation at Post-cooling	OK

Figure 28: Optimized System Settings for Current Requirements

TYPE II MODEL: AHU-Dehumidifier Couple

Total Energy Cost Rate of the System	
10.24	$/hr



Supply Air Check

Supply air is within specification

Item	Result
Temperature	OK
Relative Humidity	OK
Air Change Rate	OK
Fresh Air Percentage	OK

System Error Check

System configuration is OK

Item	Result
Pre-cooling Coil	OK
Post-cooling Coil	OK
Reheat Loop	OK
Condensation at Post-cooling	OK

Figure 29: Optimized System Settings when 27% RH is Specified

Limitations of the Models

The above models are built with theoretical calculations. The results have not been validated with experiments. Some parameters such as the chiller efficiency and the hot water loop efficiency are assumed to be constant. But they exhibit considerable variations in practice. In addition, they are also functions of real-time consumptions, i.e., the chiller efficiency would be different when the total chilled water consumption on site is changed.

In addition, some modeling assumptions may not be valid. For example, the dehumidifier's ability to remove moisture would actually depend on the supply air flow rate: higher flow rate of supply air may result in less reduction in humidity ratio as the time each unit mass of air spends in the desiccant is less. Also, possible air leakage and significant heat loss are neglected in the modeling.

6. CONCLUSION

Energy cost accounts for about 20% of the total operating cost in AFT Singapore. To maintain corporate competitiveness and achieve more environmentally friendly operation, energy management plays a crucial role.

Data on electricity and natural gas consumption was collected, analyzed and benchmarked against industrial average figures. It was found that the current energy efficiency is not satisfactory. The HVAC system is the main contributor of the high energy consumption.

A pharmaceutical manufacturing environment has its unique indoor air quality requirements to ensure product safety and quality, as well as the comfort of occupants. Most of the time, the highest level of these requirements is maintained throughout the year, which may result in significant amount of waste. Developing and revising operation schedules for the HVAC system regularly, relaxing the environment standards by shutting down equipment that is not necessary and optimizing system settings would reduce wasteful usage of energy, without compromising the indoor environment standard.

In this project, an energy management spreadsheet is developed, which enables the user to effectively monitor the energy efficiency after various forms of energy consumptions are known. It also allows the energy manager to find out the heat gain and cooling load of the HVAC system.

For the office building, a better HVAC operation schedule for office building is developed and implemented, which may potentially realize 16.5% energy saving in the AHU motor electricity. Motion detection lighting control was implemented in the office building, which could reduce electricity consumption by 54,082 kWh annually.

For the production facility, shutting down HV, PV and DC during non-production hours in PF2 may result in cost savings of $67,227 and electricity savings of 278,950 kWh from June to December 2009. The dehumidifier is disabled in PF1, as the supply air humidity can be controlled within specification with only the pre-cooling coil. The annual energy savings by this measure amounts to 170,566 kWh electricity and 4046 mmBTU of natural gas, which are equivalent to cost savings of $84,877.

With the implemented energy saving strategies, the EUI for GSB would become 356 $kWh/m^2/year$, a 6.68% reduction from that in 2008. The EUI for PF1 and PF2 white areas would become 6085 $kWh/m^2/year$ and 3957 $kWh/m^2/year$, equivalent to 6.58% reduction and 2.32% reduction from that in 2008 respectively.

Theoretical modeling of AHU-Dehumidifier couple gives the user deeper insight into the cooling and dehumidification system. When the required relative humidity is higher than 46%, the Type I system, which has the dehumidifier disabled, is preferable. When lower relative humidity is specified, the Type II system with the dehumidifier enabled has to be used. Optimizing the system settings to eliminate unnecessary cooling and heating loads would result in minimum energy consumption.

7. RECOMMENDATIONS AND FUTURE WORK

This chapter lists the recommendations and possible future work. The recommendations are based on the methodologies and results obtained in the project, while the future work includes promising energy saving strategies that can be studied and implemented in the near future.

7.1 Recommendations

7.1.1 Reschedule the HVAC Operating Schedules Regularly

The HVAC operating schedule should follow the activity plan in the building. Once there is change in the building activity schedule, the HVAC operation should be adjusted accordingly at the same time. This is both to avoid the degradation of indoor environment in the case when HVAC does not operate while needed, and to minimize waste of energy in the case when HVAC operates beyond the time needed.

7.1.2 Enable Motion Detection Lighting Control

Motion detection lighting control would save significant amount of energy in the lighting of office buildings. Detailed analysis can be found in Mr. Wu Li's thesis [17].

7.1.3 Standardize the Procedures of HV, PV and DC Shutdown during Non-production Time

As discussed in Chapter 5, HV, PV and DC shutdown would realize more than $67,000 savings in PF2 electricity if executed properly during non-production time. This would not affect the product quality or occupant's comfort.

7.1.4 Disable the Dehumidifier and Adjust the Pre-cooling Off Coil Temperature to 15.5 °C

The RH of the supply air would be within 55% even without 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 15.5 °C. Above this temperature, the room RH requirement may not be met.

7.1.5 Increasing Set-point Temperature of the 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 15 °C. 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 would eventually be 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 significant amount of energy from the both chiller and the boiler sides.

To satisfy the current indoor environment criteria, the post-cooling coil is not needed when the dehumidifier is disabled. When the Type II system is used, the post-cooling off-coil temperature should be set to 21.1 °C to both ensure minimum cooling load on itself and eliminate the need of reheating.

7.2 FUTURE WORK

7.2.1 Invest in Water Evaporative Cooling on Rooftop and Roof Garden

Energy saving strategies related to office buildings, involving water evaporative cooling on the rooftops and a roof garden are described in Mr. Wu Li's thesis [17].

7.2.2 Reduce Air Change per Hour during Non-production Time

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 considerable energy saving in various parts of the HVAC system. For example, the fan motor can operate at lower frequency with less power consumption; chilled water consumption is reduced as less supply air is needed, resulting in energy saving in the chiller; less steam is needed for dehumidification and reheat, therefore natural gas consumption would be less.

7.2.3 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. Parameters which may deviate considerably from the theoretical estimation, such as the hot water loop efficiency, should be determined from reliable experiments. An empirical model can also be derived with repeated experiments on the system and compared with the theoretical model. A data-validated model would generate more accurate results.

On the whole, through the eight-month attachment at Company AFT, we not only strategized and implemented some energy saving measures in the office building and the production facilities, but also developed energy management tools and models to monitor and analyze the HVAC system in the company. These tools and models, albeit being preliminary in the development stage, establish systematic ways to analyze the energy consumption data and provide critical insight into the process and behavior of the HVAC equipment, which could help the energy manager to further find opportunities to achieve higher energy efficiency. In this sense, these methods have long lasting values. In future, the energy management tools and models can be continuously improved and applied to other buildings in the company. If these methods are found to be effective through the site's practices, they can also be shared with AFT's other sites globally to achieve corporate-wise improvement in energy efficiency.

REFERENCES

[1] Barney L. Capehart, Wayne C. Turner and Willian J. Kennedy, *Guide to Energy Management*, fifth edition, The Fairmont Press, Indian, 2006.

[2] *AFT Energy Management Course Materials,* Company AFT, 2008.

[3] *GMP Area Design Standard for Non-Sterile Pharmaceutical Dosage Form Facilities,* Company AFT, 2005.

[4] Lee Siew Eang, "Energy Efficiency of Office Buildings in Singapore, School of Design and Environment", National University of Singapore, 2000.

[5] Energy Sustainability Unit, retrieved from http://www.esu.com.sg

[6] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1993 *ASHRAE Handbook Fundamentals*, SI Edition, 1993.

[7] Bes-Tech, "Phase II – Detailed Assessment Report for Company AFT Singapore," 2007.

[8] *Munters Service Training Package*, Munters, 2009.

[9] E.H. Mathews, C.P. Botha, D.C. Arndt, A. Malan, "HVAC Control Strategies to Enhance Comfort and Minimize Energy Usage", *Energy and Buildings, 33* (2001), 853-863.

[10] Harry Suehrcke, Eric L. Peterson, Neville Selby, "Effect of Roof Solar Reflectance on the Building Heat Gain in a Hot Climate", *Energy and Buildings, 40* (2008), 2224-2235.

[11] Chil-Fang Fang, "Evaluating the Thermal Reduction Effect of Plant Layers on Rooftops, Energy and Buildings", *Energy and Buildings, 40* (2008), 1048-1052.

[12] N.H. Wong, D.K.W. Cheong, H. Yan, J. Soh, C.L. Ong, A. Sia, "The Effects of Rooftop Garden on Energy Consumption of a Commercial Building in Singapore", *Energy and Buildings, 35* (2003), 353-364.

[13] Christina Galitsky, Sheng-chieh Chang, Ernst Worrell, Eric Masanet, "Energy Efficiency Improvement and Cost Saving Opportunities for the Pharmaceutical Industry", Ernest Orlando Lawrence Berkeley National Laboratory, University of California, 2008.

[14] Christina Galitsky, Sheng-chieh Chang, Ernst Worrell, Eric Masanet, "Improving Energy Efficiency in Pharmaceutical Manufacturing Operations – Part II: HVAC, Boilers

and Cogeneration", Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, 2006. Retrieved from http://www.pharmamanufacturing.com/articles/2006/106.htm?page=1 on February 24, 2009.

[15] S.C. Sekhar, L.T. Tan, "Optimization of Cooling Coil Performance During Operation Stages for Improved Humidity Control", *Energy and Buildings, 41* (2009), 229-233.

[16] Nunnally, Brian K. *Six Sigma in the Pharmaceutical Industry: Understanding, Reducing, and Controlling Variation in Pharmaceuticals and Biologics*, CRC Press, 2007.

[17] Li, W., 2009, "Improving Energy Efficiency in a Pharmaceutical Manufacturing Environment – Office Building," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA.

[18] Liu, H., 2009, "Improving Energy Efficiency in a Pharmaceutical Manufacturing Environment – Analysis of EUI and Cooling Load," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA.

APPENDIX A: Standardized Work for Utilities Shutdown Planning

Who	Product Facilitator, Maintenance Eng	
What	Monthly Utility Services Plan	
When	Weekly, every Monday, 1400 hrs to 1415 hrs	
Where	IPT office area	
How	1) Prod Facilitator:	Review and update production plan for current month
	2) Maint Eng:	Review and update utility services start/stop plan for current month
	3) All:	Repeat steps 1 and 2 for next month
	4) Maint Eng:	Update "updated on date" at top right hand corner
	5) Maint Eng:	Save soft copy in I drive - Maint Eng
Who	Maintenance Eng	
What	Weekly Utility Services Plan <PF1, PF2> and <PF3>	
When	Weekly, every Monday, 1415 hrs to 1430 hrs	
Where	IPT office area	
How	1) Maint Eng:	Update two weekly production status for PF1, PF2
	2) Maint Eng:	Update two weekly utility services start/stop plan for PF1, PF2
	3) Maint Eng:	Repeat steps 1 and 2 for PF3
	4) Maint Eng:	Save soft copy in I drive - Maint Eng
	5) Maint Eng:	Print and replace copy in <PF1>, <PF3>, <Engineering Workshop>
Who	Product Facilitator, Maintenance Eng	
What	Weekly Utility Services Plan <PF1, PF2> and <PF3>	
When	Daily, <PF1, PF2> 1000 hrs to 1010 hrs, <PF3> 0900 hrs to 0910 hrs	
Where	Production Planning Board, PF1 White Area Level 2 corridor, PF3 Black Area Corridor	
How	1) Prod Facilitator:	Review and update production status for next 3 days (hardcopy)
	2) Maint Eng:	Review and update utility services start/stop plan for next 3 days (hardcopy)
	3) Maint Eng:	Update soft copy in I drive
	4) Maint Eng:	Print and replace copy in Engineering Workshop

APPENDIX B: Psychrometric Equations Used in the Models

When temperature and RH are known, saturation vapor pressure can be found using

$$\ln(p_{ws}) = C_8 / T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln(T)$$

where

p_{ws}=saturation pressure, kPa

T = absolute temperature, K

$C_8 = -5.8002006E+03$

$C_9 = -5.5162560E+00$

$C_{10} = -4.8640239E-02$

$C_{11} = 4.1764768E-05$

$C_{12} = -1.4452093E-08$

$C_{13} = 6.5459673$

Partial pressure of water vapor is:

$p_w = RH \times p_{ws}$ where p_w = partial pressure of water vapor, kPa

Humidity ratio and saturation humidity ratio are:

$$W = 0.62198\frac{p_w}{p - p_w}$$

$$W_s = 0.62198\frac{p_{ws}}{p - p_{ws}}$$

where

W = humidity ratio, kg moisture/kg dry air

W_s = saturation humidity ratio, kg moisture/kg dry air

p = atmospheric pressure

Dew-point temperature is:

$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0\ 1984}$$

where

t_d = dew point temperature

$\alpha = \ln(p_w)$

$C_{14} = 6.54$

$C_{15} = 14.526$

$C_{16} = 0.7389$

$C_{17} = 0.09486$

$C_{18} = 0.4569$

Specific enthalpy is:

$h = 1.006t+W(2501+1.805t)$

where

h = specific enthalpy of moist air

Specific volume is:

$$v = \frac{R_a T(1+1.6078W)}{p}$$

where

v = specific volume, m^3/kg

R_a = 287.055 J/kg/K

APPENDIX C: Example of the Calculated State of Air

Fresh Air

Parameter	*Value*	*Unit*
t_fsh	29	C
T_fsh	302.15	K
RH_fsh	80%	
Q_fsh	2629	CMH
Pws_fsh	4.008285232	kPa
Pw_fsh	3.206628186	kPa
ln(Pw_fsh)	1.165219976	
v_fsh	0.883969706	CM/kg
m_fsh	2974.083821	
tdp_fsh	25.19502527	
W_fsh	0.020327066	kg moisture/kg dry air
Ws_fsh	0.02561814	kg moisture/kg dry air
xa_fsh	0.9604413	
xw_fsh	0.0395587	
ha_fsh	29.174	kJ/kg
hg_fsh	2553.345	kJ/kg
h_fsh	81.0760118	kJ/kg
hw_fsh	121.651	kJ/kg