DEVELOPMENT OF AN ENERGY MONITORING AND TARGETING METHODOLOGY FOR THE MOST EFFICIENT OPERATION OF CHILLED WATER SYSTEMS

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Engineering
in
Energy Management

at Massey University, Palmerston North, New Zealand

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2008

ABSTRACT

The increasing price of oil and the destabilisation of the world's climate are urging governments, businesses and individuals to constantly investigate energy-efficient technologies and methodologies and pursue the adoption of energy efficiency programmes in a global effort to reduce energy consumption, greenhouse gas emissions and ultimately energy costs.

In New Zealand, one of the biggest industrial energy efficiency projects was started in 2002 by a multinational dairy company, the Fonterra Co-operative Group, in partnership with the energy service company Demand Response Ltd; the project currently aims at reducing by 15% the energy costs at all Fonterra's major production sites throughout the country. This thesis, undertaken as part of the above project, examines the development and implementation of a structured and integrated energy monitoring and targeting methodology (M&T) for the most efficient operation of all Fonterra's chilled water systems, with an initial focus on the ones installed at Clandeboye, one of the Fonterra's sites involved in the energy saving project.

A data collection system (*Insite*) was already in place at Clandeboye to enable storage and analysis of some of the site's utility metering data. After identification of key chilled water system components and definition of data requirements for M&T purposes, an analysis of past energy consumption trends (based on multiple regression calculations) was carried out to develop an historical benchmark of the energy used, compare it with current energy performance and thus identify opportunities for future improvements. The creation of an M&T reporting system for presenting findings to operators and management was the last essential part of the thesis development.

The study has highlighted that the robustness of the proposed regression model was badly affected by the unreliability of the existing data collection system and the uncertainty associated with poorly documented changes to operating conditions/plant configuration that had occurred over time. The conclusion is that, while the developed M&T methodology is theoretically valid and readily applicable, further developments are necessary (and recommended) to make it suitable for other similar systems.

ACKNOWLEDGEMENTS

I wish to thank my thesis supervisors, Prof. Don Cleland, Dr Richard Love and Dr Wyatt Page, for providing me with much needed support and encouragement throughout the development of this project. Their guidance has been invaluable.

I am also pleased to acknowledge the assistance of all Demand Response engineers, who gave me their time and resources to help me understand their work with Fonterra and build my knowledge of their database.

My thanks also go to Christine Lang, the Fonterra Process Technologist at Clandeboye who was my main point of contact on site and an essential source of system information and data.

My sincere gratitude goes to Allan Davidson, my managing director, who not only accommodated flexible working arrangements but also gave me his unconditional support, which translated into the necessary concentration and tranquility to keep working on this project even at times of high workload.

Finally, my hearty thanks go to my husband Dominic, who patiently and understandingly shared his wife with this demanding project and to my parents in Italy, whose constant love and encouragement has given me the strength to persevere and eventually complete this thesis.

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CHAPTER 1 – INTRODUCTION

1.1 Project Background

The promotion of energy efficiency has become an important step in the global effort to reduce greenhouse gases emissions since the Kyoto Protocol came into force in February 2005. Over 130 countries in the world are now officially bound by this international agreement and are continuously investigating new and improved methods to achieve the Protocol's goal of "*reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012*" (Kyoto Protocol, Article 3).

Today, energy efficiency programmes are adopted by an increasing number of businesses and organisations and the world of energy-efficient technologies, methodologies and products is being actively explored to find new opportunities for reducing energy consumption, noxious gases emissions and ultimately energy costs.

In New Zealand, one of the biggest industrial energy efficiency projects was commenced in 2002 by the Fonterra Co-operative Group, a multinational dairy company with an annual turnover of NZ$ 12.3 billion, which represents approximately 10% of New Zealand GDP (Statistics New Zealand, 2005 GDP). The project, which originally aimed at reducing by 10% the energy costs at three of Fonterra's largest sites, has since been expanded to include all Fonterra's major sites and now aims at reducing energy costs by 15%, that is an estimated $21 million savings per year at today's energy prices (J. Miller, 18 August, 2006, personal communication).

Fonterra has embarked on its energy reduction project in partnership with Demand Response Ltd, a New Zealand owned energy service company that has set up a web-based monitoring and utility modeling system, called *Insite*, to collect, store and analyse most of Fonterra's utility metering data, such as production throughput, electricity, steam and water consumption. This database allows the comparison of current and past energy consumption of all monitored processes, provides the basis for an evaluation of current energy performance and helps to identify new opportunities for ongoing improvements. The techniques used to monitor and interpret energy data are based on the principles of a methodology called Energy Monitoring and Targeting (M&T), a conceptually simple yet powerful tool for managing energy using processes in the most energy-efficient way.

Although the origins of M&T are over thirty years old (its early stages of implementation go back to the years following the oil crisis of 1973) very little research has been done so far to apply this technology to energy intensive industrial processes like evaporation and drying, refrigeration, mechanical refining and pumping. This is probably due to the fact that in small and medium size enterprises, which represent the majority of companies in industry, usually the share of energy costs in the total costs is low and companies consider it easier to simply pay for their energy use rather than invest in new, commercially unproven technology. Furthermore, if companies do not have the internal expertise to investigate energy efficient solutions, which has been often the case in the past, they would rather not investigate at all than resort to external consultants, especially if proprietary production processes are involved (Jochem et al., 2004).

For industries with a seasonal cycle, like the dairy industry, the analysis of energy performance information is often complex due to many interacting factors like changing production patterns, time of day, time of season, product mix and ambient condition. Energy use is spread across a number of different and sometimes independent processes that require individual analysis of their correspondent energy data. This makes the overall success of any energy reduction project dependent on many incremental improvements.

Between 5 and 15% of a dairy plant's total electricity consumption is typically used by refrigeration plants to chill water used in various processes. This translates to an estimated 100 GWh of electricity used in chilled water systems over all Fonterra's New Zealand sites (J. Miller, 18 August, 2006, personal communication) and proves how even small percentage changes of the total energy consumption can positively impact the overall energy reduction project.

1.2 Project Objectives

The overall goal of this research project is to develop a well structured and integrated M&T methodology that is applicable to all Fonterra's chilled water systems to continuously improve their energy performance. The research will concentrate in particular on one of the four chilled water systems installed at Clandeboye, near Timaru, which is one of the ten Fonterra sites involved in the energy saving project. It is envisaged that the methodology would also be applicable to other industrial refrigeration systems with minor modifications.

The detailed objectives are summarised below:

- To conduct a literature review on energy M&T techniques to investigate the state of knowledge on the topic with particular regard to chilled water systems' applications.
- To identify the key components of the Clandeboye's system.
- To define data requirements for M&T purposes.
- To develop a benchmark model of the energy used by the chilled water system at issue, using both a top-down approach, based on production data, and a bottom-up approach, based on chilled water equipment.
- To create an M&T status report suitable for reporting results to operators and management.
- To develop a calculation engine to automate the generation of status reports
- To assess the effectiveness of the M&T methodology and the status reports and to update them if necessary.
- To make recommendations on future improvements to the M&T method and on how it could be applied to other similar industrial operations.

CHAPTER 2 – CHILLED WATER SYSTEMS

2.1 Introduction

This chapter provides an overview of chilled water uses, in particular within milk processing facilities, and a brief description of the refrigeration cycle and of refrigeration system components. Then, an introduction to the Clandeboye site and all its chilled water systems will be given, followed by a more detailed description of the chilled water plant selected for this project.

2.2 Chilled water

Reticulated chilled water is commonly used to provide cooling duties in air conditioning systems of commercial buildings and industrial facilities as well as to support many different types of industrial processes, from chemical engineering to food processing plants. Different industrial processes require different operating temperatures but due to the freeze limits, chilled water use is generally restricted to processes that require cooling to temperatures no lower than 4ºC.

In dairy processing plants, be they dedicated to fluid milk production (for direct consumption) or to industrial milk processing (for production of cheese or butter, milk powder or other value added by-products), chilled water is used as the heat absorbent medium for rapid milk cooling from the very early stages of the processing chain. When milk is received at the plant and before it undergoes any other treatment, it is usually cooled to a low temperature (5ºC or lower) to prevent the growth of micro-organisms. After the pasteurisation process, which consists in heating the milk to a specific temperature for a specified period of time (generally to 72-75ºC for 15-20 seconds) to destroy harmful bacteria, milk is also cooled again (to about 4ºC) to prevent serious quality deterioration (Bylund, 2003).

Chilled water is also used in other major dairy process sequences (ultrafiltration (UF), deodorisation or cooling of silos) for the production of fluid milk, cheese, ice creams and other frozen products, cultured products, butter and evaporated/dried products (National Dairy Council of Canada, 1997).

The cooling of process water occurs in dedicated heat exchangers where it comes into contact with a cooling medium (refrigerant) that vaporises and absorbs heat from the water, cooling it down to its required temperature. From the heat exchanger, chilled water is then sent to its end users via the distribution system.

2.3 The Mechanical Vapor-Compression Refrigeration Cycle

The refrigerant used to cool the water is circulated in a closed-loop system and made undergo a cyclic change of pressure (from high to low) that causes it to change its phase accordingly from vapour to liquid and vice versa. This cycle enables heat absorption from and heat rejection to other mediums.

Figure 2.1 (p.6) shows a typical vapour-compression refrigeration system schematic consisting of its four components: evaporator, compressor, condenser and expansion valve. The evaporator is where the useful chilling of the external medium (either water or air) takes place. The liquid refrigerant enters the evaporator and comes in contact with the process water (or air, in some applications) from which it absorbs the heat required to make it fully evaporate. After the evaporator, the refrigerant is pressurised by the compressor to the highest pressure in the cycle and is sent to the condenser. Here, it becomes liquid again and releases its latent heat of condensation to another external cooling medium (again, either air or water). Once out of the condenser, the liquid refrigerant is passed through an expansion device that lowers its pressure to its initial value (the lowest pressure in the cycle) and makes it ready to re-enter the evaporator for another heat removal cycle.

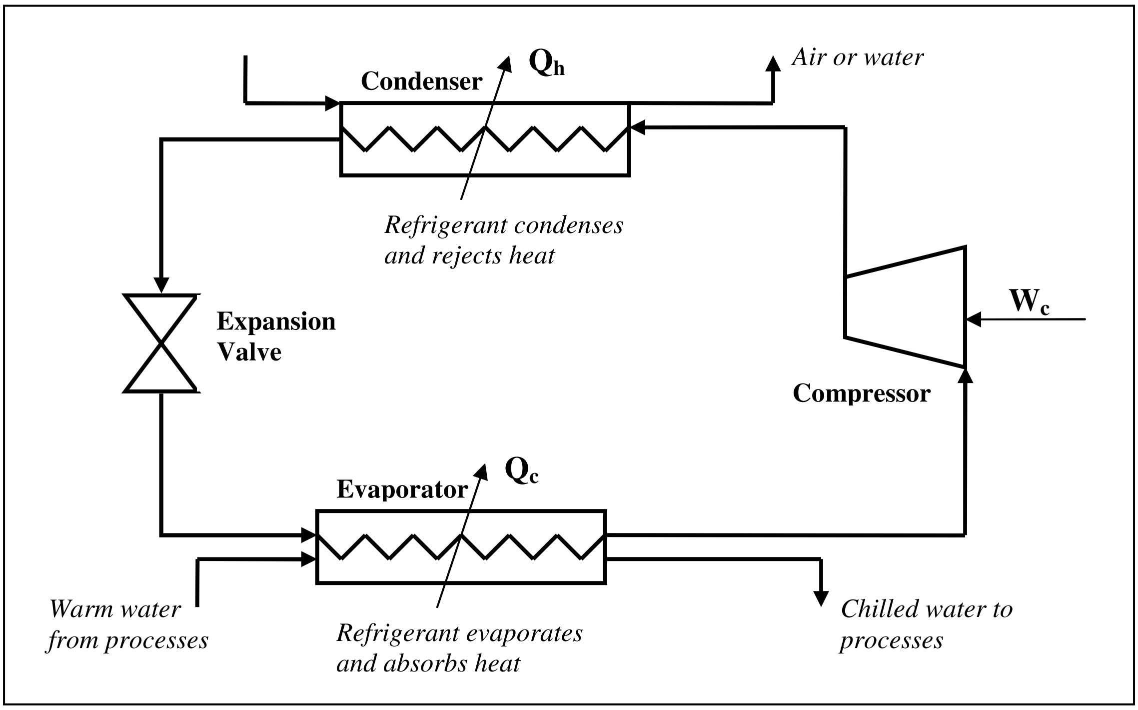


Figure 2.1: Schematic of a vapour-compression refrigeration system

The described theoretical processes can be graphed, for each refrigerant, on a pressure-enthalpy chart, called Mollier diagram, as shown in figure 2.2 (p.7). The area enclosed by the curve, the saturation envelope, represents the refrigerant during its phase change from liquid (left side of the curve) to vapour (right side of the curve). The points outside the curve to the left define the liquid refrigerant state while those to the right define the superheated vapor refrigerant state. Lines of constant temperature are horizontal within the saturation envelope (most pure compound refrigerants change phase at constant temperature for a particular pressure) and almost vertical to the left of it (heating the liquid has little effect on its pressure). To the right of the saturation envelope, as the gas is compressible, the isotherms follow more complex relationships.

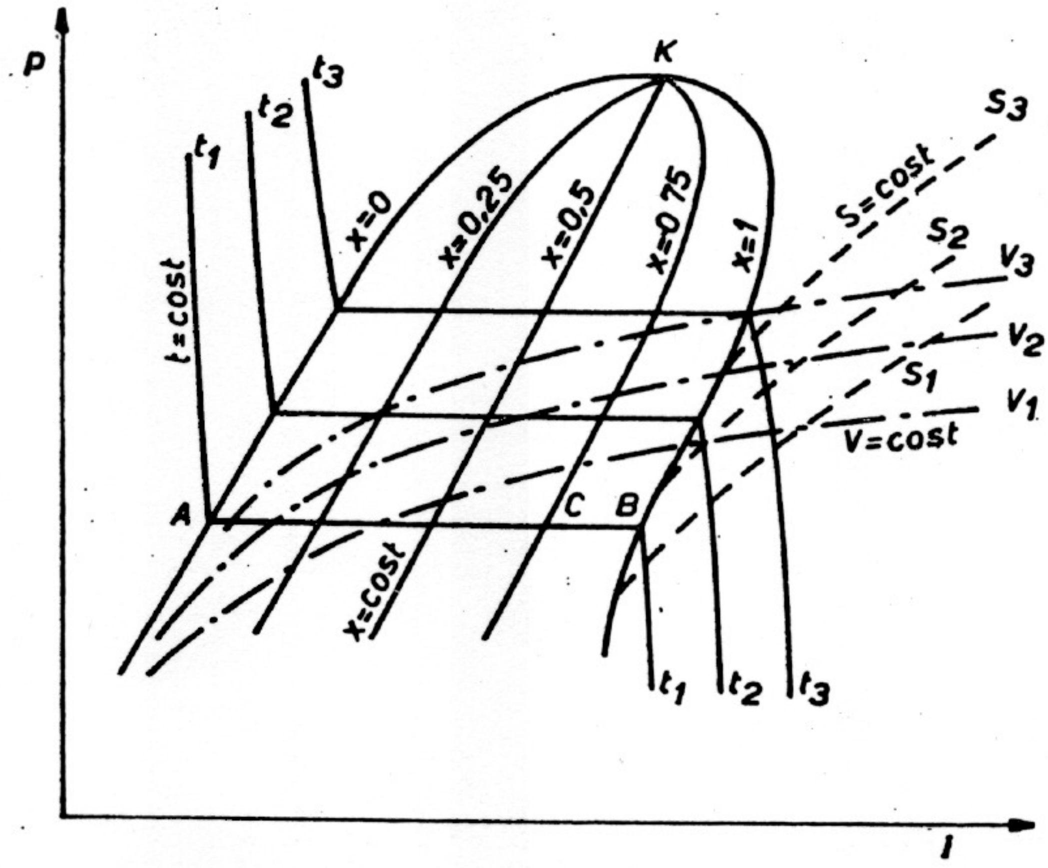


Figure 2.2: Example of a Mollier diagram (source: Pizzetti, 1980)

Figure 2.3 (p.8) shows an ideal refrigeration cycle represented on a pressure-enthalpy chart. The process line 1-2 represents the evaporation of the liquid refrigerant, which occurs at almost constant pressure. In refrigeration applications, this process represents the useful part of the cycle. It is important that no liquid enters the compressor, so usually the refrigerant exits the evaporator slightly superheated (the amount of superheat is controlled by the expansion valve that regulates the refrigerant flow) and in reaching the compressor, its pressure slightly decreases due to pipe friction in the suction line. Therefore, in real systems, point 2 in figure 2.3 (p.8) slopes slightly downwards in the superheated vapour region.

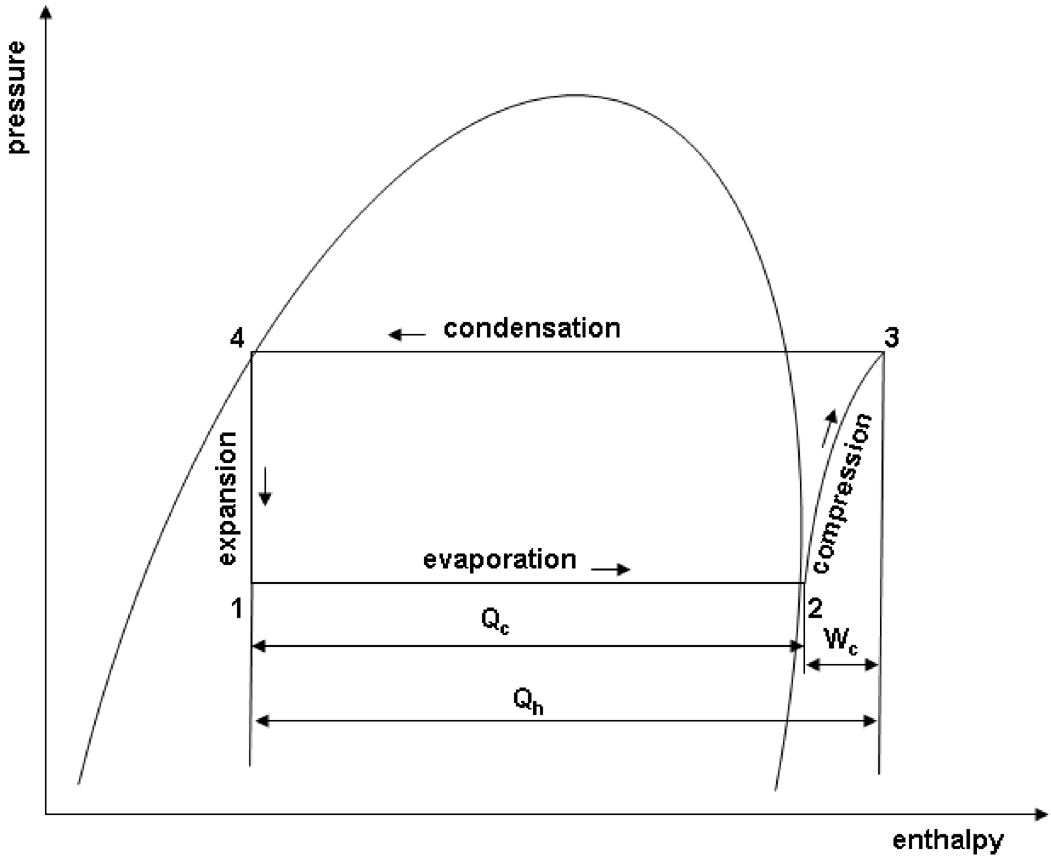


Figure 2.3: Ideal refrigeration cycle on a pressure-enthalpy chart

The total cooling achieved Q_c is given by the increase in refrigerant enthalpy between points 2 and 1:

$$\mathbf{Q_c = h_2 - h_1} \qquad \textit{(2.1)}$$

where:

Q_c= cooling achieved per unit mass of refrigerant [J/kg];

h = enthalpy of refrigerant per unit mass [J/kg].

The line 2-3 represents the compression stage that increases the refrigerant pressure from that of the dry saturated (or slightly superheated) vapor to that of the superheated vapor at the condensing temperature. The ideal compression process follows an isentropic line and the work required by the compressor W_c is given by:

$$\mathbf{W_c = h_3 - h_2} \qquad \textit{(2.2)}$$

where:
W_c= ideal compressor work per unit mass of refrigerant [J/kg];
h = enthalpy of refrigerant per unit mass [J/kg].

Real systems though are not so efficient and therefore a greater work of compression than what the ideal diagram indicates is needed. The compressor isentropic efficiency summarises all the inefficiencies (mechanical, electrical and volumetric) of a real system so that the actual compressor energy requirement, $\mathbf{W_{c,\,act}}$ can be expressed as:

$$\mathbf{W_{c,\,act} = W_c / \eta_i} \qquad \textit{(2.3)}$$

where:
η_i= compressor isentropic efficiency.

The condensation stage is represented by the pressure-constant line 3-4. The superheated vapor refrigerant enters the condenser over which colder air or water is circulated. The refrigerant rejects heat to the colder medium and changes its phase becoming liquid again. The heat rejected at the condenser Q_h is given by:

$$\mathbf{Q_h = h_3 - h_4} \qquad \textit{(2.4)}$$

where:
Q_h= rejected heat per unit mass of refrigerant [J/kg];
h = enthalpy of refrigerant per unit mass [J/kg].

At the exit of the condenser (point 4), the refrigerant, now totally liquid, passes to a liquid receiver (storage vessel). In real systems, the flow through the condenser is not friction-free, nor is the passage from the condenser to the storage vessel and therefore the line 3-4 ends with a slight downward slope in the liquid region, past point 4.

The line 4-1 represents the expansion process occurring in the metering device, which occurs at constant enthalpy. In case of natural circulation systems, this device is a simple expansion valve, which regulates the liquid refrigerant flow entering the evaporator in order to maintain the correct pressure and superheat in the evaporator. From the storage vessel that receives the liquid at the end of the condenser, the refrigerant passes through the expansion valve and undergoes an abrupt decrease of pressure, which results in the adiabatic flash evaporation of part of the saturated liquid and in the reduction of its temperature to the saturation value corresponding to the new pressure. Then, both the vapour and the residual liquid enter the coil or tubes of the evaporator, ready to start a new cycle.

2.3.1 Performance of a Refrigeration Cycle

The ratio of the amount of cooling provided to the energy consumed by the system is called the Coefficient of Performance (COP) and is expressed as:

$$\mathbf{COP = Q_c / W_{c,\,act}} \qquad \textit{(2.5)}$$

The COP is a useful way of comparing different refrigeration systems or evaluating the effect of changes to a refrigeration system. For the same cooling effect $\mathbf{Q_c}$, the smaller the energy input required at the compressor ($\mathbf{W_{c,act}}$) the bigger the COP. Vice versa, for the same energy input $\mathbf{W_{c,act}}$ the bigger the effective refrigerating capacity ($\mathbf{Q_c}$) the bigger the COP.

The compressor energy requirement $\mathbf{W_{c,act}}$ depends on the pressure ratio chosen for the cycle: acting on the evaporation and condensation temperatures (and pressures), for example by increasing the former or decreasing the latter whenever the process allows, has a positive effect on the efficiency of the system as it reduces the energy requirement.

An increase in the refrigerating capacity $\mathbf{Q_c}$ can be obtained by means of an economiser, which is a heat exchanger located between the condenser and the evaporator (figure 2.4, p.11).

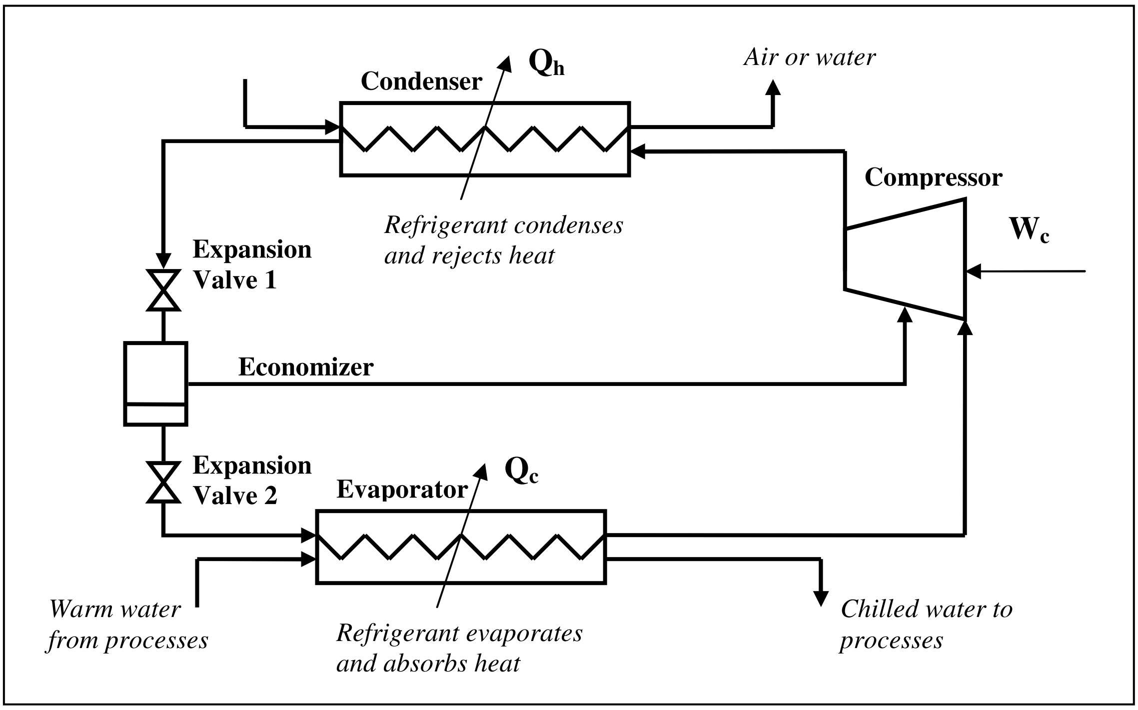


Figure 2.4: Schematic of an economised refrigeration system

The high pressure liquid refrigerant coming from the condenser goes through a first expansion valve into the economiser at an intermediate pressure between condensation and evaporation pressure. The refrigerant vapour generated from this first expansion enters the compressor through a secondary port (economiser port) between the primary compressor suction and discharge ports. The balance liquid in the economiser, subcooled to the saturation temperature corresponding to the intermediate pressure, is throttled through a second expansion valve, enters the evaporator and is then sucked into the compressor through its primary suction port.

Figure 2.5 (p.12) shows the theoretical economised cycle on the pressure-enthalpy chart. It shows how the subcooled refrigerant passing through the evaporator has increased its refrigeration capacity (per kilogram of refrigerant) from Q_c to $Q_{c,\,econ}$. The compressor energy requirement is also slightly bigger, however the percentage increase in power input is lower than the percentage capacity increase, hence the improved efficiency.

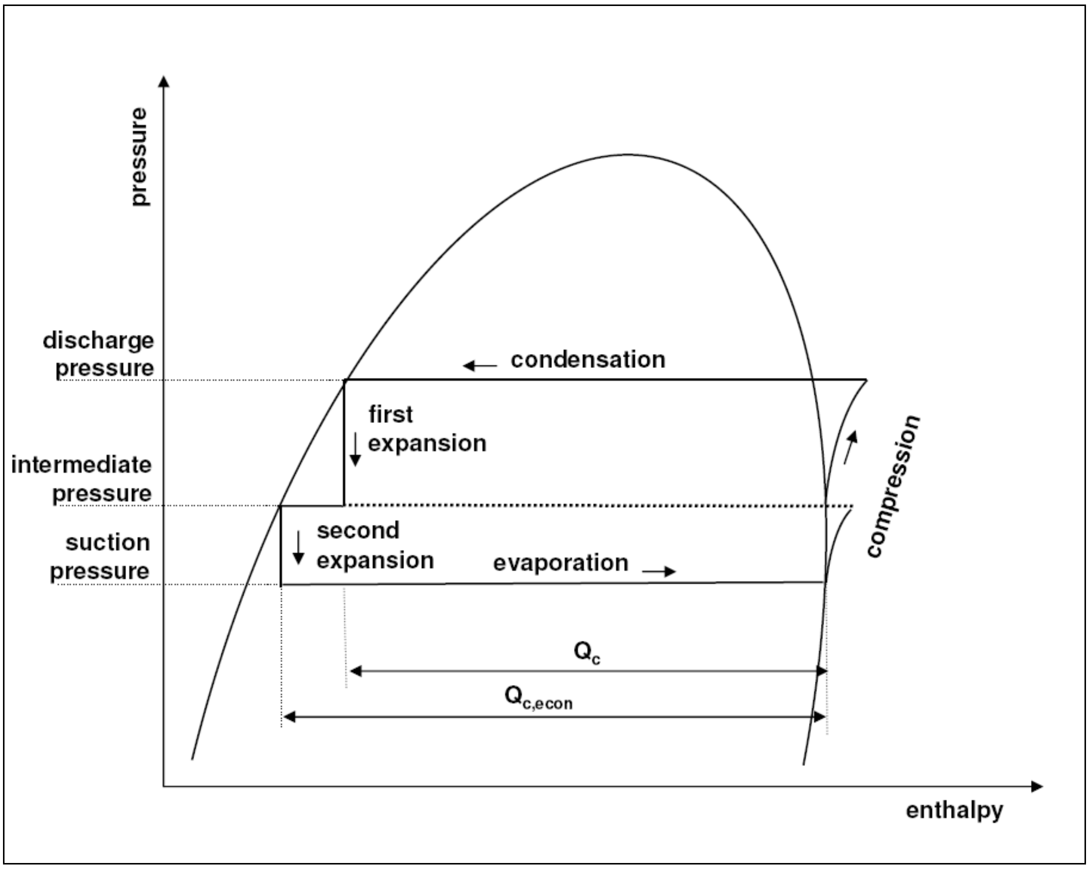


Figure 2.5: Theoretical economised cycle

2.4 Refrigeration System Components

As seen in the previous sections, a vapour compression refrigeration system consists of four main mechanical parts linked together in a closed loop: the compressor, the condenser, the expansion device and the evaporator. There is also often a storage vessel that receives the liquid at the exit of the condenser and passes it to the expansion valve. A number of ancillaries complete the system, such as circulating pumps, valves, motors and motor controls.

2.4.1 Compressors

Compressors can be classified according to different characteristics such as the method used to increase the refrigerant vapour pressure (positive displacement or dynamic compressors), the number of compression stages (single or multi-stage compressors), the type of motor that drives them (mechanical or electrical) and the corresponding capacity control (single or variable speed), the type of enclosure that contains them (open, hermetic or semi-hermetic), the cooling method (air, water or oil) and the lubrication used (oil or oil-free, i.e. no contact between the oil and the gas). The two main categories of compressors though are *positive displacement* and *dynamic*.

2.4.1.1 Positive Displacement Compressors

Positive displacement compressors increase the pressure of the gas by reducing its volume. This can be achieved by means of pistons that move up and down within cylinders (*reciprocating compressors*) or by using two or more rotors that rotate within a casing (*rotary compressors*).

Figure 2.6 below illustrates the basic structure of a typical *reciprocating compressor* piston.

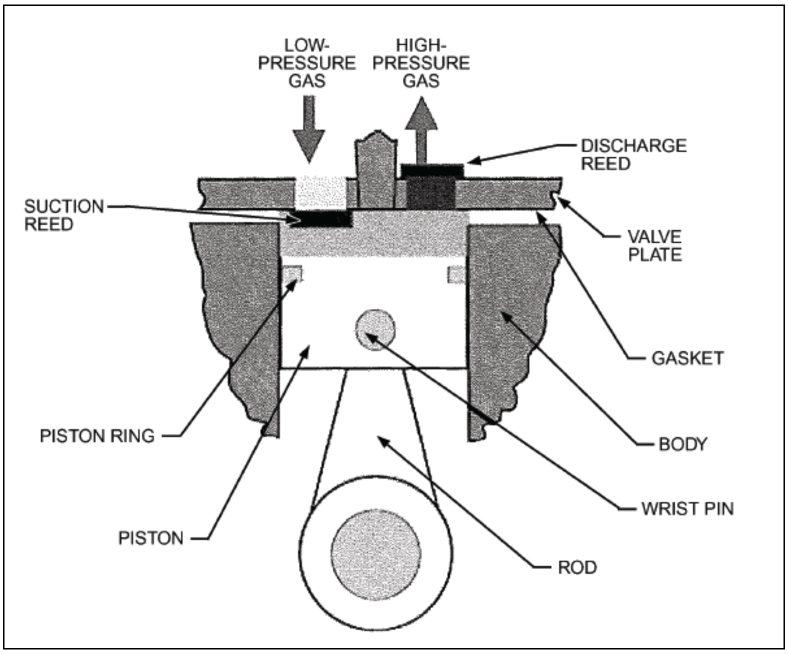


Figure 2.6: Basic reciprocating piston (source: ASHRAE Handbook, 2008)

The main sequential stages of a reciprocating compressor's pumping cycle (suction, compression and discharge) can be represented on a pressure-volume diagram as shown in figure 2.7 (p.14).

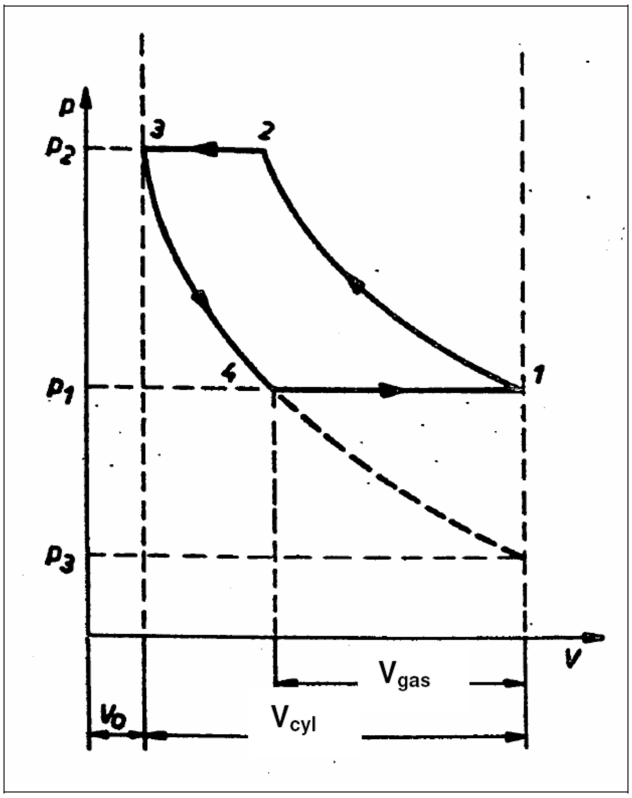
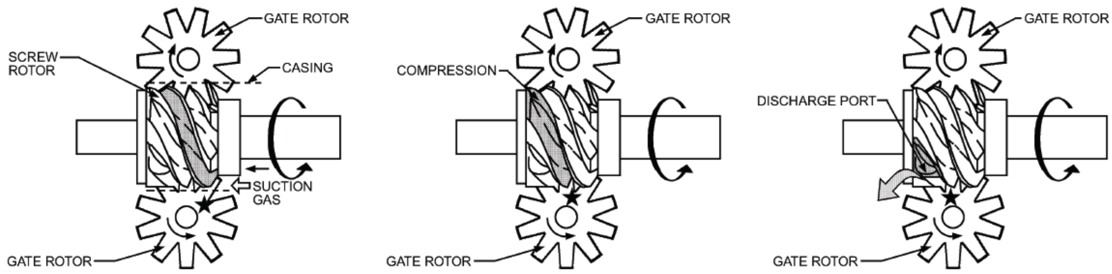


Figure 2.7: Reciprocating compressor cycle on a pressure-volume diagram (adapted from Pizzetti, 1980)

The line 1-2 on the diagram represents the compression stage occurring during the piston upstroke; both the suction and the discharge reeds are closed and the pressure increases from the suction value p_1 to the discharge value p_2. At this point, the discharge reed opens and the gas is discharged to the condenser (line 2-3) until the piston reaches the end of its upstroke (point 3); here, a small volume of high pressure gas remains in the clearance space between the valve plate and the piston top (V_o). This "clearance gas", being at higher pressure than the suction gas, prevents the suction valve from opening as soon as the piston starts its suction stroke (line 3-4). The suction reed can only open once all the clearance gas has expanded enough to reach the lower pressure value p_1, which happens when the piston has moved to some extent on its suction stroke (point 4). The line 4-1 represents the suction of the gas coming from the evaporator. It is apparent how the volume occupied by the clearance gas limits the volume of suction gas that can enter the cylinder during the suction stage to a value (V_{gas}) that is necessarily lower than the total cylinder volume (V_{cyl}). The ratio V_{gas}/V_{cyl} is the compressor's volumetric efficiency and depends upon the clearance volume and the pressure ratio p_2/p_1 (it decreases as the pressure ratio increases).

Rotary compressors include *fixed-vane compressors*, which are normally used in household refrigerators and air-conditioning units in sizes up to 2 kW, *rotary-vane compressors*, more suitable for transport applications, and *screw compressors*, which are the ones commonly used for refrigeration and air conditioning applications.

Screw compressors can, in turn, be of two different types: *single-screw compressors*, consisting of a single cylindrical main rotor that works with one or two gate rotors, and *twin-screw compressors*, consisting of two mating helically grooved rotors that rotate in a fixed casing. Figures 2.8 below and 2.9 (p.16) show the compression process sequence for a single-screw and a twin-screw compressor respectively.



Suction. During rotation of the main rotor, a typical groove in open communication with the suction chamber gradually fills with suction gas. The tooth of the gate rotor in mesh with the groove acts as an aspirating piston.

Compression. As the main rotor turns, the groove engages a tooth on the gate rotor and is covered simultaneously by the cylindrical main rotor casing. The gas is trapped in the space formed by the three sides of the groove, the casing, and the gate rotor tooth. As rotation continues, the groove volume decreases and compression occurs.

Discharge. At the geometrically fixed point where the leading edge of the groove and the edge of the discharge port coincide, compression ceases, and the gas discharges into the delivery line until the groove volume has been reduced to zero.

Figure 2.8: Sequence of compression process in single-screw compressor (source: ASHRAE Handbook, 2008)

Both single and twin screw compressors are available with a secondary suction port between the primary compressor suction and discharge ports, which can be used with an economiser to increase the compressor capacity efficiency.

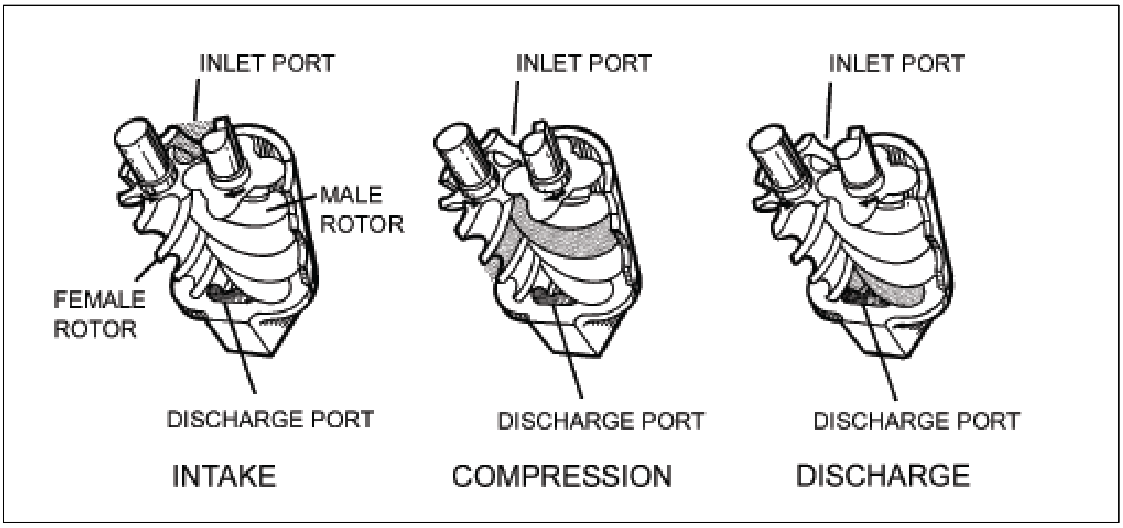


Figure 2.9: Twin-screw compression process (source: ASHRAE Handbook, 2008)

2.4.1.2 Dynamic Compressors

Dynamic compressors increase the refrigerant vapour pressure by transferring energy from a rotating impeller to the gas. Centrifugal compressors belong to this category (figure 2.10, p.17). The refrigerant flows axially through the rotor and is discharged radially from the rotor blades at high velocity. This causes a transfer of kinetic energy (dynamic pressure) to the gas, which is then converted to an increase in static pressure by slowing the flow through a radial diffuser and volute outboard of the impeller. The energy transfer between the rotor and the refrigerant is given by (ASHRAE Handbook, 2008):

$$\mathbf{W_i = u_i \times c_u} \qquad \textit{(2.6)}$$

where:

W_i = impeller work input per unit mass of refrigerant [J/kg];

u_i = impeller blade tip speed [m/s];

c_u = tangential component of refrigerant velocity leaving the impeller blades [m/s].

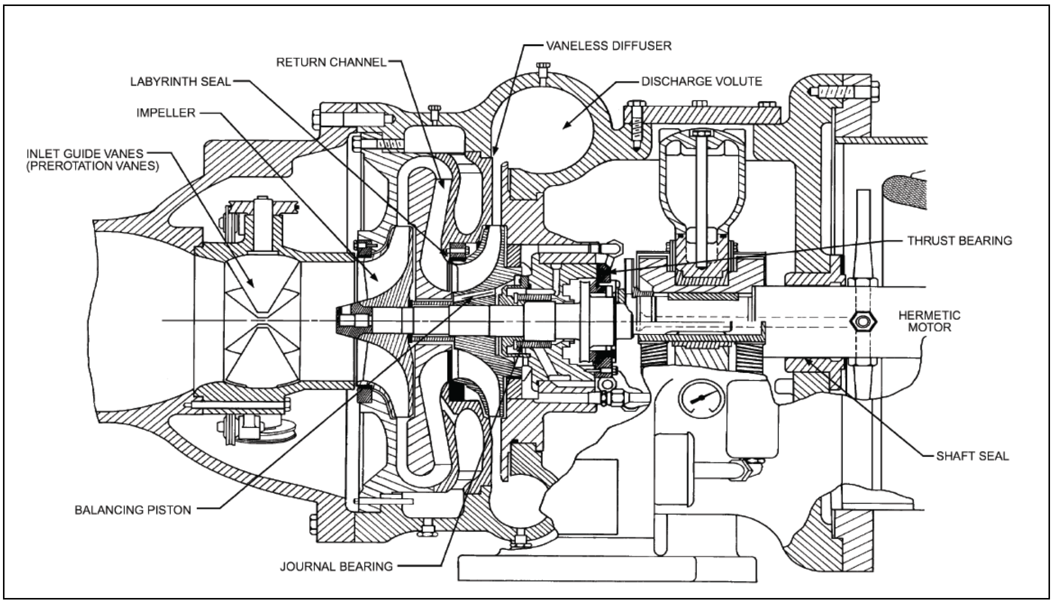


Figure 2.10: Cross section of a centrifugal compressor (source: ASHRAE Handbook, 2008)

Figure 2.11 below shows a diagram of the impeller exit velocities, where *b* is the relative velocity and *c* the absolute velocity

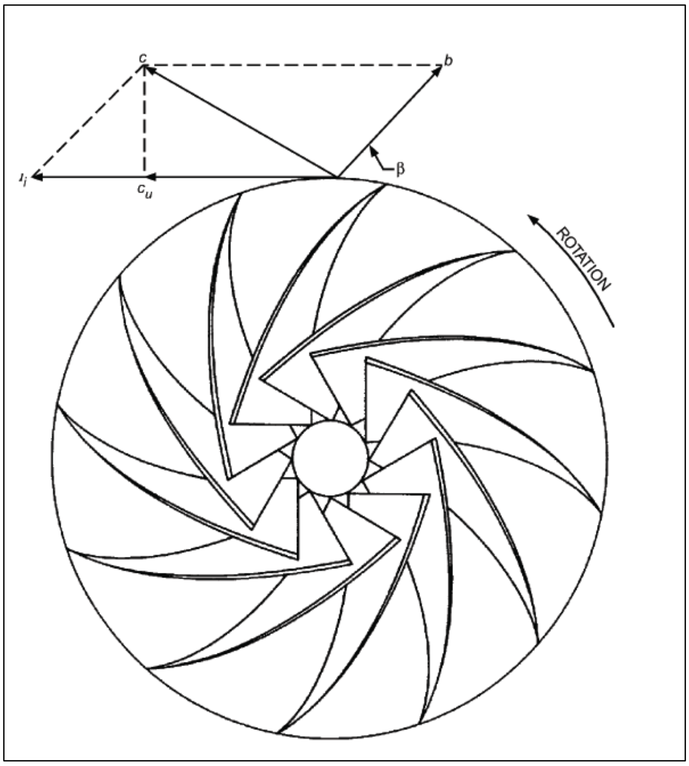


Figure 2.11: Impeller exit velocity diagram (source: ASHRAE Handbook, 2008)

Centrifugal compressors have generally higher capacities than positive displacement machines and have less wear and vibration due to the absence of rubbing parts. They are widely used in the refrigeration and air-conditioning industry. High pressure ratios can be achieved by using multiple stages with two or more impellers mounted on the same casing (process refrigeration can have as many as 10 stages).

2.4.2 Condensers

Condensers are heat exchangers whose function is to reject the heat absorbed by the refrigerant during the evaporation (plus the small amount gained during the compression process due to the compressor's power input) by means of a cooling medium (either air or water). According to the type of cooling medium used, condensers can be classified as *air-cooled, water-cooled* or *evaporative condensers.*

2.4.2.1 Air-Cooled Condensers

Air-cooled condensers are commonly used in small refrigeration plants or in residential air conditioning systems, which use ambient air to cool the refrigerant. In small units the air circulation can be achieved by gravity while bigger condensers have one or more motor-driven fans. There are three main construction styles for these types of condensers: *plate-and-fin*, constituted of copper, steel or aluminum round-profile tubes with fins attached perpendicularly to the exterior; *integral-fin*, made of either copper or aluminum coils with fins obtained by extrusion of the tubes; and *micro-channel*, made of small, all-aluminum, flattened tubes arranged into serpentines with zigzag fins nested between the tubing runs (these are mostly used where lightness and compactness are essential, like in automotive and aviation applications).

2.4.2.2 Water-Cooled Condensers

The most common type of water cooled condenser is the s*hell and tube condenser,* where the colder water flows through a loop of pipe externally touched by the condensing refrigerant and the whole circuit of water and gas is enclosed within a cylindrical shell (figure 2.12, p.19, shows a typical U-tube design).

The heat rejection rate is expressed by:

$$q = U \times A \times \Delta T_m \qquad (2.7)$$

where:

q = total heat transfer rate [W];

U = overall heat transfer coefficient [W/m^2 K];

A = heat transfer surface area associated with U [m^2];

ΔT_m = log mean temperature difference [K].

The volumetric flow rate of condensing water required is given by:

$$Q = q / (\rho \times c_p \times (t_2 - t_1) \qquad (2.8)$$

where:

Q = volumetric flow rate of water [m^3/s];

q = heat rejection rate [kW];

ρ = density of water [kg/m^3];

t_1 = temperature of water entering the condenser [^{o}C];

t_2 = temperature of water leaving the condenser [^{o}C];

c_p = specific heat of water at constant pressure [kJ/(kg K)].

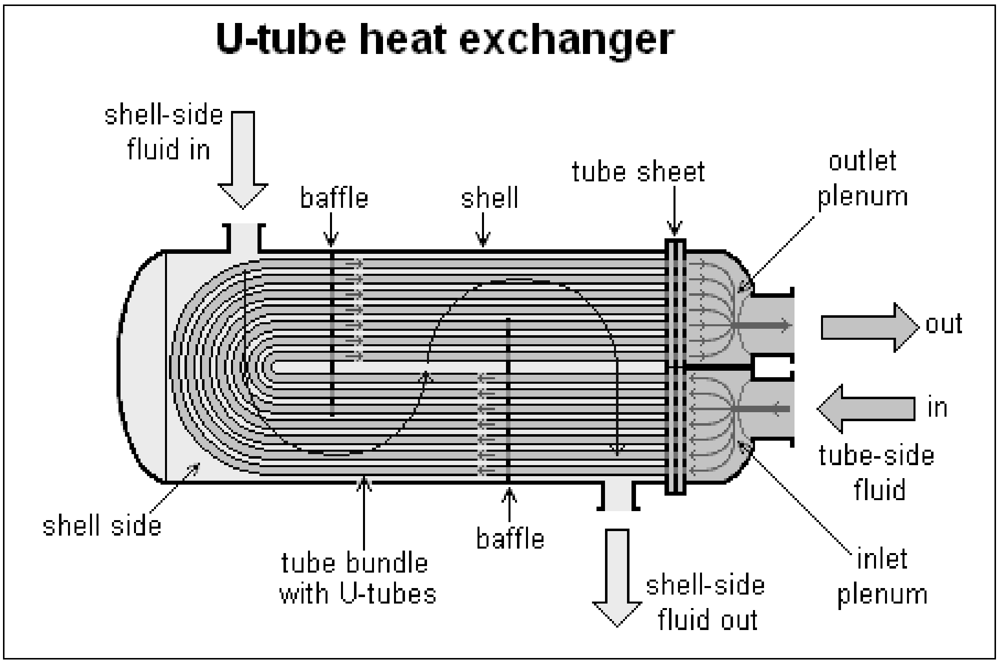


Figure 2.12: Shell and tube heat exchanger, U-tube design (source: www.wikipedia.org)

Very rarely is the cooling water flowing through an open circuit as this would require the availability of great amounts of cold water at constant temperature, such as that provided by a river or the sea. More commonly instead, the cooling water circulates in closed loops and, after absorbing the heat rejected by the refrigerant, is sent to *cooling towers.* Here, the cooling is achieved by sprinkling the water through an air current induced by fans so that while a little amount of the water (usually less than 1%) evaporates due to its contact with the ambient air, the rest of it cools down because of the latent heat of vaporisation that it has provided. The use of cooling towers reduces the condenser cooling water requirement to the amount necessary to compensate for the small evaporation losses.

Theoretically, the minimum temperature which the condensing water can be cooled down to is the ambient wet bulb temperature, which defines the content of water vapour in the air and therefore its level of saturation. Practically though, to avoid over sizing the cooling towers, they are designed so that the temperature of the condensing water leaving them is 4 or 5 ^{o}C higher than the ambient wet bulb temperature.

It is important to check the performance of the refrigeration system in cases of ambient humidity higher than the design value as this would cause a temperature increase in the condensing water leaving the towers which can, in turn, cause a compressor motor overload.

2.4.2.3 Evaporative Condensers

Evaporative condensers combine in a single piece of equipment the functions of both a water cooled condenser and a cooling tower. The refrigerant circulates through the condensing coil in the heat exchanger while re-circulated water is directly sprinkled through nozzles onto the outside of the pipes (figure 2.13, p.21). At the same time, air is blown over the coil causing the evaporation of a small portion of water and hence the cooling and condensation of the refrigerant.

Advantages of an evaporative condenser are that they are more compact than the other two types (for the same capacity, an air-cooled condenser requires more coil surface and higher airflows) and can operate at lower condensing temperatures than both an air-cooled condenser and a water-cooled one combined with cooling towers. In an air-cooled condenser heat rejection is limited by the ambient dry bulb temperature (normally a few degrees higher than the wet bulb temperature) while in water-cooled/cooling tower condensers the heat and mass transfers between the mediums take place in two separate pieces of equipment, thus causing more sensible heating of the cooling water during the processes.

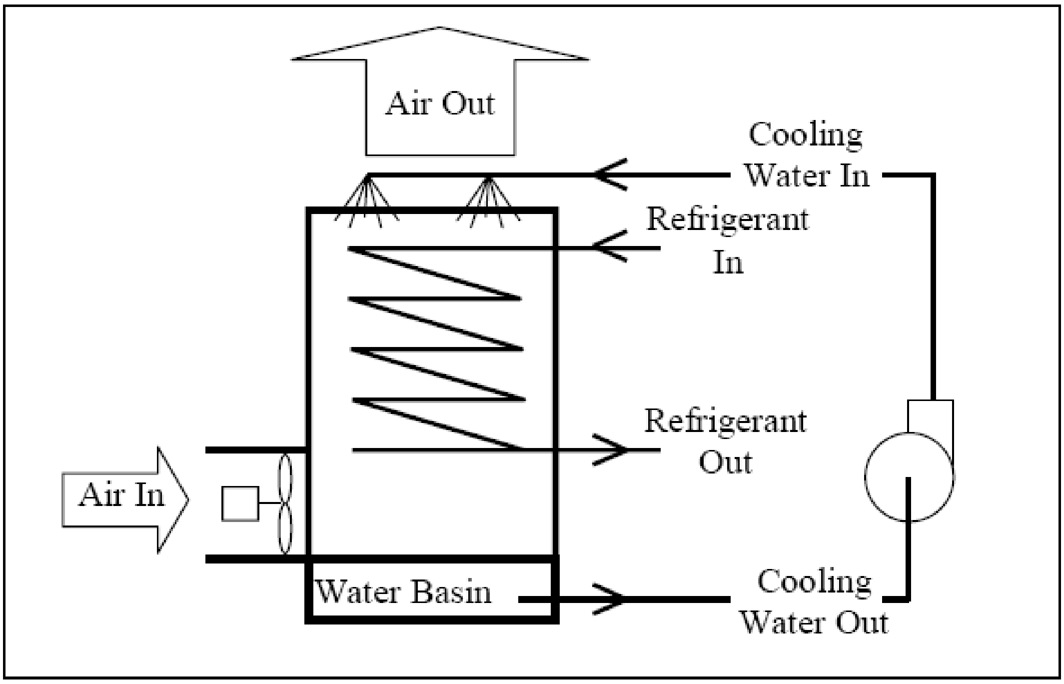


Figure 2.13: Schematic representation of an evaporative condenser (source: Manske et al., 2001)

2.4.3 Expansion Devices

The purpose of these devices is to reduce the pressure from the condensing to the evaporating value and to modulate the flow of liquid refrigerant that goes into the evaporator.

There are three main types of expansion valves used in commercial and industrial refrigeration: *thermostatic expansion valves, high pressure float valves and low pressure float valves.*

The thermostatic expansion valve, shown in figure 2.14 below, senses the changes of refrigerant temperature (due to changes in the load) at the exit of the evaporator and adjusts the flow of refrigerant by a needle and diaphragm arrangement so that in any load condition the refrigerant leaves the evaporator slightly superheated and no liquid reaches the compressor.

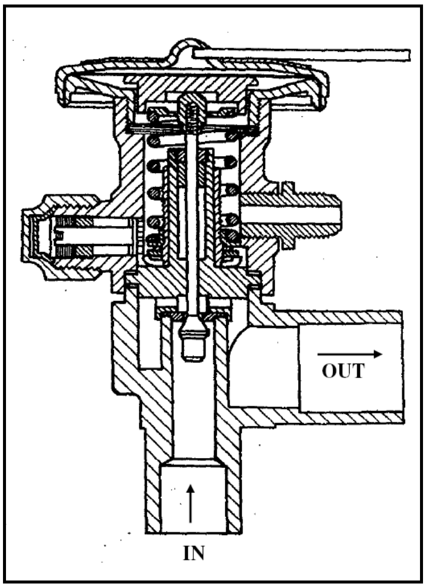


Figure 2.14: Thermostatic expansion valve (source: Pizzetti, 1980)

The high and low pressure float valves (used at the receiver and at the evaporator pressure respectively) use a float chamber to maintain a liquid level and a separate modulating expansion valve connected by a pilot line (figure 2.15 below).

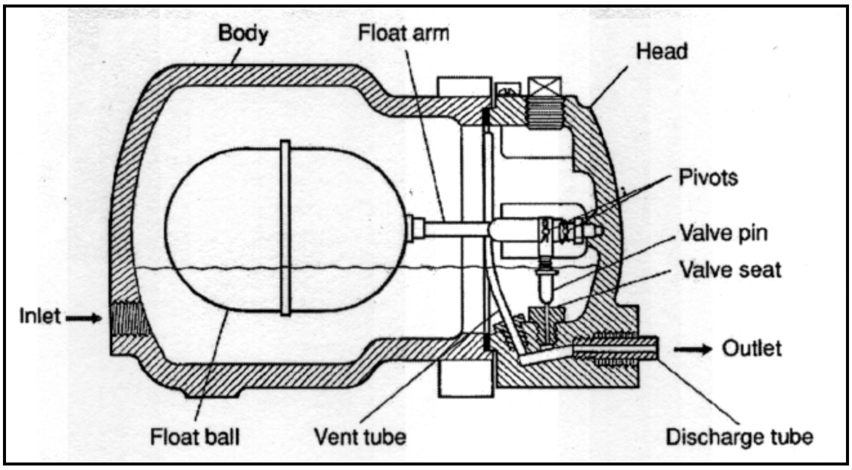


Figure 2.15: High pressure float valve (source: The 3EStrategy, Guide Book4)

2.4.4 Evaporators

Evaporators are heat exchangers in which the liquid refrigerant is evaporated for the purpose of removing heat from the refrigerated space (air) or product (water). They can be classified according to type of construction, type of application, method of refrigerant feed (i.e. type of expansion device used), method of air (or liquid) circulation etc.

If the refrigerant removes heat directly from the air (small air conditioning systems), the evaporator is of a "*direct-expansion*" type and consists of copper tubes (either plain or finned) through which the air is circulated. Figure 2.16 below shows a schematic of this type of evaporators, which are generally fed by one or more thermostatic expansion valves.

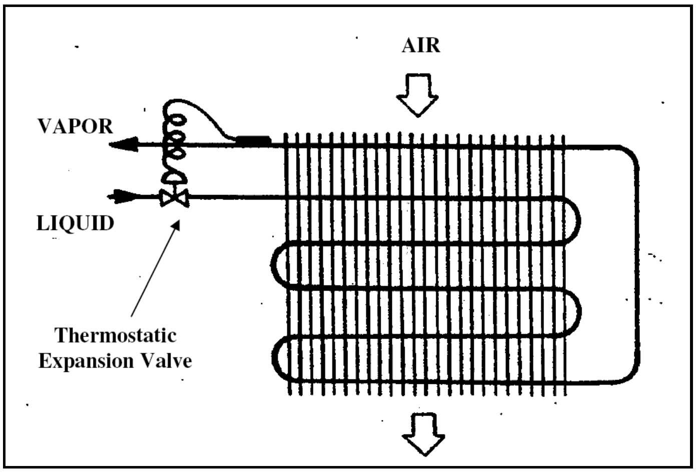


Figure 2.16: Schematic of direct expansion evaporator (source: Pizzetti, 1980)

The other two main types of construction, commonly used in refrigeration applications, are the *shell-and tube* type (figure 2.12, p.19) and the *plate heat exchangers* (figure 2.17, p.24), consisting of pairs of metal plates arranged to provide separate flow paths for two fluids and mounted in series (gasketed, welded or brazed) on a frame.

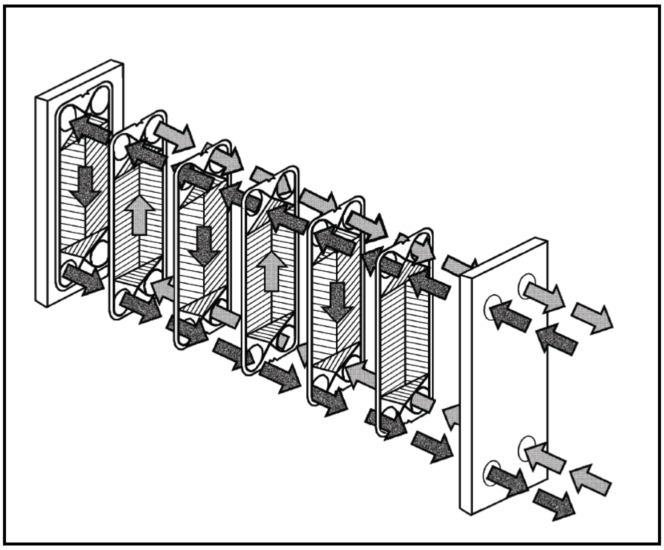


Figure 2.17: Welded plate heat exchanger showing separate flow paths (source: ASHRAE Handbook, 2008)

The type of expansion device used in the system is another common way of classifying the evaporators: these can be *dry-expansion evaporators*, when used with thermostatic expansion valves or *flooded evaporators*, when used with float valves.

In a *dry expansion evaporator* the two-phase refrigerant entering the heat exchanger downstream of the thermostatic expansion valve leaves the evaporator tubes as a superheated vapour. Control of the refrigeration load is achieved by controlling the refrigerant load through the expansion valve.

One of the major disadvantages of this type of evaporators is that some refrigerant inevitably vaporises when passing through the expansion valve and therefore there is a certain amount of vapour that flows through the evaporator's tubes without contributing to useful cooling.

In *flooded systems* the liquid and vapour refrigerant are separated in a surge pot so that only liquid refrigerant enters the evaporator while the vapour part is sent to the compressor directly. The refrigerant level is maintained by a float valve. A schematic is shown in figure 2.18 (p.25).

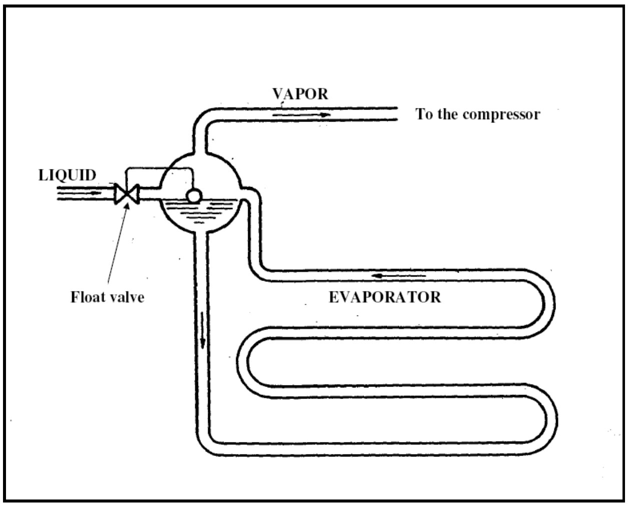


Figure 2.18: Schematic of flooded evaporator (source: Pizzetti, 1980)

These systems are usually of the *shell-and-tube* type where the fluid to be cooled is passed through the tubes while the whole body of the shell is completely filled with liquid refrigerant that evaporates at contact.

2.5 Clandeboye's Chilled Water Systems

A number of chilled water systems are installed on the Clandeboye site. These are (Demand Response engineers, personal communication):

1. The powder chilled water plant, which supplies chilled water to powder plants numbers 1&2, the cheese factory, the ultrafiltration process in the Whey Protein Concentrate plant (WPC UF3) and the butter factory deodoriser.
2. The WPC chilled water plant.
3. The milk reception chilled water system, which was originally used to cool milk supplied to the cheese factory from the raw milk silos but is not currently in use.
4. The butter factory blast freezer glycol/water chiller plant.
5. The butter factory cream crystallising chilled water system.

Recent changes made to this system include the modification of the chilled water piping so that all the chilled water demand for the WPC plant (including that for the UF3 process) would be supplied by a dedicated chilled water system (WPC chilled water system). Then, in 2004, a new plant was built to meet the increasing demand of milk powder (Drier 3 plant). Therefore, at the time this project was carried out, only four main chilled water systems were actually installed on site. They are:

1. Powder chilled water plant
2. WPC chilled water plant
3. Drier3 chilled water plant
4. Butter factory blast freezer glycol/water chiller plant

Of all the above systems, the one supplying chilled water to the powder plant seemed from the very early stages the only system for which a relatively complete data set was readily available on Demand Response's database, *Insite*. For instance, data related to the WPC plant was only limited to a few product flows and did not include any chilled water data. The same lack of data was observed for the Drier 3 chilled water system and besides, because the plant was not yet operating at full capacity, any available data would have been unsuitable to represent typical working conditions anyway. As data availability was an essential condition to initiate all future energy analyses, it was agreed to concentrate the study on the chilled water system dedicated to the powder plants. While the choice was somewhat forced by circumstances, it was nevertheless the best possible one to study for energy saving opportunities. This was because the powder system was the most significant of all in terms of chilled water demand, with an estimated cooling load of 7,000 kW (for the 2004/2005 season) versus an estimated 3,000 kW of the WPC plant (Demand Response engineers, personal communication).

2.5.1 Powder Chilled Water Plant

2.5.1.1 Powder Plant Chillers

Figure 2.19 (p.27) shows a schematic of the powder chilled water system. It consists of four chillers providing chilled water to a supply tank, which is then reticulated to site according to requirements. Water returning from site is converged into another buffer tank before it goes through the chillers again. The four chillers, connected by series piping, were installed in two stages: chillers 1 and 2, which are nominally identical, are part of the original plant while chillers 3 and 4 are later additions. They are run in a sequential order and their control strategy is based on chilled water temperature sensing: the first nominated chiller is started and then the next chiller in the series turns on if the chilled water temperature exceeds 3°C.

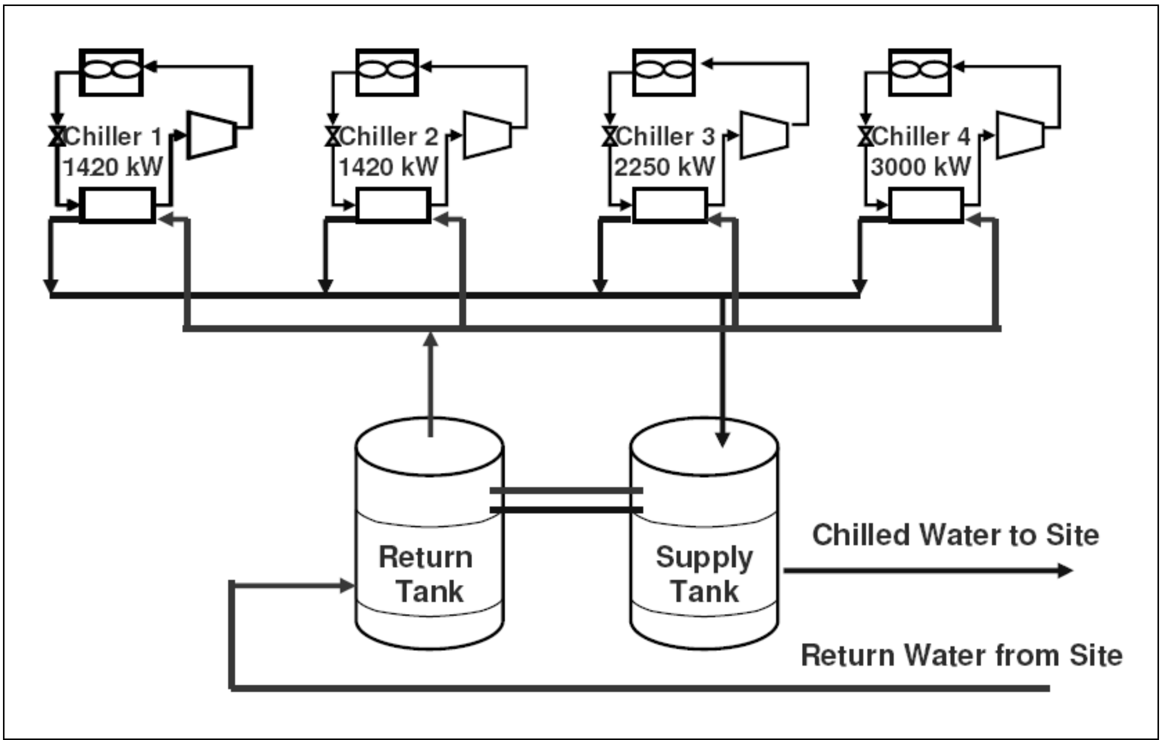


Figure 2.19: Powder plant system layout: chillers

The chillers' technical specifications are given in table 2.1 (p.28) (Cleland et al., 2005).

All systems consist of a positive displacement, rotary compressor (single-screw and twin-screw compressors), two of which are economised, an evaporative condenser with variable speed fan drives and a plate-type evaporator.

Chiller	Refrigerant	Compressor*	Condenser*	Evaporator*
1	R717	Howden WRV 255/130 twin screw compressor. 335 kW motor. VR 2.1. Thermosyphon oil cooling. ***Design:*** 1420 kWr @ -2.0ºC/31ºC (SET/SCT)	BAC CXV-424, evaporative condenser (16.5 kW VSD fan, 5.5 kW pump). ***Design:*** 1672 kW @ 31ºC/21ºC (SCT/WB). UA of 167 kW/K	APV LR9 MGS-11 Plate heat exchanger. 87 cassettes. 140 m^2. 30 kW pump. ***Design:*** 1700 kWr @ CW: 6.0ºC/2ºC, 100 kg/s, -2ºC SET. UA of 294 kW/K
2	R717	As above	As above	As above
3	R717	Mycom 250 VLD Screw Compressor. Economised. Thermosyphon oil cooler. Variable VR. ***Design:*** 2247 kWr @ -2.0ºC/35ºC (SET/SCT)	BAC VXCS-680, evaporative condenser (37 kW VSD fan, 4 kW pump). ***Design:*** 2772 kW @ 35ºC/21ºC (SCT/WB). UA of 198 kW/K	Alfa Laval M20-MWFGR Plate heat exchanger. 79 cassettes. 133 m^2. 30 kW pump. ***Design:*** 2250 kWr @ CW: 7ºC/2ºC, 107 kg/s, -2ºC SET. UA of 365 kW/K
4	R717	Mycom 320 VSD Screw Compressor. Economised. Thermosyphon oil cooler. Variable VR. ***Design:*** 3011 kWr @ -2.0ºC/35ºC (SET/SCT)	Two, BAC VXCS-454, evaporative condenser (37 kW VSD fan, 4 kW pump each). ***Design:*** 1785 kW (each) @ 35ºC/21ºC (SCT/WB). UA of 128 kW/K (each)	Alfa Laval M20-MWFGR Plate heat exchanger. 108 cassettes. 182 m^2. 37 kW pump. ***Design:*** 3000 kWr @ CW: 7ºC/2ºC, 143 kg/s, -2ºC SET. UA of 486 kW/K
* SET = saturated evaporation temperature; SCT = saturated condensation temperature; WB = wet bulb temperature; VR = volume ratio; CW = chilled water; UA = overall heat transfer coefficient x heat exchanger area; VSD = variable speed drive.				

Table 2.1: Powder plant chillers: technical specifications

2.5.1.2 Powder Plant End Users

The identification of the system's end users was a high priority goal because knowing where the chilled water was being used would allow to ascertain if all the relevant data was already being collected and available to use and, if not, how the data recording system could be improved to include missing data. This represented the starting point of all future analyses. Data collection issues will be discussed in details in chapter 4.

A process schematic developed in 2005 by Demand Response engineers (figure 2.21, p.31), which was part of a larger "Clandeboye Process and Utility Models" Excel spreadsheet, showed that the process plants installed at Clandeboye manufacture the following products, all of which use chilled water in one of more of their production stages:

- Cream, manufactured into the following:
  - Anhydrous Milk Fat (AMF)
  - Butter
- Skim Milk Powder (SMP)
- Cheese, including:
  - Dry Salt (DS) cheese such as Egmont, Cheddar and Colby
  - Brine Salt (BS) cheese such as Parmesan, Gouda and Edam
- Whey Protein Concentrate (WPC)
- Lactose

With the exception of the skim milk powder produced in the powder plant, which is clearly served by the powder plant chilled water system, and of the whey protein concentrate, whose production plant is served by its own dedicated chilled water system, the other end products are all manufactured in plants that could equally be served by the powder plant chilled water system or by another system. In fact, in spite of several site visits and in-depth analyses of all the available information, including process schematics, screen dumps, piping and instrumentation (P&ID) drawings and data logged on *Insite*, it was still not possible to ascertain all of the powder plant end users (see chapter 4).

Figure 2.20 (p.30) shows a schematic of the powder plant chilled water reticulation to the various end users. The water meters and temperature probes shown in the figure are those already logged on to the database. The modules 1, 2, 3 and 4 are the pasteurising units for the production of skim milk. The cross hatched lines to and from the AMF plant indicate that the actual chilled water pipes to this particular process could not be physically identified on site, however some evidence suggested that this contribution to the powder plant chilled water use could not be excluded. The extent of such contribution was tested during the analyses carried out for the benchmark generation (see chapter 5).

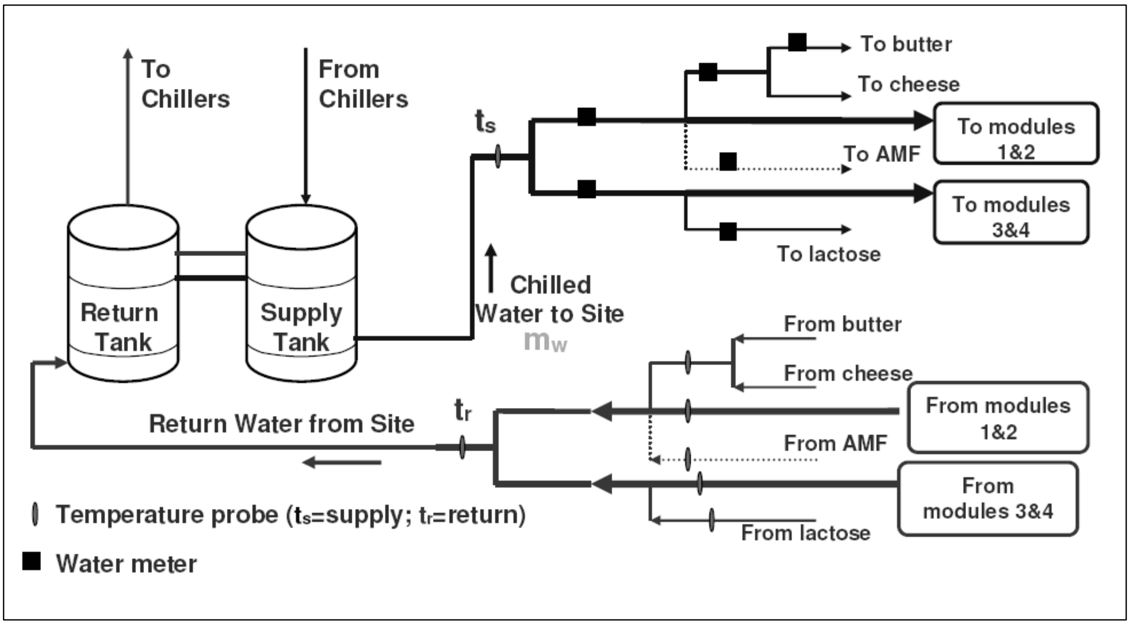


Figure 2.20: Powder plant system layout: end users

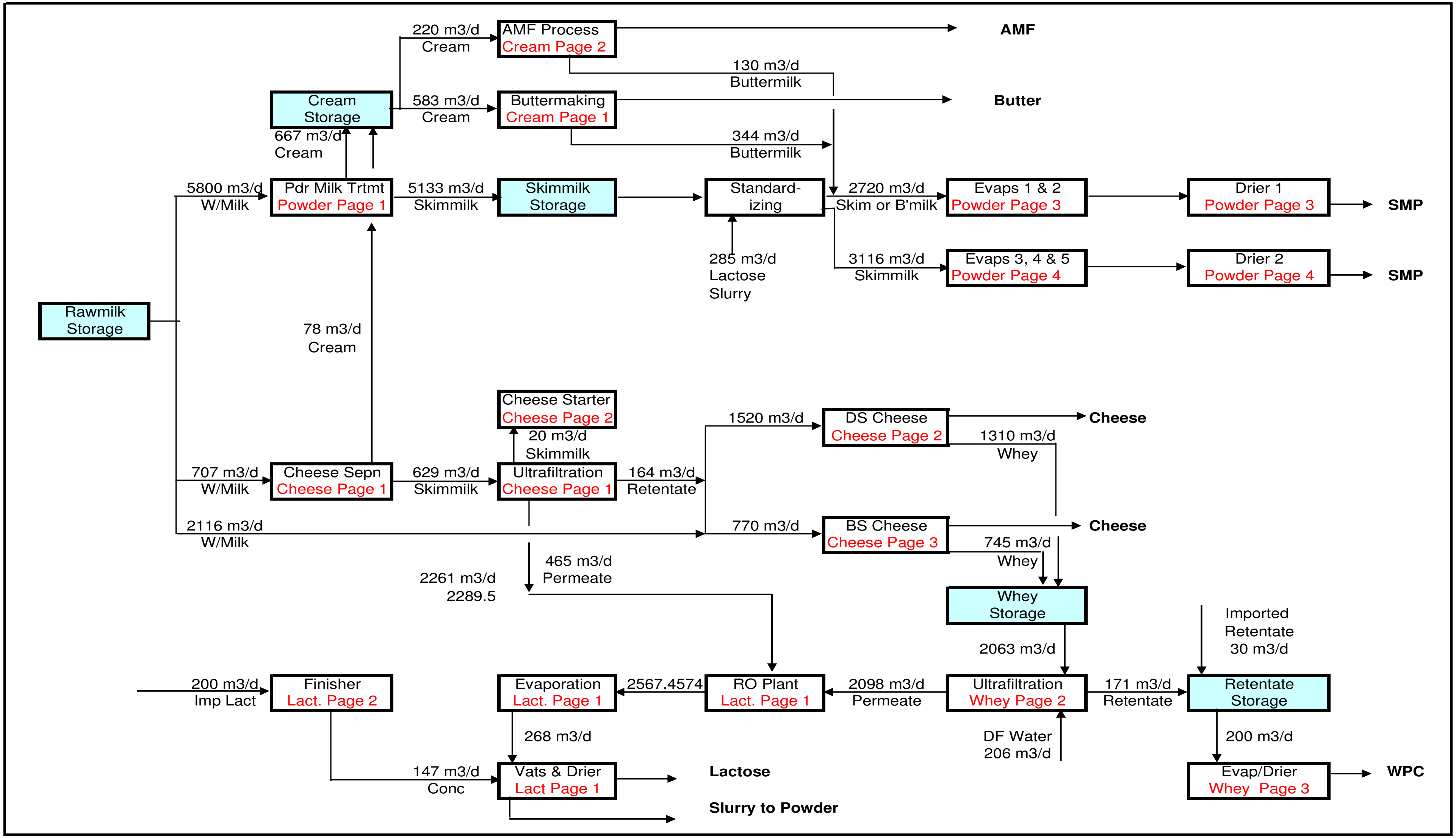


Figure 2.21: Clandeboye process schematic

CHAPTER 3 – MONITORING AND TARGETING

3.1 Introduction

Energy Monitoring and Targeting (M&T) is an energy management tool based on the concept that energy can be treated as a controllable resource and that energy saving opportunities can be identified by analysing data and taking actions as a result of such analysis (CIPEC, 2002). The Energy Efficiency and Conservation Authority (EECA), a New Zealand Crown entity that promotes energy efficiency, energy conservation and the use of renewable energy sources, defines M&T as a "disciplined energy management process that allows organisations to monitor and control energy consumption and costs" (EECA, 2002). The ultimate goal of M&T is to try and reduce energy usage (and consequently costs) without affecting the energy-using processes.

The following literature review analyses the state of development of M&T methodologies and its existing fields of application. The main objective of this review is to verify and endorse the need of either new methodologies or new ways of implementing the existing methodologies on specific industrial applications such as chilled water systems.

The infancy of Energy Monitoring and Targeting has been identified with the period that goes from the oil crisis of 1973 to the early 1980s (Fawkes, 2001). Originally, the main focus was energy conservation rather than energy efficiency and the implementation of energy management policies within organisations was limited to switch-off campaigns to encourage people to use less energy. In that period, Energy Monitoring and Targeting was an energy management technique adopted by only a few organisations, it was far from being structured in the way it is now and there was no common approach to its implementation (Fawkes, 2001). The energy managers dealing with this embryonic field were initially engineers with other roles within their companies and often their experience in energy analysis was limited and their resources scarce (Harris, 1989; Fawkes, 2001).

In the following period, which Fawkes identifies as 1981–1993, the term "energy management" slowly replaced "energy conservation". Technological advances in other areas (IT) made powerful tools easily available: personal computers started to be adopted and the use of utility bill analysis software was being slowly introduced, which allowed to account for factors that were ignored earlier, such as weather and/or production data (Fawkes, 2001).

The development of the Kyoto Protocol in 1997 was a clear sign of the increased sensitivity to environmental issues and its ratification, in February 2005, has impelled many governments to launch awareness campaigns and promote energy efficiency practices in the common effort to meet the stringent requirements of the Protocol. Some governments have also published good practice guides on energy efficient behaviours which include overviews of Monitoring and Targeting methodologies and provide guidelines on how to translate basic concepts into practice. Some of these publications also provide case studies of successful implementations (The Carbon Trust, 1998; CIPEC, 2002; EECA, 2002; The 3E Strategy-Guide Book1, n.d.). However these guides, though useful, are neither research papers nor technical reports as they are often not intended to be used by a specialised audience and therefore do not examine procedures and results in sufficient detail. No other specific study was found in the literature that has directly addressed research on M&T methodologies as a whole, although each key element of an M&T system is today well known and often also already utilised.

3.2 M&T Key Elements

The elements of the M&T process are recording, analysing, comparing, setting targets, monitoring, reporting and controlling (EECA, 2002). These elements can be effectively summarised in the three main discrete tasks that the implementation of M&T requires (The Carbon Trust, 1998):

1. Data collection
2. Data analysis
3. Reporting of findings

3.2.1 Data Collection

Good data collection plays an important role in laying a solid foundation for the subsequent M&T steps (Hooke et al., 2003).

Significant progress has been made since manual data collection was seen as preferable to automatic on-line systems due to cost considerations (Gluckman & Hart, 1991). Today the cost of automatic data collection is not so prohibitive and the recording of data is facilitated and made less error-prone by the many integrated metering and communication systems commonly available.

In most cases, much of the required data is already being collected for purposes like cost and production control and sometimes a simple change in the way information is gathered (for example modifying the collection frequency from weekly to daily) may enable more meaningful analyses from an M&T perspective (The Carbon Trust, 1998).

The number of meters installed is often not a crucial factor: a survey done in 1992 on M&T systems already in place showed that the majority of them were based on either fewer than ten meters or on between 11 and 50 meters (The Carbon Trust, 1998) .

One of the biggest issues to consider when putting in place a good data collection system for M&T purposes is in fact to ensure the quality of the information collected, as inaccuracies and errors in data collection (often due to improper sensor selection and calibration) could render ineffective even the most sophisticated data collection system (Harris, 1989; The Carbon Trust, 1998).

Rishel (2001) recommended that M&T instrumentation meets the accuracy and stability standards set out by the National Institute of Standard and Technology (NIST). In his study, Rishel investigated whether the measurement of kW of electricity consumed by the plant per ton of refrigeration achieved (kW/TR) may be effectively used as a benchmark parameter to determine the overall efficiency of a central chilled water plant. He found that of all the chiller plants that were already using measurements of kW/ton to achieve “efficient” plant operation, only one had in fact been using instrumentation of sufficient quality to deliver a reliable benchmark value for further comparisons.

Different approaches to instrumentation requirements for monitoring energy performance (in the specific case, of a chiller plant) are presented by Hartman (2001) who also discusses some basic and cost effective equipment configurations to help operators and designers implement their own monitoring system.

3.2.2 Data Analysis

Data analysis is at the core of M&T because interpretation of findings derived by appropriate analysis will influence decisions on energy saving actions and ultimately determine the success of the whole M&T system (The Carbon Trust, 1998).

The first step of the analysis is to identify all the variables that affect energy consumption. Then, depending on the degree of control and the level of resolution sought, a decision has to be made as to which of these variables should be used in the analysis (The Carbon Trust, 1998). Finally, the right form of analysis has to be chosen, which can then be carried out either with the aid of computer spreadsheets (often developed in-house) or by means of proprietary software, which normally require a careful evaluation prior to be used, to ensure that they meet the organisation's needs (The Carbon Trust, 1998; EECA, 2002).

A list of some M&T software available in New Zealand is provided by EECA (2002), which has also published case studies on organisations that have successfully adopted some of these software tools (EECA, 2004). Links to other M&T software used throughout the world (though mainly in US, Canada and UK), including information on their strengths and weaknesses, expertise required, users and audience, can be found through the Web site of the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy (Building Energy Software Tools Directory, retrieved June 2006).

The majority of proprietary software on the market (e-Bench, Energy Wizard, EnergyPro, Metrix, e-Track) target small to mid-size commercial buildings, schools, universities or government buildings. For such applications, the most common form of analysis adopted is regression calculations that correlate usage and weather conditions. This is because weather dependent air conditioning and heating utilities are the dominant energy users in most buildings. But simple linear regression analysis is also recommended for industrial processes where energy usage is dominated by production and can be highly correlated to a single production measure (Harris, 1989; The Carbon Trust, 1998; The 3E Strategy-Guide Book1, n.d.). This simple linear regression analysis aims to establish a baseline trend (based on historical data) of energy usage versus production throughput that is then taken as a benchmark to which current and future energy/production patterns can be compared. As long as the conditions that have caused a given energy consumption remain the same (i.e. no changes are introduced for example in plant configuration, operating strategies or production mix) the regression equation allows to identify instances of inefficient operation whenever the difference between the actual or expected consumption and the historical benchmark is unusually large. The aim is to reduce those differences over time so to achieve the best performance standard (The Carbon Trust, 1998).

Once the best-fit line of energy versus production has been identified, a powerful tool can be used to try and reduce energy consumption. This tool is another statistical technique called Cumulative Sum of differences, or CUSUM, which is used in combination with a Control Chart, one of the seven basic tools of Statistical Quality Control (Harris, 1989; The Carbon Trust, 1998).

CUSUM is a technique that allows to measure bias in equal interval time series data: same data is collected at the same time each day and then the differences between actual and expected consumption (predicted by the best fit line) are added in that same time order. These differences are then plotted over time, resulting in specific and recognisable patterns: a small, random scatter around zero indicates that no significant event has occurred to change consumption trends. On the other hand, deviations from a horizontal track highlight changes in efficiency due to a particular event that has affected energy consumption (an upward trend indicates a worsening in performance). This gives management the opportunity to discuss possible reasons for bad performance and to try and put in place a procedure that can at least minimise the consequences of that undesirable event.

Control Charts are today a familiar tool for many businesses that use Statistical Process Control to achieve quality control in manufacturing processes. Introduced by Walter

Shewhart in the 1920s, they are a graphical way of identifying a lack of control in a production process that can lead to unacceptable variations in the quality of the final product. By using basic statistics such as averages and standard deviations and displaying the observed data in a time sequence, with a Control Chart it is possible to secure a finished product with quality characteristics that lie within specified tolerances (in case of electricity consumption this means to ensure consumption is maintained within a specified control band). The theory behind that is that while part of the variation in the quality of products is due to an element of chance that can be probabilistically predicted (*chance causes*), there may be other causes of variation (*assignable causes*) that cannot be left to chance and should be identified and eliminated to secure the control of a manufacturing process (Shewhart, 1931).

Many case studies (Harris, 1989; The Carbon Trust, 1998; The 3E Strategy-Guide Book1, n.d.) appear to confirm that the most appropriate analysis is the one based on simple linear regression against a single measure of production. However, these examples are artificially simplistic as in reality the energy use of large and complex plants cannot be easily correlated to a single measure of production (see chapter 5). In such cases, it may not be an appropriate solution to just simply modify the analysis to a form of multiple linear regressions as the existence of either non-linear relationships among variables or multicollinearity (variables that are related to one another and therefore not independent) can produce totally misleading results (The Carbon Trust, 1998).

A model "misspecification error" can occur due to four main causes:

1. The model includes variables that are not relevant.
2. The model excludes important variables.
3. A linear model is used when the relationship among variables is in fact not linear.
4. The model order is incorrect like for example, when algebraic equations are used instead of differential ones.

In all these cases the analysis of residuals might help in identifying the causes, although often the real cause can only be detected after several attempts at model reformulation (Reddy & Andersen, 2002).

3.2.2.1 Data Analysis Techniques for Chilled Water Systems

In the specific case of refrigeration or chilled water systems, regression analysis is mainly utilised for diagnostic purposes (Grimmelius et al., 1994; Comstock et al., 2001) or for predicting chilling system performance (Browne & Bansal, 2001; Reddy & Andersen, 2002). This is achieved by correlating the chillers' Coefficient of Performance (COP) with independent parameters such as the cooling capacity (kW), the supply chilled water temperature and the condenser water temperature. The common goal is still to establish a benchmark of energy consumption for a particular set of operating conditions so that the ones that minimise consumption can be sought as best practice.

Different modelling techniques used to assess the chillers' performance include the use of software-based simulation of first principles approaches with equations for mass and energy conservation (Browne & Bansal, 2001; Castro, 2002; Ha, 2003; Le et al., 2004), the use of refrigeration expert systems (Shibata et al., 1989; Gluckman & Hart, 1991) and the use of artificial neural network (Bechtler et al., 2001). All these techniques have been tested in a number of applications and have often proved appropriate to each individual case they have been used for. However, this appropriateness was often also limited to that individual case as the results produced were dependent on the specific system considered and/or its operating condition at the time of the test. This has ultimately affected the possibility of generalising the model.

A good comparison of all these simulation models is provided by Browne and Bansal (2001), whose study aimed at testing the different models' ability to predict the chillers' performance under different operating conditions, from the quasi-steady to the dynamic behaviour typical of start-up or fluctuating load conditions. The models analysed include regression, steady-state models using an elemental method approach, physical dynamic models and artificial neural networks. They found that steady-state models have a prediction accuracy of within ±5% under mildly dynamic conditions. However, when stronger dynamics were involved, such as unloading conditions, discrepancies between prediction and experimental data were as high as 20%. In all these cases the dynamic models provided representation of the actual performance within ±10% and proved to be preferable, provided they are also economically viable.

Diehl et al. (1999) suggested that dynamic modeling could be approached by using a kind of *"box of bricks method"*, that is by treating the whole refrigeration plant as constituted of many basic class objects that can be combined to describe each individual system component (the elemental method approach). This would lead to a model formulation that is very flexible and that could potentially be used to simulate nearly any compression plant, but often the cost to develop such a model is too high both in money and time to justify its application.

Another way of detecting and diagnosing faults in refrigeration systems, thus to ensure its optimal performance, is the use of Refrigeration Expert Systems. These systems usually consist of two parts: a predefined "knowledge base" that contains all the rules governing the process as defined by the human expert, and an inference engine that analyses these rules and infers possible causes of malfunctions whenever an abnormality is detected (Gluckman & Hart, 1991). The inference engine is much like a common spreadsheet that incorporates an empty framework (the shell) with built-in calculations into which users can enter their specific requirements. This makes Expert Systems relatively easy to use: they do not require specific knowledge of traditional programming but simply an understanding of what is needed from the computer and how the mechanism of the expert system shell works (Anderson & McNeil, 1992). Expert Systems have been successfully tested on a number of applications (Brown & Fairlie, 1987; Gluckman & Hart, 1991) including HVAC systems (Shibata et al., 1989) but their applicability is limited to simple systems as an increase in system complexity could require too much computing resources and cause the system to become too slow (Anderson & McNeil, 1992).

A relatively new approach in dynamic modelling for performance prediction is represented by the use of dynamic neural network models (Bechtler et al., 2001). Artificial neural network models, which are inspired by the learning mechanism of biological systems based on "experience", are structured in a way that allows to seek patterns in data that no one knows are there. This means that these models are able to provide problem solving capabilities without the use of an expert or the need of programming: they try to provide a tool that both programmes itself and learns on its own. However, for the model to be effective, some important conditions have to be met, including the provision of an adequately sized data set with all the information that can characterise the problem (Anderson & McNeil, 1992). A perceived limitation of artificial neural networks is that once the network is developed, there is no way to ensure that it is *optimal*. In addition, because the model learns through experience, it is still possible for it to continue to make mistakes (Anderson & McNeil, 1992).

3.2.3 Reporting of Findings

The reporting of findings is the last but not least stage of an M&T system. If done in an effective way, energy reporting allows to take the necessary actions to improve the efficiency of the analysed processes and ultimately contributes to the achievement of energy and cost savings (CIPEC, 2003).

Ideally, reports should be tailored both to their intended audience (operational staff, senior management, etc) and to their purpose (The Carbon Trust, 1998; EECA, 2002; CIPEC, 2003). The reporting method can also vary depending on available resources and may be implemented as word-processed documents, spreadsheets or Web browser interfaces (Hooke et al., 2003). Today it seems common for reports to be delivered via a Web browser interface.

Numerous M&T software include standard report formats, both graphical and tabular, which can be printed or pasted into other documents and in some cases can also be configured by the users without the need to buy another programme to do so. However, none of the available software is specifically tailored to suit chilled water applications therefore the standard reports that are automatically generated may not contain all relevant information or may not be designed to effectively convey it.

Effective user interface designs are those based on some basic Human Computer Interaction Design principles (Dix et al., 1993; Cooper, 1995; Preece et al., 2002) such as simplicity and familiarity, obviousness and encouragement, satisfaction and availability, safety and personalisation (User Engineering, retrieved June 2006). One of the most important aspects is to keep the design as simple as possible. Generally, users do not need to know (let alone want to know) complex details on the structure of their software; they simply want to be able to easily use the software in order to derive the information they need (Cooper, 1995).

Cooper (1995) distinguishes between what he calls the "*implementation model*" that represents the real way in which a machine works and the "*mental model*" that represents a personal perception of how that working mechanism is achieved. As users would rather have a computer that matches their way of thinking than the other way round, good interface design should try to represent the functioning of the computer by imitating the user's mental model as closely as possible (Cooper, 1995).

3.3 Conclusions

This review of the available literature has highlighted that while all the key elements of energy monitoring and targeting systems are today well known and often also already utilised, they have never been applied to chilled water systems in an organised and integrated way. A well structured methodology specifically targeting chilled water applications would become an important and effective tool for the continuous energy efficiency improvements of these systems.

CHAPTER 4 – DATA COLLECTION

4.1 *Insite* – The Existing Database

A data collection system was already in place at Clandeboye through Demand Response's database, *Insite*. The database, which also queries other Fonterra's systems, was periodically updated with data ultimately sourced from the various metering devices installed around the plant and recorded at regular intervals (usually every 30 minutes). The time series datasets loaded into *Insite* represented metered flows either entering a specific plant or process (electricity or product-related ingredients such as milk, lactose or cream) or exiting it (product outputs or waste). Each data source (specific meter channel) had been assigned a unique meter ID number or a similar label that identified the set of values it recorded. If a meter had more than one channel (for example one to record pressure and one to record temperature), each set of recorded values also had a sub-identifier.

To view data users had to specify the following parameters:

- the site of interest (Clandeboye was only one of the several monitored sites)
- the data type (chilled water, milk, electricity, etc.)
- the date range (from/to dates)
- any special data treatment (data aggregation within resource types or unit of measurement, or interval roll-up such as hourly, daily or weekly).

Once these selections had been made, *Insite* could extract the data from the database and allow users to download it as raw data or in graphic form (or both) depending on the action selected.

Figure 4.1 (p.43) shows a screenshot of *Insite*.

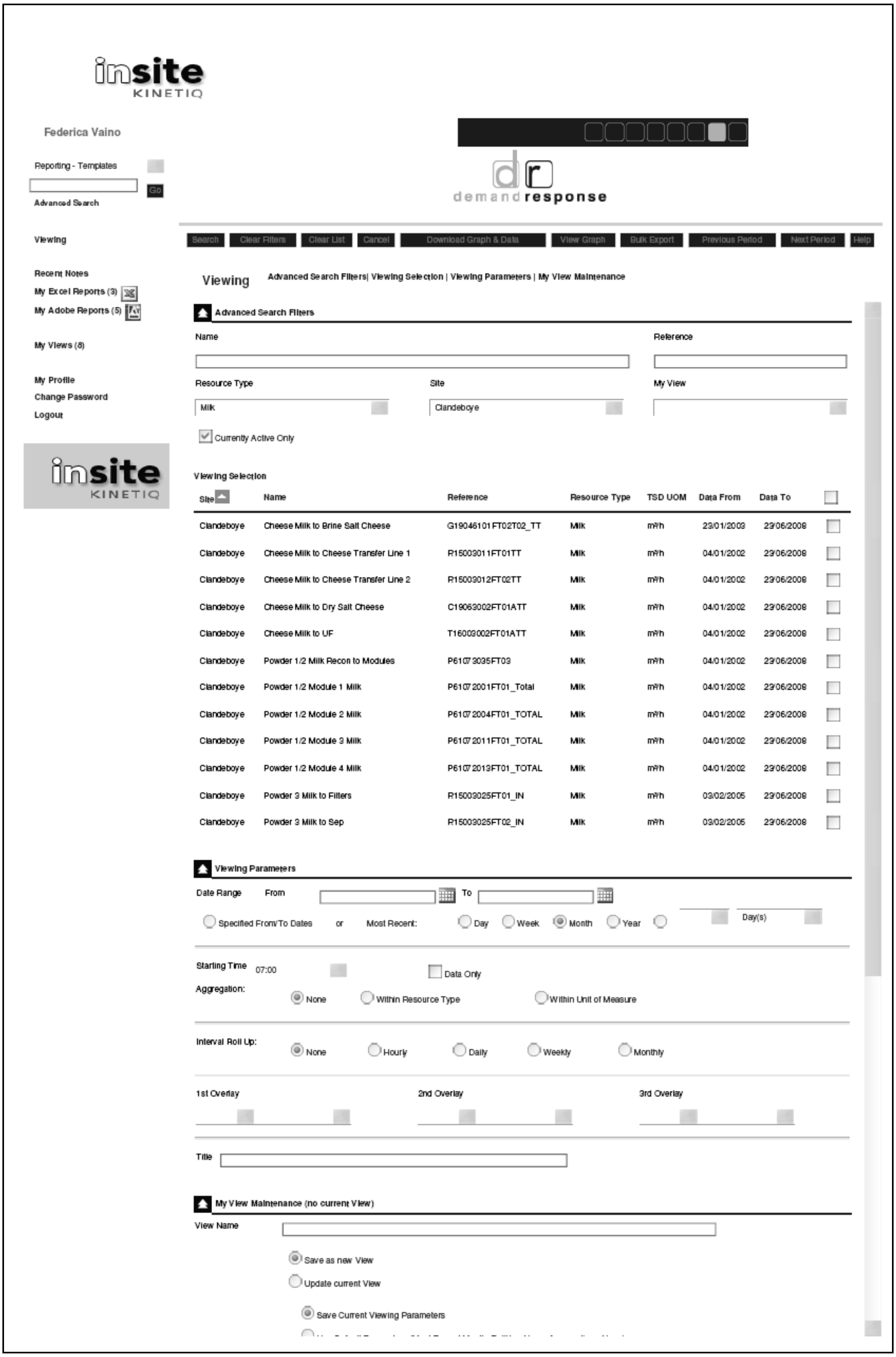


Figure 4.1: Screenshot of *Insite*

4.2 Additional Data Sources

Among the time series data recorded on *Insite* there were already a few relevant to the project, however some important data was also missing, so the first thing to ascertain was precisely which data was available and which needed to be added to the database.

A number of different data types could be found on *Insite* for Clandeboye, which included "air", "chilled water", "compressed air", "electricity", "milk", "product" and "steam" and each would have one or more set of values being monitored, such as flow or temperature. The identification tags of the various metering devices provided an approximate indication of whether or not the metered flows were related to the powder plant chilled water but only a detailed knowledge of the plant and of all the processes involved could ensure a correct evaluation. In fact, as discovered later, some of the labels misleadingly referred to variables that were no longer linked to the use of chilled water produced by the powder system under analysis. This was probably due to subsequent changes in the system configuration that had not been reflected into the labelling system. For instance, the ID label "Ch Water to Modules 1&2, Cheese and UF3" on *Insite* suggested that the same chilled water that flowed to two of the pasteurising modules and to the cheese plant (from the powder system), was also going to the Ultrafiltration process of the whey protein concentrate plant (WPF UF3). However this was no longer the case since the piping of the UF3 plant had been modified from its original layout (see chapter 2). The ultrafiltration process was in fact chilled by its own dedicated system and the label had obviously not been modified since the change was introduced.

A preliminary insight into the various production processes carried out in the powder plant was gained through the Excel spreadsheet developed by Demand Response's engineers in 2005, "Clandeboye Process and Utility Models", which was already mentioned in chapter 2. Figures 4.2 and 4.3 show a couple of flow diagrams taken from this spreadsheet.

Figure 4.2 (p.45) is a flow diagram of the milk treatment, the first of the processes that milk undergoes to eventually become skim milk powder (SMP) in the powder plant; part of lactose treatment is also visible in the figure. The whole milk enters the pasteurising modules and gets separated along the line into cream and skim milk, which then go to their respective treatment plants (cream and powder plant).

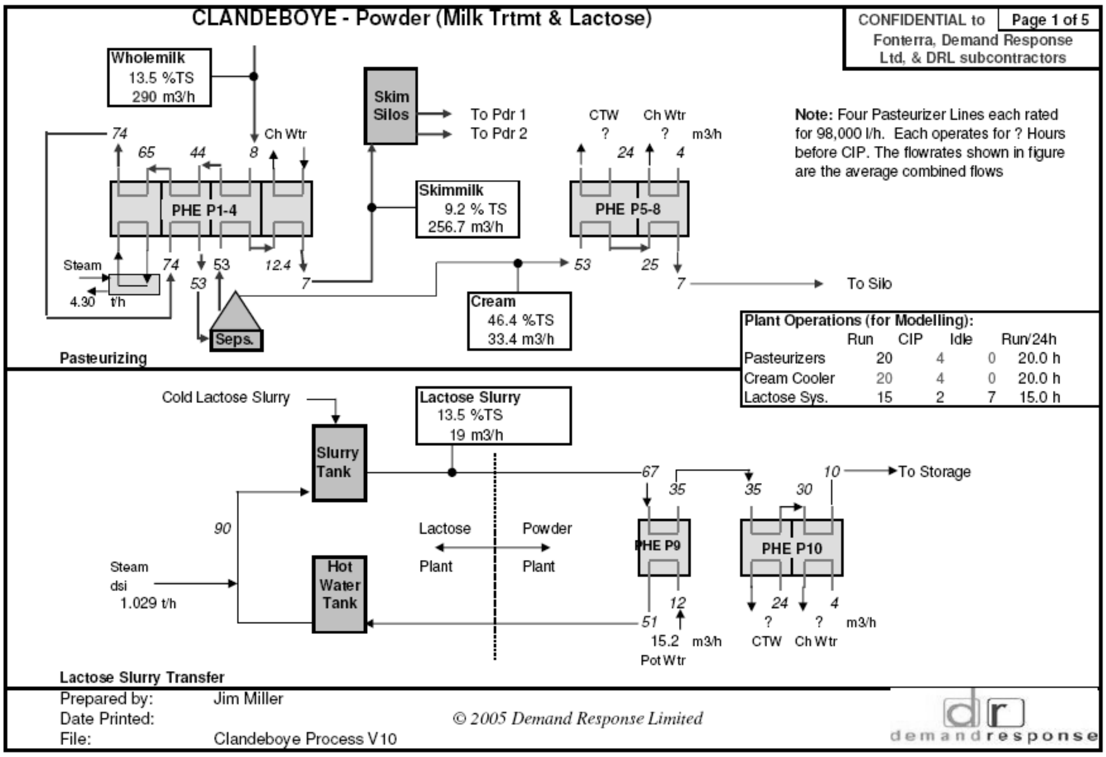


Figure 4.2: Powder plant process schematic (milk treatment and lactose)

Figure 4.3 (p.46) shows the processes occurring in the powder plants 1 and 2, where the skim milk coming from the milk treatment modules is processed into the evaporators first, then into the spray driers to yield the final product.

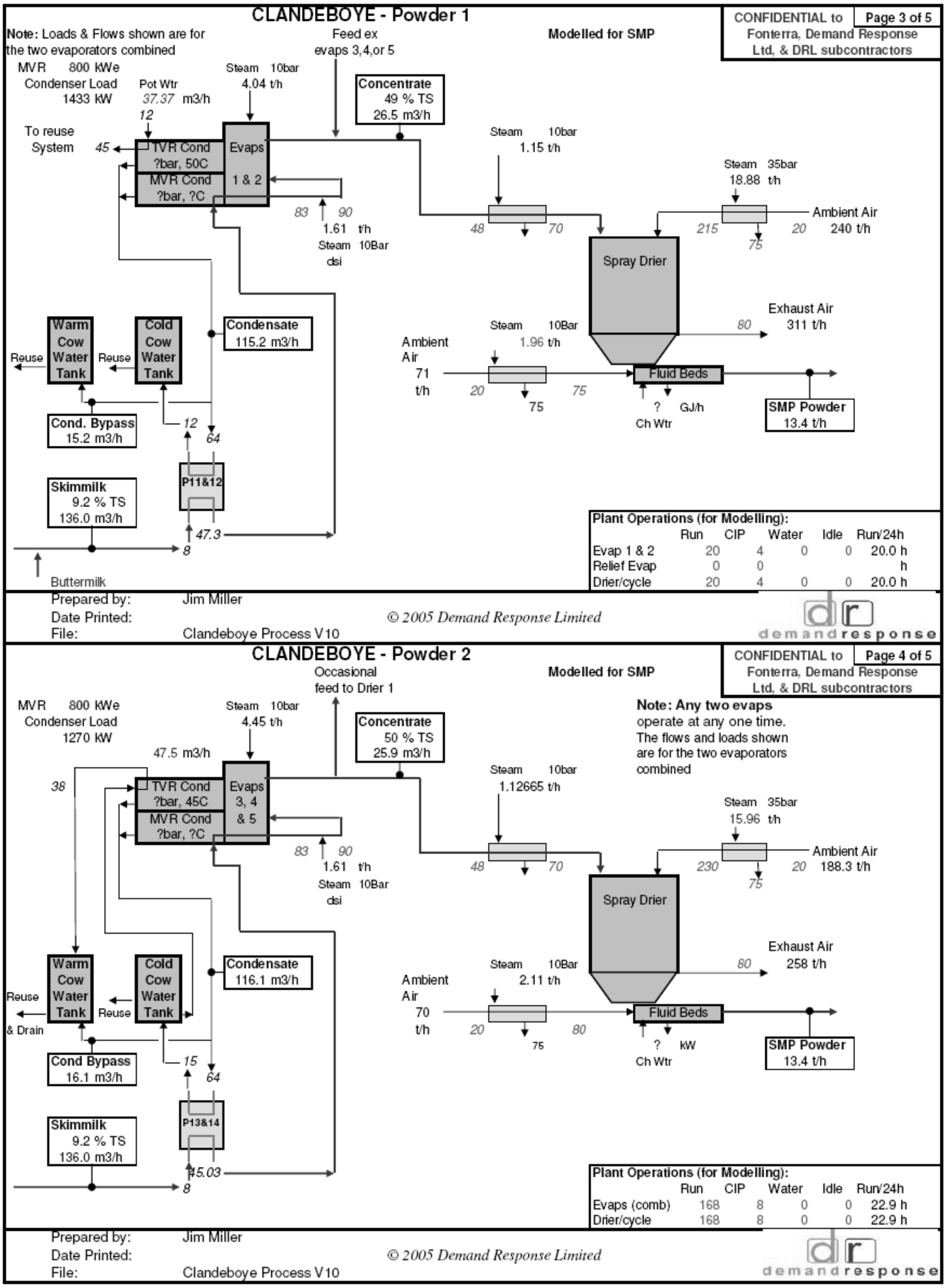


Figure 4.3: Powder plant process schematic (powder 1 & 2)

Graphic screens used by the operators as well as piping and instrumentation drawings (P&ID) also contained useful information on the piping schematic. Figure 4.4 below shows one of the screen dumps of the SCADA system on site.

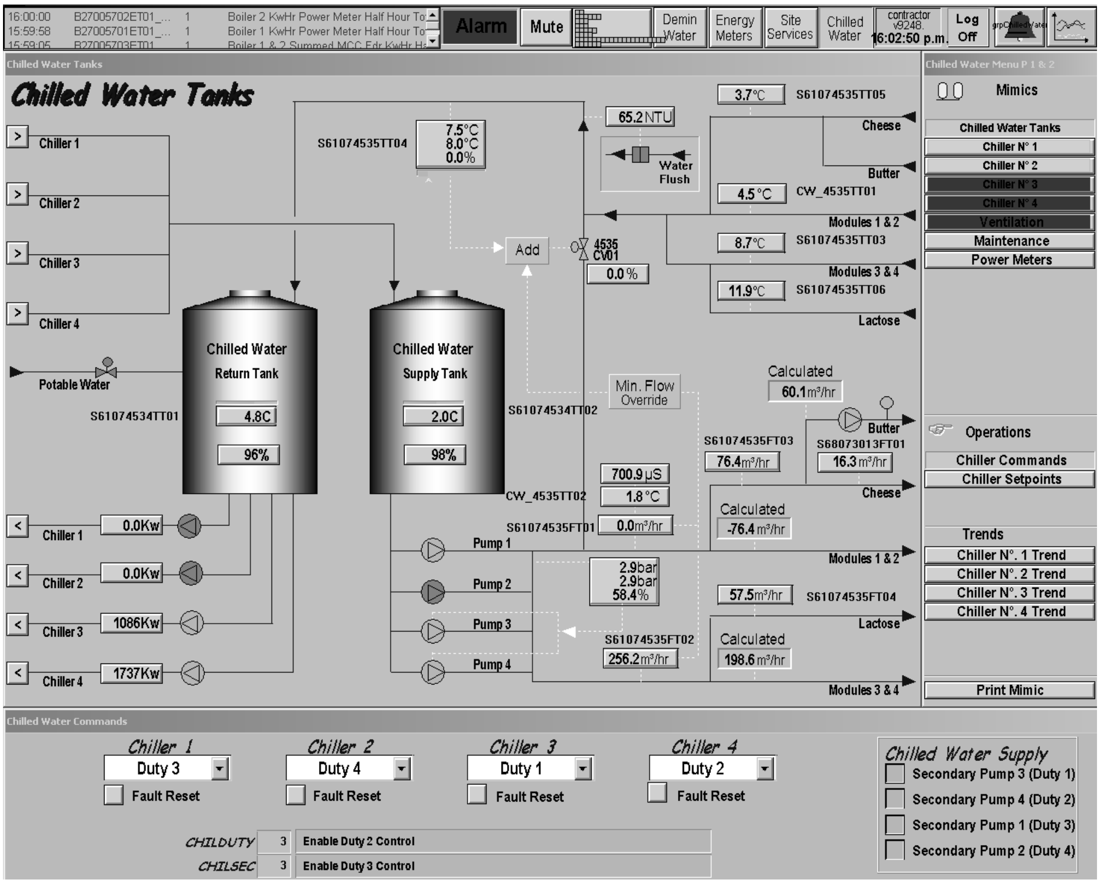


Figure 4.4: Screen dump of powder chilled water reticulation system (source: Clandeboye SCADA system)

In addition to studying available documents, a couple of site visits were also conducted to verify the precise site configuration.

4.3 Data Identification and Collection

The identification process of all the data relevant to the study started with the attempt to locate the heat exchangers that were part of the powder plant system. This was considered the basis to carry out all the flow-related calculations, such as site load estimates and comparisons between chilled water flows versus milk/product flows. Only after could all the sought datasets started to be collected. These are:

- chilled water flows to end users, m_w (kg/s)
- supply and return chilled water temperatures from each end user T_s and T_r (ºC)
- electricity to chillers and ancillary, E (kW)
- chiller compressors data like suction and discharge pressure, run time, percent of loading (kPa, min, %)
- outside temperature/humidity data (ºC, kg/kg).

The first two datasets would allow to calculate the site cooling load (kW) as:

$$\text{Cooling load} = m_w \text{ x } c_p \text{ x } (T_r - T_s) \qquad \textbf{\textit{(4.1)}}$$

where c_p is the specific heat capacity of water (kJ/kg K).

The cooling load and the electricity to the chillers would allow to derive the system COP as:

$$\text{COP} = \text{Cooling load} / \text{E} \qquad \textbf{\textit{(4.2)}}$$

Chillers' data and outside temperature data would allow to derive important information on the system operating conditions and to evaluate the possibility to implement changes (for instance in the discharge pressure set point) to promote energy savings.

The identification methods and findings are described in the next sections.

4.3.1 Process Heat Exchangers

In spite of all the available documentation, the identification of all the heat exchangers served by the powder plant chilled water system was one of the most challenging and at times frustrating tasks to be accomplished. This was partly because some plant modifications made over time had not been accurately documented.

It was known that chilled water was being used in the last stage of the pasteurisation process and the process diagram in figure 4.2 (p.45) confirmed it (PHE P1-4). Chilled water uses were also found in the cream coolers (PHE P5-8) and in the lactose chiller (PHE P10). In the powder plant itself (figure 4.3, p.46) chilled water was sprayed in the fluidised bed driers where the product, arriving with residual moisture content, needs to be cooled down.

Similar flow diagrams as those in figures 4.2 (p.45) and 4.3 (p.46) were available for the cheese, cream and lactose plants, which made it possible to approximately identify all the heat exchangers using chilled water. However, except for the four pasteurising modules ad maybe the cream coolers, there was no certainty as to which of the other heat exchangers was served by the powder plant system.

The site's SCADA system showed that the powder plant chilled water was being delivered to five end users (figure 4.4, p.47). These were:

- Modules 1 & 2 (pasteurisation units)
- Modules 3 & 4 (pasteurisation units)
- Lactose
- Cheese
- Butter

However, the SCADA system gave no indication as to the number of heat exchangers involved.

Figure 4.5 (p.52) illustrates a reticulation schematic, drawn from analysis and interpretation of process diagrams and screen dumps, which combines main end users and related heat exchangers. In the schematic are also visible all the chilled water flow meters logged on *Insite* with their corresponding identification labels.

A site visit was organised with the intent to confirm or amend the schematic in figure 4.5 by physically identifying the chilled water end users and determine the exact number and type of all the heat exchangers associated with the powder plant system. It was hoped that the findings would be consistent with all the information collected up to that point.

The plant inspection started from the powder plant chilled water supply tank and progressed to the various processes that the supply pipes led (or seemed to lead) to. Unfortunately, the pipe reticulation was so intricate at certain points (splitting into two or more branches that would hide over or inside buildings) that it was too time consuming to accurately trace all the branches. The only pipes that could be clearly identified were the two branches coming from the supply tank and whose flow was measured and recorded on *Insite*. It was soon clear that a final schematic could only show the primary supply and return chilled water pipes leading to the main production processes but could not be completed with the individual heat exchangers. This schematic is shown in figure 2.20 (p.30) and although inferred from incomplete evidence was nevertheless accepted as based on sound assumptions.

The diagram of figure 2.20 is similar to the one in figure 4.4 (p.47) (screen dump of powder chilled water reticulation system) except for the branch to the AMF plant. Based on a hand-drawn sketch of chilled water reticulation retrieved at Demand Response (and originally provided by Fonterra) it was initially thought that the AMF supply was branching off Module 1&2 as drawn in figure 2.20; this could not be confirmed during the site inspection, however a hatched line was left there as the layout was considered highly possible given that the AMF plant was located right next door to the milk treatment plant. It was therefore decided not to exclude the hypothesis and see how the study developed.

4.3.2 Chilled Water Flows

The total supply flow rate to site was confirmed to be the sum of the two flows through the two main pipes branching off the supply tank. As shown in figures 4.4 (p.47) and 4.5 (p.52), these flows were already being measured and the relative data recorded on *Insite*. During the site inspection the corresponding meters were identified and their ID labels confirmed as being:

- S61074535FT01

- S61074535FT02

The other flows, which were thought to be relevant as per the drawn schematic, were all found on *Insite* but their corresponding meters could not be physically identified on site. The meter ID numbers on *Insite* were:

- S61074535FT03 (combined flow to cheese and butter)
- S68073013FT01 (flow to cheese)
- A43003011FT01 (flow to AMF)
- W61074535FT04 (flow to lactose)

Data collection and analysis would verify that recorded values were consistent and therefore suitable for the purpose. This will be dealt with in section 4.4.

4.3.3 Supply and Return Chilled Water Temperatures

The existent temperature probes were installed on the total supply and total return flows and on each of the return flows from the individual main end users: butter, cheese, AMF and lactose (figure 2.20, p.30, shows these probes). All of these, except the total return temperature, were logged on *Insite.* However, the uncertainty on the individual chilled water flows to the end users caused the individual return temperatures to be of little use. The total return temperature was in fact the only worthwhile value but it could only be obtained directly from site operators as it was not available on *Insite*. This situation, though not ideal, lasted the whole duration of the project.

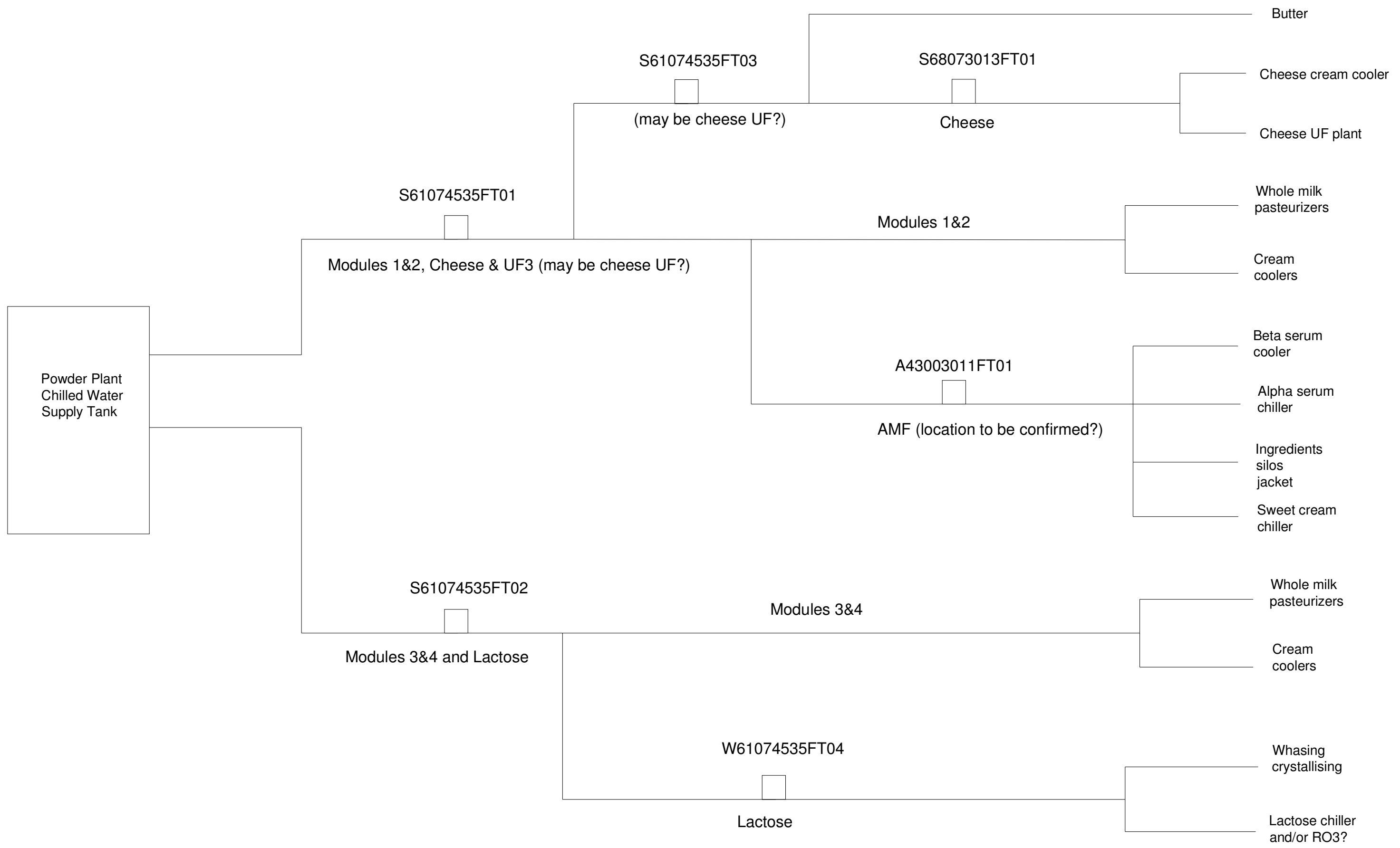


Figure 4.5: Chilled water reticulation schematic showing the flow meters and probable end users (heat exchangers)

4.3.4 Electricity to Chillers and Ancillary

The electrical meters related to the powder plant and logged on *Insite* are shown in figure 4.6.

Clandeboye	*Elect to Chilled Water Incomer1*	*S61075700ET01_LHH*	*Electricity, Power*	*kW*	*24/11/2004*	*13/12/2005*	☐
Clandeboye	*Elect to Chilled Water Incomer2*	*S61075700ET02_LHH*	*Electricity, Power*	*kW*	*24/11/2004*	*13/12/2005*	☐
Clandeboye	*Elect to Chilled Water Incomer3*	*S61075700ET03_LHH*	*Electricity, Power*	*kW*	*24/11/2004*	*13/12/2005*	☐
Clandeboye	*Elect to Chilled Water Incomer4*	*S61075700ET04_LHH*	*Electricity, Power*	*kW*	*24/11/2004*	*13/12/2005*	☐

Figure 4.6: Screenshot of *Insite* showing the powder plant electrical meters

Information from site confirmed that the incomers 1 and 2 were feeding chillers 1 and 2 respectively while the incomers 3 and 4 were bus coupled to feed chillers 3 and 4 together. The supply pumps were thought to be hooked up to incomers 1 and 2.
The same transformers though were also feeding other electrical motors not related to chilled water production or distribution, such as the motors driving the warm potable water distribution pumps, the nitric acid supply pumps or the hot cow water pump. A list of these motors complete with their size is given in table 4.1 (p.54).

Most of the extraneous motors (mainly those driving the pumps for the CIP - Cleaning in Place - procedure for equipment cleaning) were between 0.5 and 5.5 kW except for the two warm potable water distribution pumps (75 kW each) and the hot cow water pump (22 kW). The electricity use of those motors might have been significant compared to the total use, especially if operating times were long enough to have an impact on it. Apart from the motor size, no other specific information was provided on the pumps operating schedule therefore it was needed to estimate the extraneous contributions to the electricity data recorded on *Insite*. This is discussed in section 4.4.

Description	Motor size (kW)	Transformer
Warm Potable Water Distribution Pump 1	75	Incomer 1
Warm Potable Water Distribution Pump 2	75	
Potable Water booster Pump No. 1	0.75	Incomer 2
Potable Water booster Pump No. 2	4	
Potable Water booster Pump No. 3	4	
Steam Condensate Pump No 1	5.5	
Steam Condensate Pump No 2	5.5	
Nitric Acid Supply Pump 1	2.2	
Nitric Acid Supply Pump 2	2.2	
Nitric Acid Supply Pump 3	2.2	
Ultrazolv Supply Pump 1	2.2	
Ultrazolv Supply Pump 2	2.2	
Ultrazolv Supply Pump 3	2.2	
Concept C20 Supply Pump 1	2.2	
Concept C20 Supply Pump 2	2.2	
Chlorine Analyser Pump	0.55	Incomer 3
Hot Cow Water Pump	22	Incomer 4
TOTAL	**209.9**	

Table 4.1: Pumps fed by chillers' transformers but unrelated to chilled water

4.3.5 Chillers' Data

At the moment the project started (and for nearly as long as it lasted) none of the chillers' data was available on *Insite* and once again collection had to rely on site operators. The desired data was suction and discharge pressure, percent of compressors loading and chillers' times of operations; all this was essential to monitor performance and be able to make relevant recommendations on possible energy saving strategies.

4.3.6 Outside Temperature/Humidity Data

Outdoor air conditions play an important role in chillers' performance optimisation, in particular the wet bulb temperature, which allows the amount of moisture in the air to be estimated. The air moisture content affects the evaporative condenser ability to reject heat; a lower air moisture (wet bulb temperature) means there is a possibility to lower the condensation temperature. This in turn lowers the compressor's energy consumption.

Ambient data was not logged on *Insite*. During the project, it was not possible to obtain it from alternative sources either (such as the NIWA database, CliFlo). However, provision for handling the data in case it had become available was made since the first report workbook drafts (discussed in chapter 6). Formulas for the calculation of the wet bulb temperature from dry bulb and moisture content data were also developed in case the wet bulb data was not directly obtainable.

4.4 Data Collection Issues

It became apparent from the very beginning that, in spite of the existing database and the numerous metering devices already installed throughout the plant, the data collection process was going to be complicated by several problems. Lack of data, data errors and data ambiguity about what was being measured were the primary impediments to the implementation of the monitoring and targeting system under development. Relying on site operators to collect and email data was another issue and unfortunately this dependency situation did not change for the whole duration of the project. The main factors that prevented a prompter addition of new tags to the database were cost and viability. It was only after the winter shut down that some of the requested tags were finally added to *Insite* for automatic download in the report.

The next sections will describe the above issues (and the attempts to resolve them) for some of the variables involved.

4.4.1 Milk and Product Flows Uncertainty

The main consequence of not identifying the process heat exchangers was that there was no certainty on all the related milk or product flows going through them, flows that were ultimately the sole drivers of the site cooling demand.

Electricity consumption is directly related to the milk and product flows. Not knowing how many of these variables were involved in the relationship has significantly affected the quality of the final model. This is addressed further in chapter 5.

4.4.2 Incorrectness of Chilled Water Flow Data

As mentioned in 4.3.2, the only chilled water supply pipes that could be physically identified on site and linked to the chilled water system at issue were the two main legs branching off the supply tank. The total flow rate through these two pipes would give the total chilled water supply to the powder plant. Also, the flow through a secondary pipe would have to be lower than the flow through the corresponding main pipe and the flow through all the sub-branches would have to equal the total flow through the two main pipes (mass balance). The initial data collected from *Insite* though seemed to be in contrast with this logic.

Inconsistently with findings and expectations, *Insite* chilled water flow values relative to one of the two main branches (meter No S61074535FT01) were found to be lower than the flow values recorded at its sub-meter (meter No S61074535FT03). The site inspection gave the opportunity to compare actual data provided by the on-site SCADA system with the same period data collected on *Insite*: the values did not match, with the values from *Insite* being lower than those from site. This suggested that the meter logged on *Insite* was in fact measuring another variable whose values had erroneously been associated with one of the two main chilled water pipes. This error on *Insite* was not corrected during the project period and so the corresponding data was collected by site operators.

4.4.3 Purging of Electricity Data

Attempts were made to estimate the extent of electricity uses extraneous to chilled water based on the data provided. According to an unofficial communication, the three biggest pumps among those not related to chilled water (the two warm potable water distribution pumps and the hot cow water pump) were run about 20 hours per day. The other smaller pumps were assumed to be operating for the same period as the three big pumps, to simulate a worst case scenario. This eventuality would equate to a combined rating for all the pumps of 175 kW.

Half hourly electricity data (kW) to the four incomers was collected from *Insite* for one week period (from 23 to 30 January 2006) and every time the total was found to be higher than 175 kW, it was lessened by that amount to get the supposedly true chillers' consumption. If the total electricity was less than 175 kW, then the average value between previous and subsequent half hour was considered. By comparing the total electricity to the incomers and the total electricity to the chillers so obtained, the contribution of the extraneous motors was found to be 19%.

Several months later, when more information was given about the exact motors fed by each of the transformers (table 4.1, p.54) a different attempt at estimating the impact of pumps usage on total electricity was made. It was imposed that every time a chiller was supposedly on (this condition was also derived by best guess assumptions as no data on chiller run times was yet available) the extraneous pump's capacity fed by the corresponding incomer was to be deducted by the total recorded electricity for that incomer. This was in essence equal to assuming that the pumps were operating with the chillers all the time, which was clearly not the case. The result was that the percent of the non chilled water related electricity usage for the week from 17 to 23 January 2006 was on average 21%.

Both the above estimates provided only a mean of assessing the magnitude of the electricity consumed by the equipment unrelated to chilled water production or distribution. If, in the worst case scenarios, this equipment usage was approximately 20% of the total electricity consumption, the average percent was likely to be lower and to affect it less. Therefore, given also the inability to do a better estimate, it was decided to disregard this contribution altogether.

CHAPTER 5 – CREATING BENCHMARKS

5.1 Introduction

This chapter illustrates the procedure undertaken to benchmark the energy consumption of the chilled water system at Clandeboye and highlights the key issues that arose during the application of such procedure.

The comparison of energy use with established benchmarks is a common way to evaluate the energy performance of industrial plants and to assess the efficiency of energy saving measures (CIPEC, 2001; Vaino & Cleland, 2005). In this case, an historical benchmark was used in the status report to measure the actual performance of the chilled water system's energy consumption. This allowed the user to investigate unusual patterns and identify areas of possible implementation of energy efficiency strategies.

Regression calculations are the most common form of analysis used in industrial applications to derive benchmarks of energy usage based on historical energy\production data (Merts & Cleland, 2004; Werner et al., 2005). They are a relatively easy and straightforward method of analysis, especially if the energy use can be linked to a single measure of production. The drawback associated with the use of an historical benchmark is that it is only reliable when nothing in the process changes behind the limits circumscribed by the benchmarking data. As soon as conditions like set points, production volume/mix, plant configuration etc. change beyond these limits, the regression equation is of questionable validity and should be interpreted with caution. A well chosen regression model though should still be able to predict how the benchmark adjusts to small perturbations in the process conditions.

The Demand Response team often used simple linear regressions to analyse the energy consumption of many applications within Fonterra factories, such as steam generation or compressed air (Corson, 2005) and the results have usually proved to be consistent and reliable enough to endorse the choice of such analysis.

The problem though becomes more complicated when multiple variables are likely to influence the energy use and a simple linear relation between production and energy use is difficult to determine. Chilled water applications are included in these more complex instances, which are usually modeled with a multiple linear regression equation (Harris, 1989). In these cases, in order to ensure reliability of results, the analyst needs to correctly predict which process variable will or is likely to change and needs to have also access to data where those variables do change. Bearing this in mind, a multiple linear regression approach was adopted to analyse the energy consumption of the chilled water system at Clandeboye.

5.2 Identification of variables

The first step to be undertaken was the identification of all the production data and other related variables relevant to the use of chilled water and therefore to the energy consumption. As highlighted in previous chapters, this was one of the biggest issues as it is known that an incorrect variable selection could result in the analyses being significantly less accurate (Reddy & Andersen, 2002). The process took several months to complete, unfortunately only to a medium degree of satisfaction, as discussed in chapter 4. Besides, the number of variables that could be selected was necessarily restricted to those that were already available on *Insite*.

There were numerous production-related variables recorded on Demand Response's database but many of them had ambiguous labels that made it difficult to ascribe the variable to the corresponding part of the process. Therefore, it was not always possible to be sure of the influence that each of those variables had on the electricity consumption. Analysis of plant piping and instrumentation drawings (P&IDs) plus site visits were conducted to try and resolve the issue but the situation was so intricate that in the end many results could only be surmised. Experts from Demand Response who were familiar with the processes involved helped in the task.

Table 5.1 (p.60) shows a list of all the variables chosen for the regression analyses, together with their average values, and a brief description of their likely effect on the electricity consumption. All the variables are flows of liquid streams in various parts of the process.

.No	Parameter	Variable label	Avg(1) value	Effect on the electricity consumption
1	***Milk to Modules***	Powder 1&2 Module 1 – Milk Powder 1&2 Module 2 – Milk Powder 1&2 Module 3 – Milk Powder 1&2 Module 4 – Milk	23 m^3/h 48 m^3/h 48 m^3/h 48 m^3/h	The Modules in the Milk Treatment plant are heat exchangers which use chilled water during the last stage of milk processing.
2	***BS Cheese***	BS Cheese - Milk to Brine Salt Cheese	17 m^3/h	The Cheese plant uses chilled water for its processes but part of it comes from a separate dedicated system. However, due to the complexity of the water distribution system, it could not be ascertained which part of the plant was served by the chilled water system under analysis and which was the part with its own dedicated system.
3	***UF Cheese***	Cheese UF - Milk	10 m^3/h	
4	***DS Cheese***	Dry Salt - Milk to Dry Salt Cheese	40 m^3/h	
5	***Cheese Transfer***	Milk to Cheese Transfer Line 1 Milk to Cheese Transfer Line 2	28 m^3/h 27 m^3/h	
6	***Recon***	Milk Recon to Modules	3 m^3/h	It was unclear where this flow comes from or goes to. It was included in the analyses to avoid missing a potentially important flow as the tag name suggested some kind of link with the milk flow to the Modules.
7	***AMF***	AMF Cream Feed to Concentrators	238 m^3/h	Some processes in the AMF plant were believed to be cooled by the powder plant chilled water system though no confirmation of this could be found either during site visits or in any available documentation.
8	***Flavour***	Butter - Cream to Flavourtechs	69 m^3/h	Screen dumps of schematics showed that some chilled water is reticulated to the butter production plant. Again, it was unclear where to exactly and these variables were included to test their relevance.
9	***Butter***	Buttermaker - Cream to Buttermaker	12 t/h	
10	***Evap 1***	Evap 1 Feedrate Evap 2 Feedrate	18 m^3/h 19 m^3/h	All these variables refer to the skim milk flow coming from the Milk Treatment plant and going, through the two Evaporators, to the two Spray Driers as milk concentrate. A process schematic developed by Demand Response showed that a chilled water flow was supplied to the fluid bed driers during the final drying stage.
11	***Evap 2***	Evap 3 Feedrate Evap 4 Feedrate Evap 5 Feedrate	13 m^3/h 12 m^3/h 15 m^3/h	
12	***Drier 1***	Drier 1-Conc to Drier 1 Feedline 1 Drier 1-Conc to Drier 1 Feedline 2	10 m^3/h 10 m^3/h	
13	***Drier 2***	Drier 2-Conc to Drier 2 Feedline 1 Drier 2-Conc to Drier 2 Feedline 2	4 m^3/h 4 m^3/h	
14	***Lact Evap***	Lactose Evaporator Feed	13 m^3/h	Chilled water is used in the final stages of lactose production. These two variables were the only lactose-related ones available on *Insite* and were both included in the analysis for completeness.
15	***Lact Dec***	Lactose Feed Decanter 1 Bal Tank Flow Lactose Feed Decanter 2 Bal Tank Flow	1 m^3/h 1 m^3/h	
(1) Average values refer to the analysed period.				

Table 5.1: Regression variables

5.3 Data Set

The data available covered approximately a 1 year period from 1 March 2005 to 28 February 2006 and included a shut down period in June/July/August when only maintenance was performed. The choice of the data set was a compromise between data availability at the time of the analysis and the need for a good number of data points that would ensure the best model fit. The period of non operation, although not indicative of any trend, was nonetheless included as the electricity consumption was expected to drop and then near zero due to the decrease and final cease of production. The data generally confirmed this expectation as shown in figure 5.1 below.

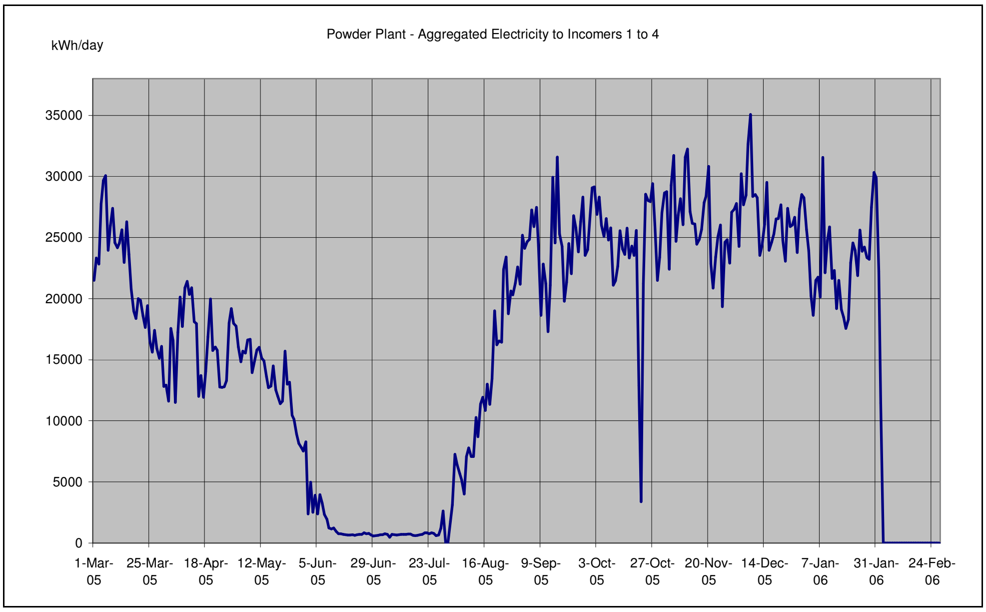


Figure 5.1: Daily electricity to powder plant during the observation period

The big dip in the electricity use just before the 27 October was due to a fault on *Insite* (the raw half hour data reported on the database showed zero values for all the variables from 21:30 on 21st October to 18:00 on 22nd October). Faults like this were found to be not infrequent. Their occurrence, especially when the fault is not so obvious, should not be underestimated because the analyst could misinterpret the resulting values and be led to deceptive conclusions. In this instance, all the identified outliers in the data set have been eliminated as specified in section 5.3.3.

It is worth pointing out that, as discussed in chapter 4, the electricity consumption recorded was not actually dedicated to the chilled water plant. The transformers also fed other equipment but the influence of these extraneous contributions could not be assessed. It was estimated that, in the worst case scenario, these non chilled water electricity uses were approximately 20% of the apparent electricity for chilled water use but because of all the uncertainties associated with this estimate it was ultimately decided to work with the unpurged data set (see chapter 4).

5.3.1 Data Aggregation

The raw data available on *Insite* (see Appendix B) was recorded at half-hour intervals. These values were aggregated in 3-hour, 8-hour and 24-hour intervals in the attempt to determine the optimal level of aggregation that would have to be acquired for M&T purposes. The aggregates started at 7am with the 24-hour intervals going to 7am the following day. The search was for the smallest number of data points that would still ensure reliability of results and no or minimal loss of information about variation in energy use and performance of the chilled water system.

5.3.2 Multicollinearity

As is often the case in multiple regression analyses, many of the predictors were found to be significantly correlated to each other and therefore not independent. In particular, many pairs of variables had a correlation coefficient higher than 0.5. The cross-correlations increased with the increase of the interval data. This suggests, as expected, that there were time lags in the system.

Tables 5.2 (p.63) and 5.3 (p.64) show the cross-correlation matrixes for the half hour and the 24-hour aggregated data for all 15 variables. When the cross-correlation was greater than 0.5, this was noted and when the regression was performed the elimination of these variables from the regression was evaluated. The exclusion of redundant variables is in fact one of the easiest ways to effectively lessen multicollinearity (Selvanathan et al., 2000). The least general variable of the pair was chosen to be eliminated. The difference between the regressions with or without one of the correlated variables was assessed to see if the regression was significantly affected. This elimination process is described in section 5.4.

	Electr	Milk to Modules	BS Cheese	UF Cheese	DS Cheese	Cheese Transfer	Recon	AMF	Flavour	Butter	Evap 1	Evap 2	Drier 1	Drier 2	Lact Evap	Lact Dec
Electr	1.00															
Milk to Modules	**0.79**	1.00														
BS Cheese	0.38	0.30	1.00													
UF Cheese	0.22	0.20	-0.03	1.00												
DS Cheese	0.11	0.10	-0.05	0.47	1.00											
Cheese Transfer	0.24	0.20	0.19	0.30	0.14	1.00										
Recon	-0.01	0.00	0.00	-0.01	0.00	-0.01	1.00									
AMF	0.04	0.03	0.02	0.01	0.05	0.01	0.00	1.00								
Flavour	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.08	1.00							
Butter	**0.57**	0.48	0.31	0.22	0.09	0.21	-0.03	0.03	0.01	1.00						
Evap 1	**0.66**	**0.61**	0.32	0.19	0.09	0.21	0.01	0.04	0.01	0.47	1.00					
Evap 2	**0.70**	**0.62**	0.33	0.21	0.10	0.22	0.00	0.03	0.00	0.49	**0.60**	1.00				
Drier 1	**0.60**	**0.59**	0.27	0.16	0.08	0.17	0.00	0.04	0.00	0.41	**0.64**	**0.59**	1.00			
Drier 2	**0.54**	0.47	0.20	0.16	0.09	0.14	-0.01	0.03	0.00	0.33	0.44	**0.53**	0.38	1.00		
Lact Evap	**0.54**	0.43	0.25	0.04	0.02	0.11	0.01	0.04	0.01	0.35	0.38	0.43	0.35	0.43	1.00	
Lact Dec	**0.54**	0.43	0.24	0.07	0.04	0.14	-0.01	0.03	0.01	0.38	0.36	0.44	0.34	0.36	0.42	1.00

Table 5.2: Correlation matrix for half hour data (15 variables)

	Electr	*Milk to Modules*	*BS Cheese*	*UF Cheese*	*DS Cheese*	*Cheese Transfer*	*Recon*	*AMF*	*Flavour*	*Butter*	*Evap 1*	*Evap 2*	*Drier 1*	*Drier 2*	*Lact Evap*	*Lact Dec*
Electr	1.00															
Milk to Modules	**0.94**	1.00														
BS Cheese	**0.55**	**0.51**	1.00													
UF Cheese	0.31	0.32	-0.09	1.00												
DS Cheese	0.25	0.26	-0.16	**0.90**	1.00											
Cheese Transfer	**0.62**	**0.60**	0.48	**0.73**	**0.70**	1.00										
Recon	-0.02	0.00	0.03	-0.02	-0.02	0.02	1.00									
AMF	0.38	0.37	0.23	0.13	0.10	0.25	0.04	1.00								
Flavour	0.00	0.01	-0.04	-0.02	-0.02	-0.04	0.03	0.06	1.00							
Butter	**0.81**	**0.78**	0.50	0.33	0.26	**0.58**	-0.01	0.27	-0.02	1.00						
Evap 1	**0.84**	**0.86**	0.50	0.27	0.23	**0.56**	0.01	0.36	0.06	**0.67**	1.00					
Evap 2	**0.88**	**0.88**	0.49	0.29	0.25	**0.59**	-0.01	0.34	0.00	**0.71**	**0.77**	1.00				
Drier 1	**0.78**	**0.82**	0.44	0.24	0.22	**0.51**	-0.01	0.31	0.01	**0.64**	**0.85**	**0.79**	1.00			
Drier 2	**0.87**	**0.85**	0.42	0.24	0.20	0.49	-0.06	0.37	0.03	**0.63**	**0.74**	**0.84**	**0.67**	1.00		
Lact Evap	**0.73**	**0.66**	0.45	0.07	0.05	0.33	-0.07	0.39	0.00	0.50	**0.54**	**0.60**	**0.51**	**0.75**	1.00	
Lact Dec	**0.79**	**0.71**	0.46	0.16	0.13	0.42	-0.07	0.32	0.07	**0.69**	**0.59**	**0.68**	**0.55**	**0.71**	**0.71**	1.00

Table 5.3: Correlation matrix for 24-hour data (15 variables)

5.3.3 Outliers

Before undertaking the regressions, it was desirable to eliminate any obvious outlier or anomaly in the data.

It was noted that the electricity values reported on the database were all zeros in the last 27 days of observation (see figure 5.1, p.61). This was an obvious fault because production was continuing as usual during that period. Therefore, all values from the 2nd of February 2006 onwards (up to the last value referring to 28th February) were eliminated from the regressions.

A further analysis of the data showed that there were also other suspicious values requiring attention. For instance, while the four modules that pasteurise the raw milk were rated for 98 m^3/h each (for a total nominal flow rate of just under 400 m^3/h), the aggregated hourly flow reported on the database was occasionally showing some unexplained spikes, ranging from just above 400 m^3/h to nearly 9000 m^3/h (8,891 m^3/h on 21st November, see table 5.4, p.66). Therefore, regressions for each of the roll up intervals were initially performed both with and without the identified outliers. The results confirmed that the "fit" of the regression equation, as measured by the R^2 value, improved significantly in all cases where the outliers had been eliminated, so their elimination was justified (see the summary of regression results in table 5.5, p.69).

Date	Time	Recorded milk flow (m^3/hour)
20-Mar	2:30	439
29-Apr	3:30	6212
30-Apr	13:30	1569
2-May	10:30	968
3-May	13:00	1834
12-May	13:00	2155
15-May	1:00	3456
16-May	10:00	1005
18-May	18:00	1498
22-May	16:00	1074
23-May	19:30	1450
24-May	23:30	3138
26-May	20:00	1083
27-May	0:30	1645
28-May	4:30	1293
11-Aug	16:00	1076
18-Aug	1:00	1708
31-Oct	6:30	7652
21-Nov	5:00	8891
25-Nov	15:00	1230
5-Dec	21:00	4262
7-Dec	13:00	568
7-Dec	15:00	3234
8-Dec	3:00	8043
8-Dec	4:00	5881
9-Dec	1:30	7960
9-Dec	2:30	8552
14-Dec	8:30	601
18-Dec	22:30	4374

Table 5.4: Suspected outliers in milk flow readings on INSITE database (total nominal flow rate is 392 m^3/h)

5.4 Regression Analyses

Several regression attempts were made to try and find a relation between the electricity consumption and all the product flows. The analyses were all done using the regression tool of the Data Analysis tool pack provided with Excel.

A backward stepwise regression approach was taken for all regressions performed, where variables have been progressively eliminated if there was not enough statistical evidence that they were related to the dependent variable (p-values of the coefficients greater than 0.05) (Selvanathan et al., 2000).

Some variables were dropped also on the basis of their correlation. In particular, the variables *Drier 1* and *Drier 2* were eliminated from the regression because the concentrate is the direct by-product of the evaporation process and therefore the values of those variables would have been necessarily dependent on the values of the other variables *Evap 1* and *Evap 2*. The correspondent correlation coefficients in table 5.3 (p.64) (0.85 and 0.84 respectively) confirmed the case.

Evap 1 and *Evap 2* were also subsequently eliminated based on the same concept: their correlation with the milk flow to the four modules. By following this method, the number of variables in the regression equation was reduced from the original 15 to as low as four variables for different aggregated intervals (raw half hour data, 3-hour, 8- hour and 24-hour aggregated values).

A set of simple linear regression calculations was also attempted to model the electricity use as a function of only one variable. This choice was made not only to address the multicollinearity issue but also to verify the appropriateness of the multiple linear regression model. The single variable selected was *Milk to Modules*, which was the only variable that could be linked with certainty to the electricity used by the chilled water system and also the biggest of all product flows previously considered. Table 5.3 (p.64) shows that it also had the highest correlation coefficient (0.94) with regard to electricity use. Furthermore, the milk going to the four modules was the source of numerous downstream flows which were all ultimately dependent on their upstream source.

The criteria used to select the best equation were a combination of:

1. number of variables (the smallest number that would still ensure a good level of variance explanation)
2. overall model fit (highest R^2 values and best model accuracy)
3. significance of each variable coefficient (p-values < 0.05).

Table 5.5 (p.69) gives a summary of some of the regression results in terms of the above mentioned factors. The model accuracy shown in the table is based on the standard deviation of the actual values about the predicted line at the 95% confidence level. The percent error is calculated with regard to the average electricity consumption for each interval roll-up.

The following consideration can be derived from the table:

- The elimination of the outliers significantly improved the outcome in all cases (this is only shown in the first two regressions of each roll-up interval).
- The overall model fit improved with the increase of data aggregation. This could be due to time lags in the system or simply to noise reduction in the data set.
- Reducing the number of variables did not yield significant changes as all the other factors seemed to remain fairly stable after all the not statistically significant variables had been eliminated. This corroborated the initial aim for the smallest number of variables.
- The simple linear regression did not result in a satisfactory outcome as other models showed higher R^2 and better accuracies. Therefore this model was rejected.
- In all instances the model accuracy was quite poor.

Roll-up interval	Regr	Independent variables	Outliers eliminated (*)	R^2	Variables with p>0.05	Model accuracy (kWh)	Average electricity use (kWh)	% error
0.5-hour	**A1**	15	no	0.53	3	± 653	738	±88%
	A2	15	yes	0.77	4	± 435	724	±60%
	A3	11	yes	0.77	none	± 435	724	±60%
	A4	7	yes	0.77	none	± 439	724	±61%
	A5	4	yes	0.71	none	± 492	724	±68%
	A6	1	yes	0.63	n/a	± 554	724	±76%
3-hour	**B1**	15	no	0.60	5	± 1749	2201	±79%
	B2	15	yes	0.85	6	± 996	2169	±46%
	B3	9	yes	0.85	none	± 998	2169	±46%
	B4	7	yes	0.85	none	±1010	2169	±47%
	B5	4	yes	0.81	none	± 1150	2169	±53%
	B6	1	yes	0.74	n/a	± 1344	2169	±62%
8-hour	**C1**	15	no	0.65	5	± 4220	5852	±72%
	C2	15	yes	0.90	6	± 2135	5781	±37%
	C3	8	yes	0.90	none	± 2146	5781	±37%
	C5	1	yes	0.81	n/a	± 2922	5781	±50%
24-hour	**D1**	15	no	0.72	9	± 11072	18804	±59%
	D2	15	yes	0.95	8	± 4536	17315	±26%
	D3	7	yes	0.94	none	± 4602	17315	±26%
	D4	6	yes	0.94	none	± 4695	17315	±27%
	D5	**4**	**yes**	**0.93**	**none**	**± 5124**	**17315**	**±30%**
	D6	1	yes	0.88	n/a	± 6679	17315	±39%

(*) All values of milk incoming flow greater than 400 m^3/h were considered outliers.

Table 5.5: Summary of regression results

5.5 Benchmarking equation

The regression equation selected to model the electricity consumption of the chilled water system was the 24-hour data aggregation (regression D5 in table 5.5, p.69) based on the following four independent variables (numbered as per table 5.1, p.60):

1. Milk to Modules (m^3/day)
5. Cheese Transfer (m^3/day)
14. Lact Evap (m^3/day)
15. Lact Dec (m^3/day)

The Excel output for this regression is shown in figure 5.2 below.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9647
R Square	**0.9306**
Adjusted R Square	0.9297
Standard Error	2562
Observations	339

ANOVA

	df	*SS*	*MS*	*F*	***Significance F***
Regression	4	29384081548	7346020387	1119.207	**5.3607E-192**
Residual	334	2192241089	6563596.08		
Total	338	31576322637			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	**1966**	281.8107435	6.9768538	1.63E-11	1411.804833	2520.5	1411.805	2520.5
Milk to Modules (m^3/day)	**3.8**	0.138659654	27.7017402	1.51E-88	3.568357468	4.11387	3.568357	4.11387
Cheese Transfer (m3/day)	**2.0**	0.384473788	5.26741486	2.48E-07	1.268887814	2.781478	1.268888	2.781478
Lact Evap (m3/day)	**3.0**	0.594659151	5.01293742	8.71E-07	1.811240137	4.150738	1.81124	4.150738
Lact Dec (m3/day)	**43.5**	5.355402983	8.12934524	8.52E-15	33.00135197	54.07049	33.00135	54.07049

Figure 5.2: Excel output for regression D5 (4 variables, daily data, no outliers)

The resulting equation is:

$$Electr = \mathbf{1966} + \mathbf{3.8}\ \textit{Milk to Modules} + \mathbf{2.0}\ \textit{Cheese Transfer} + \mathbf{3.0}\ \textit{Lact Evap} + \mathbf{43.5}\ \textit{Lact Dec} \qquad \mathbf{(5.1)}$$

where *Electr* is the chilled water energy use, in kWh/day.

As said, the final selection was based on the best model accuracy and R^2 value among the ones calculated, considering the least number of variables necessary to run the model (which would simplify its use). In fact, the least number of variables was eventually one of the prevailing factors in the final regression choice. Table 5.5 (p.69) shows other regressions (see D3 and D4) that gave slightly more satisfactory results in terms of both R^2 and accuracy but used a higher number of variables (some of which, like *Butter*, were also particularly unreliable due to the uncertainty of their relevance). These equations were rejected to try and minimise the impact of missing data and/or faults in the data recording system, which were a recurrent and frustrating experience throughout the duration of the project.

The equation coefficients suggest what influence each variable has on the electricity consumption. They contributed to raise some initial concerns over the appropriateness of the selected model. For instance, the coefficient of the last variable was quite large suggesting that small changes in *Lact Dec* cause large changes in the electricity consumption. However, it was still unclear what the actual flow measured by that variable was and its physical linkage to chilled water use was tenuous. On the contrary, the coefficient of *Milk to Modules* suggests that this variable has a much smaller impact on the electricity use, even though it has a proven and strong connection with chilled water use. Only the relative size of the variables mitigates the effect of those coefficients and puts the result more in line with expectations. The daily average of *Lact Dec* is in fact only about 2% of *Milk to Modules* and therefore a coefficient equal to 43.5 has anyhow a smaller effect than the coefficient of 3.8 of *Milk to Modules*.

In spite of poor model accuracy, the final result seemed overall satisfactory, but some concerns still remained as to how the equation would represent the expected electricity consumption when put to the test.

5.6 Initial model test

The selected model has been tested with separate real data for a 10-week period from 31st March to 5th June 2006, when the plant was starting to shut down for its winter break.

Figure 5.3 below shows how the model performed. The upper and lower limits in the graph represent the ± 30% tolerance given by the resulting model accuracy. The target line is the unadjusted prediction of the regression model. It was intended to gradually reduce this target by some percents once the monitoring and targeting activity was up and running and the status report started to be provided on a continuous basis. This would have given a better idea of the expected performance of the system and would have assisted in setting plausible reduced targets for future energy consumptions.

Some of the spikes shown in the graph could not be explained and were drawn to the plant manager's attention in the status report. For instance, on 9th of April the product flows affecting the target equation were approximately 30% of the average daily flow for that week but the electricity usage only decreased to approximately 70% of the daily average consumption for the week. A simple explanation is often more apparent to the people who work daily in the plant and know exactly all the circumstances that occur. In other instances some poorer than target performance have been explained with the plant drawing near the end of the season and the chiller load being often smaller than the smallest chiller.

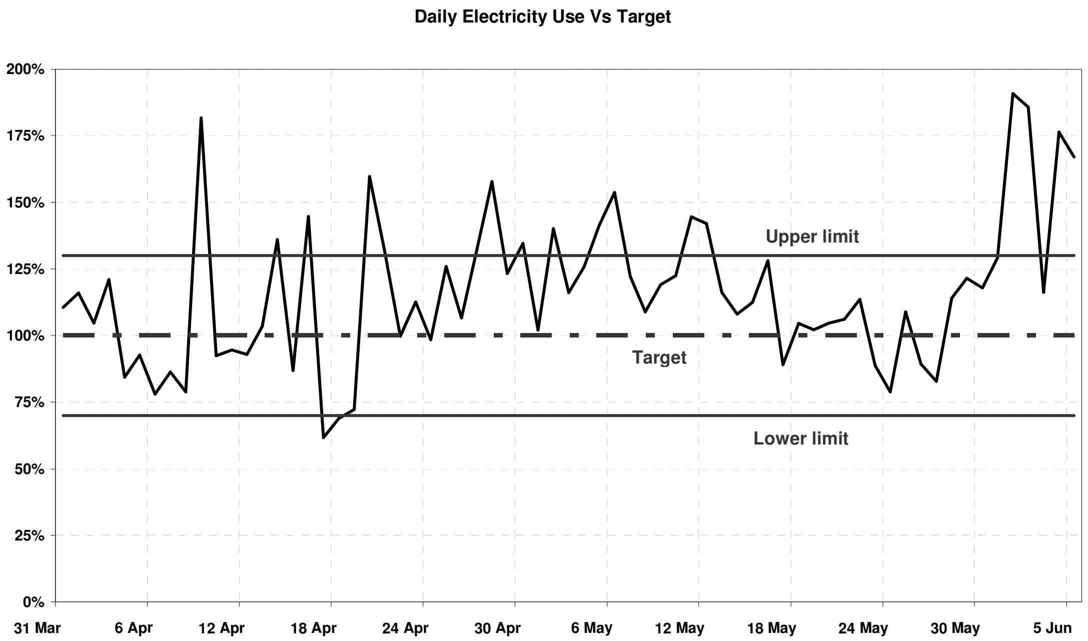


Figure 5.3: Electricity use versus target

CHAPTER 6 – THE REPORTING SYSTEM

6.1 Introduction

The creation of a benchmark for the energy used by the chilled water plant represented one fundamental step towards the implementation of a regular monitoring activity to assess the actual performance of the system and the possibility of introducing energy saving strategies. The other essential part of the process was the development of a good and effective reporting system. A regular report sheet designed to give a snapshot of the system status and to suggest some practical measures to improve energy performance would ensure that all the people responsible for the management and operation of the chilled water plant were regularly updated and able to make informed decisions on the system's operation.

The report developed for the powder plant chilled water system at Clandeboye was created in an Excel workbook and consisted of a two-page document showing graphs, statistics and performance indicators, plus a number of data assembling and calculation sheets that made up the underlying structure of the user-oriented report.

The workbook was to be imported onto *Insite* and set up to be automatically generated so that authorised staff from both Demand Response and Fonterra could access it. By selecting the end date of a default one-week period, the user would automatically be shown the resulting two page report filled with the desired information. All users would be able to access the whole workbook, although it was expected that managers and operational staff would only be looking at the two page report with graphs, statistics and comments while the person responsible for the verification and maintenance of the workbook would have to be familiar with all the underlying worksheets.

This chapter describes the Clandeboye's report in its entirety. Starting from the actual report page, all the workbook's components will be presented one by one and the logic behind some of the choices made in developing them will be explained.

6.2 The STATUS Report

The report page, called STATUS report using an acronym that means "System To Achieve Targeted Utility Savings", represents the interface between the calculation tools embedded in the other worksheets and the intended report users. All the data collected and re-arranged in the other sheets is shown in this two-page document in a way that should enable users to immediately understand how the system is performing and to make informed decisions on the system management. As discussed in chapter 3, the kind of information that appears on these pages as well as the way the information is presented could make the difference between a successful and a poor M&T system.

Drafting the report has been a real challenge from the beginning because of the poor data collection system in place. Not only was *Insite* providing a meager number of relevant variables but most of the time it was affected by incomplete or faulty recordings that made it impossible to identify trends. Therefore, in the attempt to come up with the most effective report possible in terms of content and layout, the initial drafts had to be based on a mix of data from different weeks.

Once all the variables required for the report had been identified, including those necessary for the regression equation, the corresponding metering devices needed to be logged into the database. This requirement took some time to be actioned and in the meantime most data had to be manually collected and emailed by operators on site. In fact, for some of the variables the loading into *Insite* never eventuated during the project timeframe.

The final version of the report was released during the last stage of the research project but by then the plant was approaching its shut down period and there was very little opportunity to test its effectiveness and reliability. Opportunities for further developments will be discussed in section 6.4.

Some of the changes that have been introduced in the final report in terms of content and layout have resulted from the findings of a focus group discussion among three chilled water plant operators from three different Fonterra's sites, one Process Technologist and one Energy Lead Technologist. The idea to run a focus group among some of the potential report users was supported by the knowledge that the use of facilitated sessions to capture diversity of views in order to achieve a common objective leads to more effective results. This is because “solutions are created, understood and accepted by the people impacted” (Wilkinson, 2004).

The purpose of the focus group was *to evaluate the current chilled water system STATUS reports in the attempt to develop a report format that contains all the information relevant to the target audience and conveys this information in the most immediate and effective way*. Appendix A contains the focus group agenda that was drafted to introduce the participants to the above purpose, the methodology chosen to run the meeting and the main topics that were intended to be covered.

Appendix A also contains the questionnaire that was circulated among the participants during the session and that represented the core of the discussion. The questionnaire was divided in two sections, one for the evaluation of the current report and one for the evaluation of alternatives. Some of the questions asked were about the graphical features of the report and how these were perceived by the readers; other questions looked at investigating how well the report was understood and interpreted and if it was deemed to be useful as a diagnostic tool; finally, the last section was intended to give some cues on possible modifications by guiding the participants through a selection of choices on different charts and/or a different layout.

Figures 6.1 to 6.3 (p.76, 80, 81) show some of the subsequent report designs, from the first draft to the final version delivered to Fonterra at the end of the project.

Figure 6.1 (p.76) shows two of the initial designs, where the report fit in only one page. Both drafts show a plot of site cooling duty and plant COP plus a graph of suction/discharge pressure for each of the four compressors.

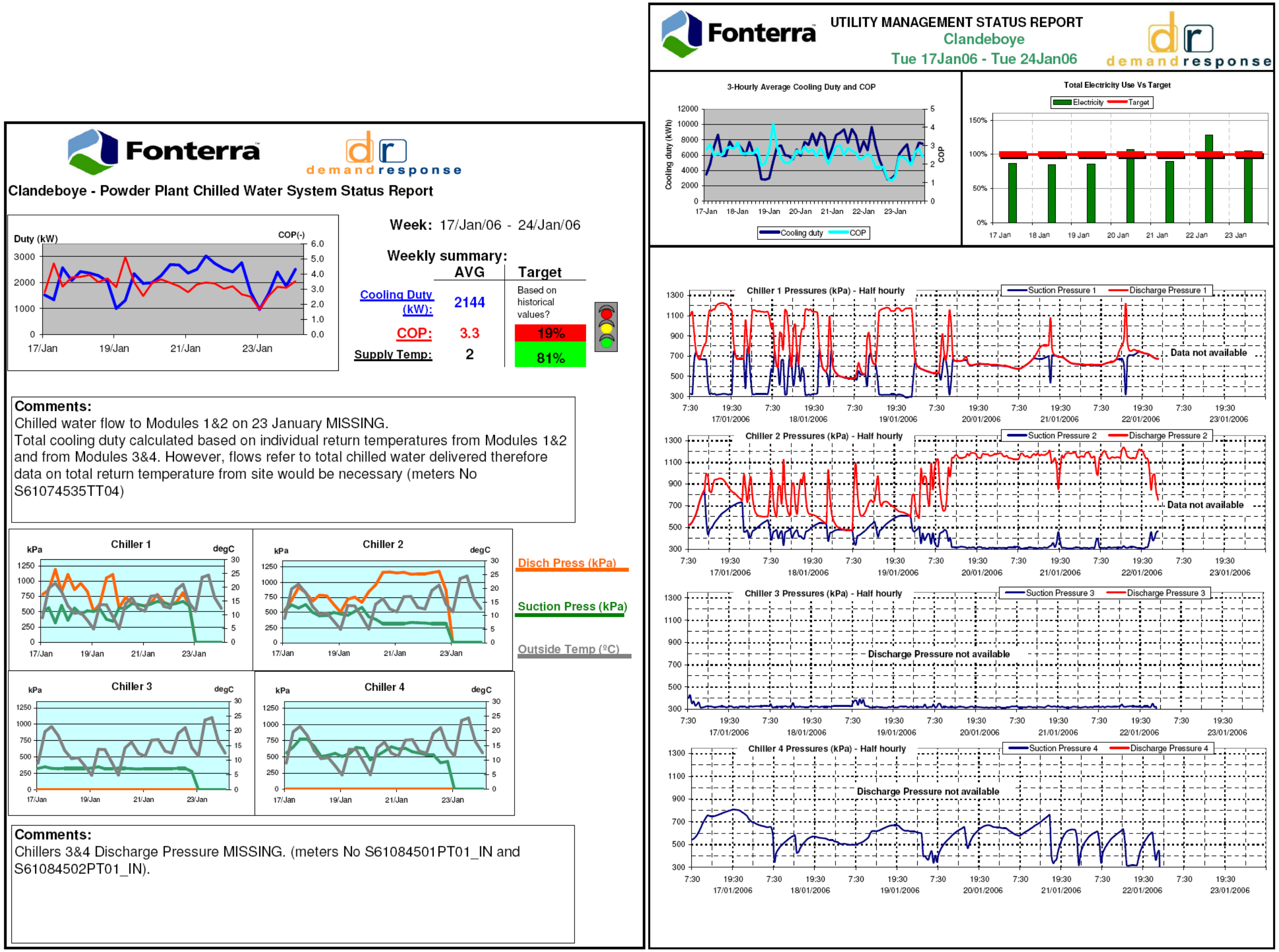


Figure 6.1: Two of the initial report drafts

Some of the changes introduced in the second draft (figure 6.1, on the right, p.76) included different data aggregation for the cooling duty and COP graph (three-hour interval data instead of half-hour); the introduction of the electricity benchmark based on historical data (the regression model) with its corresponding graph and the widening of the four compressors charts to fit the page one below the other. The latter modification was left unchanged to the final version and one of the focus group findings was in fact that it was preferable to have the x-axis of the same size and scale for each graph so to be able to physically overlay the graphs on the report.

The second report did not include comment boxes, but these were then reintroduced in subsequent drafts and finally repositioned after the focus group session, where all participants agreed on their usefulness and wanted to see the commentary straight beneath the initial summary statistics rather than at the bottom of the page. The focus group also highlighted the fact that local personnel could be providing a better insight into the plant operation and could append to the report commentary using their own knowledge and/or consulting shift logs that a remote analyst would have difficulty to access. It was therefore proposed that, after its initial generation and before its final distribution to managers and operators, the reports be passed to a local contact who would attempt to answer some of the questions raised by the remote analyst. This process would prevent the report circulating with too many unanswered questions on it though the whole process would take longer to complete.

Figure 6.2 (p.80) illustrates the first two-page report, which contained some additional information in form of new graphs (a supply and return temperature chart) and a table of statistics with data on average daily electricity consumption, milk flow, cooling duty and supply and return water temperatures to and from site.

The "Target" column in the table shows historical benchmarks to enable a quick assessment of the system performance; the electricity target was obtained as discussed in chapter 5; the cooling duty target was obtained with a similar methodology but had to be based on a much smaller dataset because all the necessary data could only be retrieved for a one-week period (part of the milk flow to site as well as the return temperature from site have been continuously unavailable). The actual duty is compared to the target to verify consistency of trends (a small tolerance is allowed so that if actual is higher then benchmark by less than 15%, it is still considered "within tolerances" and the cell is highlighted in yellow). The COP target, originally set to the maximum value observed for the week, was then set as the ratio between the cooling duty and the electricity target. The use of targets was also discussed during the focus group and all participants agreed that, to avoid misinterpretations, some sort of explanatory note about how they are generated needed to be added to the report.

The supply and return temperatures shown in the table are considered within target if during the week their average value is consistently less than 3^{o}C for the supply (design value is 2^{o}C) and within 5 and 10^{o} C for the return temperature (design value is 7-8^{o}C). The condition on the return temperature was based on the consideration that a lower than design average return temperature would indicate that chillers had been operating part loaded (and therefore inefficiently) while a high return temperature could be a sign that chilled water had not been supplied or had been supplied to cool cleaning water rather than milk and products. If any of these conditions is not satisfied, the embedded formulas calculate the percentage of time that targets are not met and the results are also shown in the table.

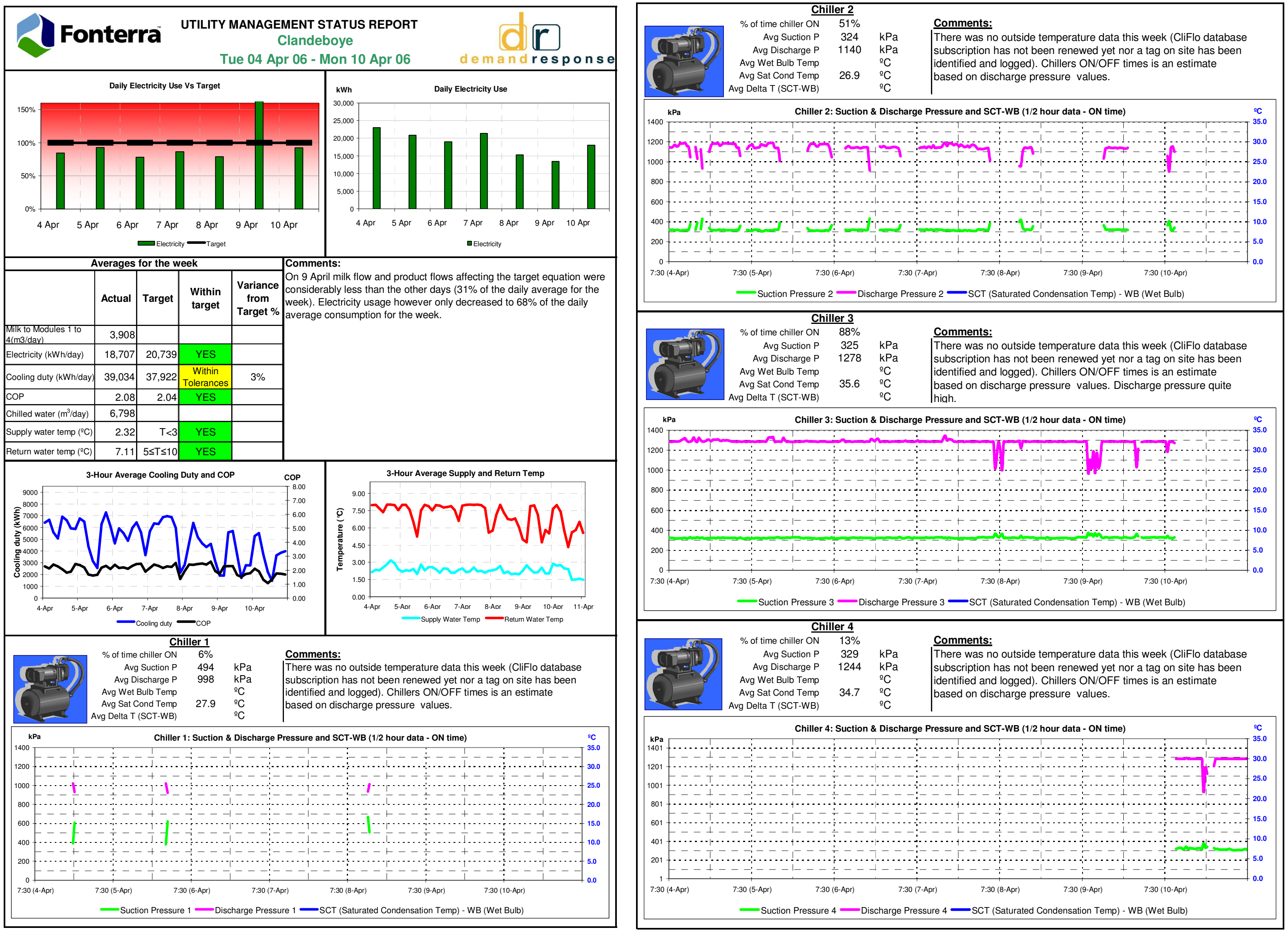
Finally, figure 6.3 (p.81) shows the latest report layout as finalised after the focus group. The comparison of daily electricity use versus target was changed from a bar chart into a line graph as this was found to be consistent with other similar reports that participant had already been using and therefore were familiar with. The upper and lower limits represent the 30% bandwidth given by the model accuracy (see chapter 5).

To improve readability, the cooling duty and COP graph as well as the supply and return temperature graph were widened to occupy the whole page and positioned one below the other while their data aggregation was set to half hourly values. Statistics for the chiller were concentrated in one table at the bottom of the first page so that the chiller suction and discharge pressure graphs could fit all together into the second page.

Another thing discussed during the focus group was the usefulness of plotting the saturated condensation temperature (STC) in the suction and discharge pressure charts of the four compressors. This variable (together with the wet bulb temperature, WB) was included in the previous version of the report though it was only a theoretical allowance as data was never actually available. The idea was to provide a visual "feel" of the condenser driving force by plotting, together with the discharge pressure, the difference between the condensation temperature (which corresponds to the discharge pressure because of the unique pressure-temperature relationship for each refrigerant) and the wet bulb temperature (STC - WB). A higher difference would mean the possibility to lower the discharge pressure (compatibly with the wet bulb temperature) and achieve reduced energy consumption.

Focus group participants saw little value in the saturated condensation temperature and felt that they could derive it themselves if required. Some people would have wanted the wet bulb temperature on the same graph as the discharge pressure, seemingly ignoring that the two variables are not comparable. It appeared as though, in spite of it being common practice to express compressor discharge conditions in terms of the equivalent SCT (Love et al., 2005), there was confusion among the operators and managers about what the condensation temperature actually means.

The confusion about the meaning of the variables, together with the fact that wet bulb temperature data, though repeatedly requested was nonetheless never provided during the course of the project due to logistic reasons, led to the decision to leave out the plot of those variables (WB, STC or their difference) from the suction and discharge pressure graphs and to just make provision for wet bulb temperature average values in the statistics box at the bottom of the first page. The decision could be revised in the future if circumstances changed (necessary data easily available and benefits more apparent to the report users).



UTILITY MANAGEMENT STATUS REPORT
Clandeboye
Tue 04 Apr 06 - Mon 10 Apr 06

Daily Electricity Use Vs Target

Daily Electricity Use

Averages for the week

	Actual	Target	Within target	Variance from Target %
Milk to Modules 1 to 4(m3/day)	3,908			
Electricity (kWh/day)	18,707	20,739	YES	
Cooling duty (kWh/day)	39,034	37,922	Within Tolerances	3%
COP	2.08	2.04	YES	
Chilled water (m^3/day)	6,798			
Supply water temp (ºC)	2.32	T<3	YES	
Return water temp (ºC)	7.11	5≤T≤10	YES	

Comments:
On 9 April milk flow and product flows affecting the target equation were considerably less than the other days (31% of the daily average for the week). Electricity usage however only decreased to 68% of the daily average consumption for the week.

3-Hour Average Cooling Duty and COP

3-Hour Average Supply and Return Temp

Chiller 1

% of time chiller ON	6%	
Avg Suction P	494	kPa
Avg Discharge P	998	kPa
Avg Wet Bulb Temp		ºC
Avg Sat Cond Temp	27.9	ºC
Avg Delta T (SCT-WB)		ºC

Comments:
There was no outside temperature data this week (CliFlo database subscription has not been renewed yet nor a tag on site has been identified and logged). Chillers ON/OFF times is an estimate based on discharge pressure values.

Chiller 1: Suction & Discharge Pressure and SCT-WB (1/2 hour data - ON time)

Chiller 2

% of time chiller ON	51%	
Avg Suction P	324	kPa
Avg Discharge P	1140	kPa
Avg Wet Bulb Temp		ºC
Avg Sat Cond Temp	26.9	ºC
Avg Delta T (SCT-WB)		ºC

Comments:
There was no outside temperature data this week (CliFlo database subscription has not been renewed yet nor a tag on site has been identified and logged). Chillers ON/OFF times is an estimate based on discharge pressure values.

Chiller 2: Suction & Discharge Pressure and SCT-WB (1/2 hour data - ON time)

Chiller 3

% of time chiller ON	88%	
Avg Suction P	325	kPa
Avg Discharge P	1278	kPa
Avg Wet Bulb Temp		ºC
Avg Sat Cond Temp	35.6	ºC
Avg Delta T (SCT-WB)		ºC

Comments:
There was no outside temperature data this week (CliFlo database subscription has not been renewed yet nor a tag on site has been identified and logged). Chillers ON/OFF times is an estimate based on discharge pressure values. Discharge pressure quite high.

Chiller 3: Suction & Discharge Pressure and SCT-WB (1/2 hour data - ON time)

Chiller 4

% of time chiller ON	13%	
Avg Suction P	329	kPa
Avg Discharge P	1244	kPa
Avg Wet Bulb Temp		ºC
Avg Sat Cond Temp	34.7	ºC
Avg Delta T (SCT-WB)		ºC

Comments:
There was no outside temperature data this week (CliFlo database subscription has not been renewed yet nor a tag on site has been identified and logged). Chillers ON/OFF times is an estimate based on discharge pressure values.

Chiller 4: Suction & Discharge Pressure and SCT-WB (1/2 hour data - ON time)

Figure 6.2: The first two-page report draft

Fonterra

UTILITY MANAGEMENT STATUS REPORT

Clandeboye

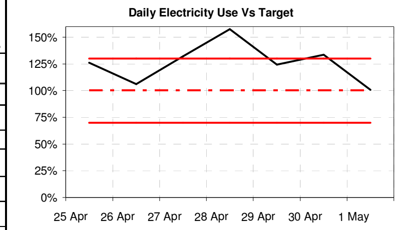
Tue 25 Apr 06 - Mon 01 May 06

demandresponse

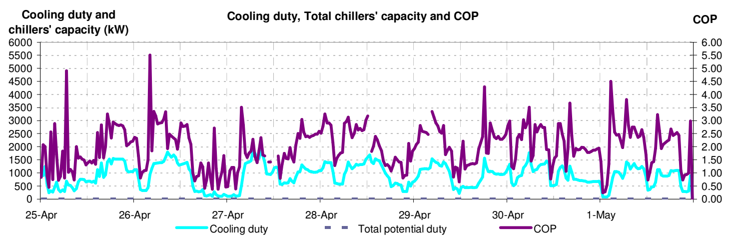
Daily Averages

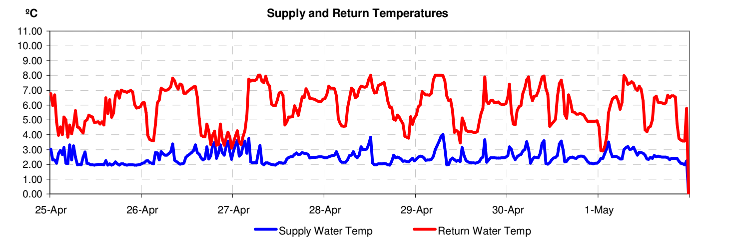
	Actual	Target	Within Target	Variance from Target %
Milk to Modules 1 to 4 (m3/day) *	1,212			
Chilled water (m^3/day)	5,231			
Supply water temp (ºC)	2.49	T<3	YES	
Return water temp (ºC)	5.84	5≤T≤10	YES	
Cooling duty (kWh/day)	21,595	23,896	YES	
Electricity (kWh/day)	10,739	8,602	NO	25%
Electricity cost ($/day)				
COP	2.02	2.54	NO	-20%

** Note that milk to modules is only one of the variables affecting the target equation. Milk to cheese and lactose also play a role though to a less extent.*

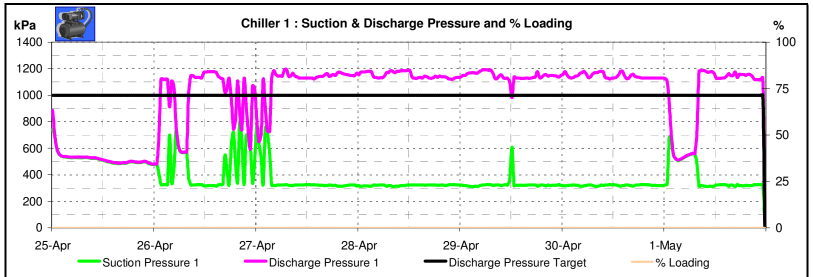


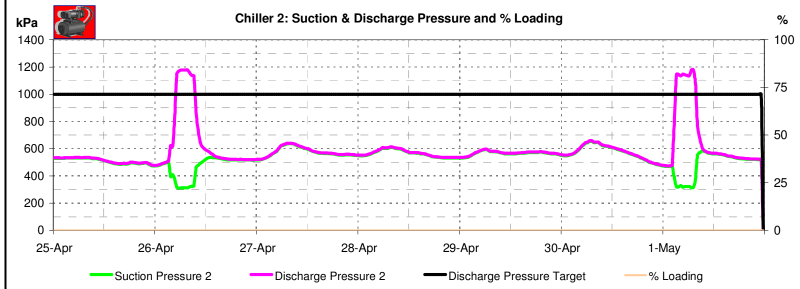
Comments

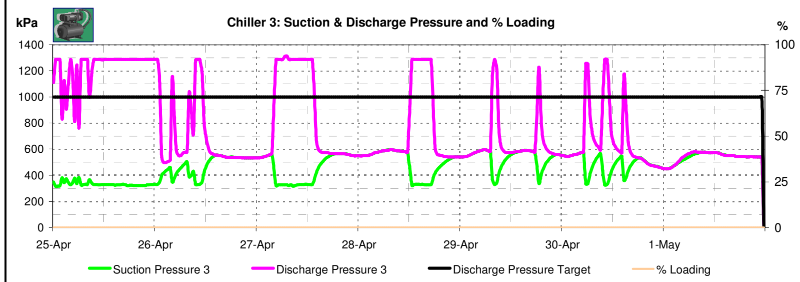




Chillers' Statistics		Chiller 1	Chiller 2	Chiller 3	Chiller 4	Remarks
Nominal capacity	(kW)	1420	1420	2250	3000	
% of time chiller ON		No data	No data	No data	No data	
% loading		no data	no data	no data	no data	
Avg Suction P	(kPa)	383	534	472	553	
Avg Discharge P	(kPa)	1002	594	766	559	
Avg Wet Bulb Temp	(ºC)	No data	No data	No data	No data	







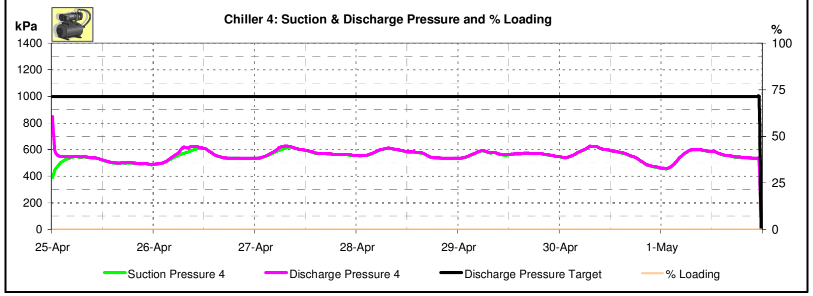


Figure 6.3: The final STATUS report

6.3 Report Structure

As anticipated at the beginning, the STATUS report represented only the interface between a series of underlying worksheets and the report user. As the development of the workbook progressed, these worksheets too, just like the STATUS report, have undergone a series of changes, which were partly reflected in the modified report layout (addition or elimination of reported data, change of data aggregation, etc.).

Together with the STATUS report, the sheets that form part of the final version of the Excel workbook are:

1. Data
2. Analysis
3. Run Macro
4. Daily
5. Targets

6.3.1 The Data Worksheet

This Excel spreadsheet contains time series data representing the flow of all the variables deemed to be pertinent to the analysis. The datasets are loaded into the sheet in half-hourly interval values, as recorded on *Insite* by the corresponding metering devices. The complete dataset is listed in table 6.1 (p.83).

Resource Type	No	Variable Label [(1)]	Tag No	Unit	Description
Chilled Water	1	Powder 1/2 ChW to Mods 1&2, Cheese & UF3	S61074535FT01	m³/h	Chilled water flow to the pasteurising modules 1 to 4
	2	Powder 1/2 ChW to Mods 3&4 and Lactose	S61074535FT02	m³/h	
	3	Powder 1/2 ChW Supply Temp	S61074535TT02_In	ºC	Chilled water supply temperature
	4	Powder 1/2 ChW Return Temp	S61074535TT04_In	ºC	Chilled water return temperature
	5	Powder 1/2 ChW Comp1 DischargeP	S61074530PE01	Bar g [(2)]	Discharge pressure of the four compressors
	6	Powder 1/2 ChW Comp2 DischargeP	S61074531PE01	Bar g	
	7	Powder 1/2 ChW Comp3 DischargeP	S61084501PT01_In	Bar g	
	8	Powder 1/2 ChW Comp4 DischargeP	S61084502PT01_In	Bar g	
	9	Powder 1/2 ChW Comp1 SuctionP	S61074530PE02	Bar g	Suction pressure of the four compressors
	10	Powder 1/2 ChW Comp2 SuctionP	S61074531PE02	Bar g	
	11	Powder 1/2 ChW Comp3 SuctionP	S61084501PT04_In	Bar g	
	12	Powder 1/2 ChW Comp4 SuctionP	S61084502PT04_In	Bar g	
	13	Powder 1/2 ChW Comp1 CV%	S61074530ZT01_In	%	Position of the slide valve for the four compressors
	14	Powder 1/2 ChW Comp2 CV%	S61074531ZT01_In	%	
	15	Powder 1/2 ChW Comp3 CV%	S61084501ZT07_In	%	
	16	Powder 1/2 ChW Comp4 CV%	S61084502ZT01_In	%	
	17	Powder 1/2 ChW Comp1 hours	CHL1_HOURTMR	hours/h	Compressors run time [(3)]
	18	Powder 1/2 ChW Comp2 hours	CHL2_HOURTMR	hours/h	
	19	Powder 1/2 ChW Comp3 hours	CHIL3_Run_Hour	hours/h	
	20	Powder 1/2 ChW Comp4 hours	CHIL4_Run_Hour	hours/h	
	21	Elect to Chilled Water Incomer1	S61075700ET01_LHH	kW	Electricity input to the four compressors & ancillaries
	22	Elect to Chilled Water Incomer2	S61075700ET02_LHH	kW	
	23	Elect to Chilled Water Incomer3	S61075700ET03_LHH	kW	
	24	Elect to Chilled Water Incomer4	S61075700ET04_LHH	kW	
Product	25	Powder 1/2 Module 1 Milk	P61072001FT01_Total	m³/h	Milk flow to the four pasteurising modules
	26	Powder 1/2 Module 2 Milk	P61072004FT01_TOTAL	m³/h	
	27	Powder 1/2 Module 3 Milk	P61072011FT01_TOTAL	m³/h	
	28	Powder 1/2 Module 4 Milk	P61072013FT01_TOTAL	m³/h	
	29	Cheese Milk to Cheese Transfer Line 1	R15003011FT01TT	m³/h	Miscellaneous milk and product flows that resulted significant for the regression model
	30	Cheese Milk to Cheese Transfer Line 2	R15003012FT02TT	m³/h	
	31	Lactose Evaporator Feed	W45001301FC01_PV	ºC	
	32	Lactose Feed Decanter 1 Bal Tank Flow	W45005601FT03_TOT	m³/h	
	33	Lactose Feed Decanter 2 Bal Tank Flow	W45005603FT04_TOT	m³/h	
Ambient Conditions	34	N/a [(4)]	N/a [(4)]	ºC	Average Outside Temperature
	35	N/a [(4)]	N/a [(4)]	g/kg	Average Moisture Content
	36	N/a [(4)]	N/a [(4)]	ºC	Average Wet Bulb Temperature

[(1)] Variable labels as shown on *Insite* and last updated in May 2007; [(2)] Pressure gauge, measured with reference to atmospheric pressure; [(3)] hr/hr*0.5*60 = compressors run minutes; [(4)] Tags requested but still not available at time of project completion.

Table 6.1: Dataset in the data worksheet

6.3.2 The Analysis Worksheet

This is the worksheet where preliminary calculations are performed on some of the data. In particular, individual flows such as chilled water to the two main supply branches and electricity to each of the four incomers are added together to derive totals; cooling duty and COP are calculated; supply and return temperatures are checked to verify that their values are within a specified range; average wet bulb temperatures, if not available as such on the database, are calculated with the use of psychrometric formulas based on dry bulb temperatures and moisture contents (provided they are available instead); compressors suction and discharge pressures are purged of chiller off-time values if compressors run time is recorded and the percentage of chiller operating time plus the total load on all the chillers is calculated; lastly, when the chiller run time and the slide valve position are recorded, the average percent of loading of each chiller over the half hour is also calculated.

Figure 6.4 below shows a graph of suction and discharge pressure for one of the chillers as it would appear if chiller operating times were not provided. In this case, there would be no means of purging the graph of the compressor transient operating conditions, which are indicated by the dropping/rising lines corresponding to the decreasing discharge and increasing suction pressure occurring during shut-down. The calculations in the *Analysis* worksheet, together with the *Macro* built in the workbook provide a mean to tidy up the chillers' chart and to include in the plot only chillers' normal operating conditions.

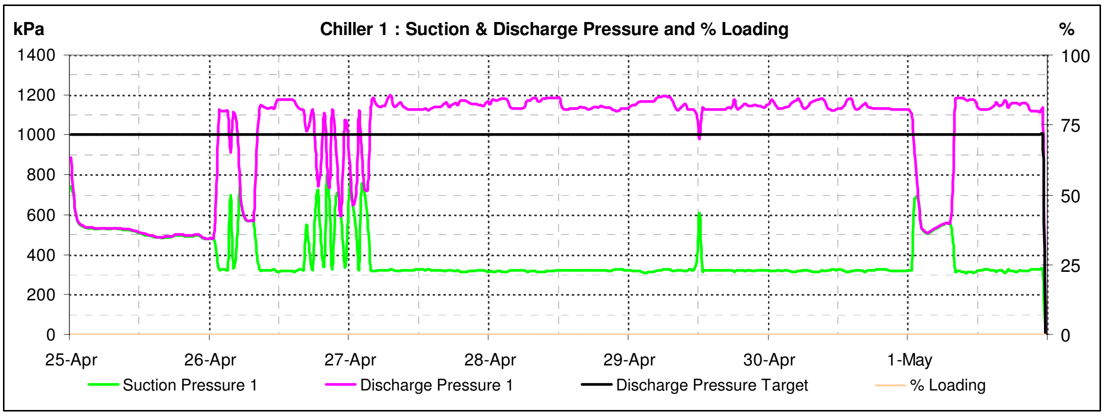


Figure 6.4: Compressor chart inclusive of transient operation

6.3.3 The Run-Macro Worksheet

This worksheet, in combination with the *Analysis* sheet, is used to de-clutter the suction and discharge pressure graphs shown in the *Report* sheet by eliminating from the graph source data all the points corresponding to chillers' shutting down times.

When chiller run times are provided, the *Analysis* sheet works out if they result to be less than 25 minutes in each half hour, in which case the corresponding suction and discharge pressure values are automatically voided. This purges the data of all the instances of transient operation, when compressors are starting up or shutting down during a half hour period. The data is then formatted with a macro, so that it displays correctly. The resulting graph is shown in figure 6.5 below.

One disadvantage of introducing the macro is that it needs to be run manually every time that a new worksheet is generated and this represents a weakness in the design as the ultimate aim was to keep the report users inputs to a minimum.

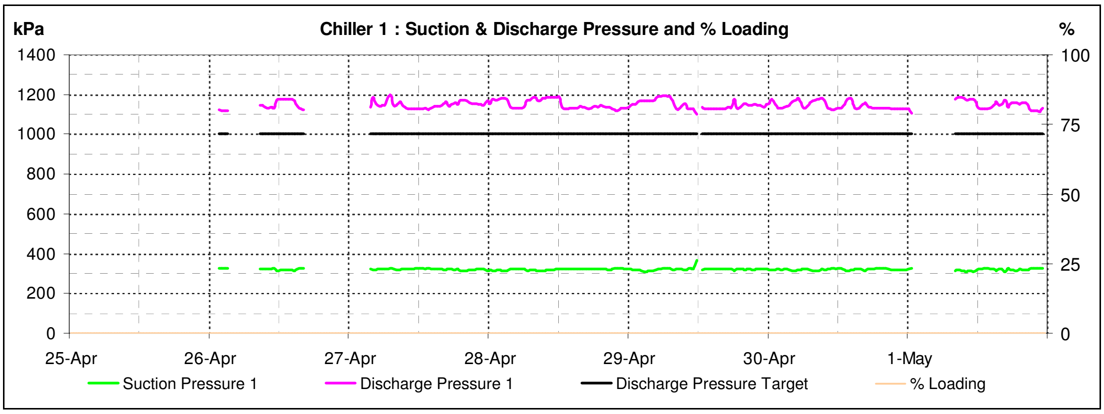


Figure 6.5: Compressor chart after the Macro activation

6.3.4 The Daily Worksheet

This is where some of the flows are grouped together in daily values to be referenced in the statistics table (Daily Averages) of the *Report* sheet (flows a, b, c, d, e, i and j as listed below) or to be used for the target generation in the *Target* sheet (flows c, f, g and h as listed below). The calculated daily flows are:

a. Total daily chilled water to site (variables No 1 & 2 of table 6.1, p.83)
b. Daily cooling duty (as derived in the *Analysis* sheet, see 6.2.1)
c. Total daily milk flow to site (variables No 25 to 28 of table 6.1)
d. Total daily electricity to the four incomers (variables No 21 to 24 of table 6.1)
e. Daily COP (obtained as "daily cooling duty/total daily electricity")
f. Total daily milk to cheese transfer lines (variables No 29 & 30 of table 6.1)
g. Daily lactose evaporator feed (variable No 31 of table 6.1)
h. Total daily lactose feed decanter tank (variables No 32 & 33 of table 6.1)
i. Daily average chilled water supply temperature (variable No 3 of table 6.1)
j. Daily average chilled water return temperature (variable No 4 of table 6.1)

Table 6.2 (p.87) gives a screenshot of the *Daily* worksheet.

Date	Tot Chilled Water m^3/day	Tot Cooling Duty kWh/day	Total Milk Income m^3/day	Total Electricity to Incomers 1 to 4 kWh/day	COP	Tot Milk to Cheese Transfer Lines 1&2 m^3/day	Tot Lactose Evaporator Feed m^3/day	Tot Lact Feed Dec 1+2 Bal Tank m^3/day	Avg Supply Temp (Daily) ºC	Avg Combined Return Temp - (Daily) ºC
25-Apr-06	5123	20438	1234	11206	1.82	0	109	44	2.22	5.47
26-Apr-06	5196	19637	1083	9677	2.03	0	293	50	2.62	5.49
27-Apr-06	5204	23082	899	12691	1.82	0	787	43	2.53	6.14
28-Apr-06	5444	24354	1057	11662	2.09	0	13	32	2.45	6.16
29-Apr-06	5275	21800	1481	10093	2.16	0	2	12	2.52	5.95
30-Apr-06	5499	22722	1397	10772	2.11	0	262	0	2.57	6.04
1-May-06	4879	19134	1331	9074	2.11	0	98	39	2.53	5.66

Table 6.2: Screenshot of a *Daily* worksheet.

6.3.5 The Targets Worksheet

This is where all the targets are calculated based on the daily values. The electricity target was discussed in chapter 5 while all the others have been illustrated in section 6.2.

6.4 Report Development

Demand Response engineers implemented the report on *Insite* as soon as it was completed but could only refine it once the milk season started again.

The major thing that needed attention was the regression model discussed in chapter 5. It was found that the equation was not reflecting a true trend and a new model became necessary. This was created using the same approach as before but with new data and one new regressor. Prior to the plant restarting its normal operation, some modifications had been made to the chiller system, including the isolation of the dryer 3 chiller. This had meant that the chilling of processes in the dryer 3 plant, formally done by the dryer 3 own dedicated system, was now to be performed by the powder chiller system. The new regressor introduced was the milk flow to the filters in the powder 3 plant.

Another problem that needed to be paid close attention to was the issue of the missing data on *Insite* as one of the reasons why the report could not be optimised was the constant provision of incorrect and/or incomplete data, even when this data was being provided directly from site. Besides, this was not an ideal situation anyway as the report generation was supposed to be automated and requiring not more than one person to be done, not to rely on operators from site to collect and load data manually.

From August 2006, the team at Demand Response worked at updating *Insite* and implemented a number of changes to make it more user-friendly and powerful. One of these changes was the introduction of a preliminary check of the datasets coming into the database to remove confirmed spikes before the data were stored and used for the report generation. The analysts also worked on debugging the software and making the reporting process easier and more robust.

The development of a new model, the addition of missing datasets into *Insite* and the database performance-improvement process yielded the first results in February 2007 when, thanks to the report, the site personnel were able to identify an energy saving opportunity estimated to be worth around $50,000 per year, which is approximately 8% of the total variable electricity costs for refrigeration at Clandeboye (S. Gillespie, 14 May, 2007, personal communication). By simply changing the chillers' run-order (chillers 1 and 2 running instead of 3 and 4) they managed to increase the system COP by approximately 15%.

CHAPTER 7 – CONCLUSIONS

Energy Monitoring and Targeting is a powerful management technique to collect and interpret energy data known since the late 1970s. However, it was never extensively applied from its early developmental stages because of the complexity of some applications, which added to the then insufficient incentives for energy saving strategies.

This thesis has examined the development and implementation of a structured M&T methodology to be applied to chilled water systems used in dairy facilities. The stages of this methodology, while conceptually similar for all applications, are more complex when the energy use is spread across a number of different but often interconnected processes (as is the case for dairy production processes). Because of this, they are also more prone to ineffectiveness if not implemented properly.

Three main problems arose during the project, all related to the data collection process, which is the first essential stage of any M&T application. This has substantiated a theoretical concept that emerged from the literature review: data collection, though apparently a simple and straightforward process, bears an intrinsic complexity which, if not managed properly, can lead to errors that invalidate the whole methodology. The problems encountered were:

- Data ambiguity: mainly caused by poorly documented changes to plant configuration.
- Lack of data: sometimes due to logistic reasons that impeded prompt data acquisition.
- Data errors: caused by inaccuracies of meters and/or software bugs.

All of the above issues resulted in collected datasets often inconsistent with expectations and almost invariably leading to incorrect interpretations during the analysis stage. This has also caused otherwise unneeded delays in the project progress.

The multiple regression analysis adopted to interpret the collected data initially gave unsatisfactory results because of all the deficiencies in the previous stage; the fast approaching end of the milking season (as well as of the expected date of completion for the project) did not allow time to refine the model and further expand its scope of application. Nevertheless, as both the literature and the experience with similar systems within Fonterra suggest, the method is believed valid and appropriate and is endorsed provided it sits on solid foundations. In fact, after the project was completed, the team at Demand Response implemented a few changes into the database and worked on developing a new model with updated and more reliable data. With these new elements and using the developed reporting methodology, in February 2007 they were able to identify a saving opportunity of about $50,000.

The report generated, once finalised after the focus group session, was positively commented on and successfully integrated into *Insite*, where it is still used as an effective informative tool to target energy saving opportunities.

The main objective of this thesis, to develop a structured methodology for the implementation of an energy monitoring and targeting system into the Clandeboye's chilled water system, has been met regardless of all the difficulties. In fact, the difficulties encountered have helped to define the methodology and to provide a caveat for future implementations. Having defined a methodology rather than a specific M&T system also means that, as anticipated in the project objectives in chapter 1, its underpinning principles can easily be applied to other industrial refrigeration systems with minor modifications (evaluated on a case by case basis) if and where necessary.

APPENDIX A

Focus Group on Chilled Water Systems Status Report

Purpose of the focus group: To evaluate the current chilled water system status reports in the attempt to develop a status report format that contains all the information relevant for the target audience and conveys this information in the most immediate and effective way.

Venue: Hamilton

Time: 9-11am (or 10am-12pm)

Duration: 2 hours approx

Focus Group Agenda

1. **Welcome ~ (5 min)**
   a. Introduction to purpose and context of the focus group.
   b. Review of agenda and methodology used to carry out the agenda (including means to record the session, if used).

2. **Status Report: Understanding Expectations ~ (10 min)**
   a. Are you familiar with status report? If yes, what kind of status report do you receive?
   b. What is the information most relevant to you that you would expect to find in a chilled water system status report?
   c. Why is this information important? What use would you make of such information?

3. **Status Report: Evaluating Current Format and Content ~ (40 |60 min)**
   [Example of an actual report is handed out together with a questionnaire. Some of the questions are listed below]
   a. What are the report features that catch your attention at first sight? (i.e. graphs, colors, text, combination of all of them).
   b. Based on your answer to question 2, is your attention drawn to the right place? (i.e. do these prominent aspects of the report lead you to immediately find information relevant to you or are they rather distracting?).
   c. Can you find what you would expect to find?
   d. How easily can you find it?
   [Participants are asked some questions, through the questionnaire, to test their comprehension of the report.]
   e. Is something missing from the report?
   f. Is something redundant?
   g. Indicate two things you like and two things you do not like about the actual report, giving a brief explanation for your selection. [A brief discussion is encouraged]

4. **Status Report: Evaluating Alternatives ~ (20 |30 min)**
    a. What changes would you make to the actual report layout and/or content to make it more respondent to your needs? [Participants are asked to sketch a few changes on the existing report]
    b. Indicate which is, in your view, the best report between the ones proposed. Briefly justify your choice. [Participants are asked to select between a couple of different report examples]

5. **Summary ~ (10 min)**
    [Ideas expressed are briefly summarised to confirm what emerged from the session. Participants may ask questions if they want]

6. **Closing of Session ~ (5 min)**
    a. Thanks to the participants.
    b. Information on project completion date.
    c. Provision of contact details for further input.

QUESTIONNAIRE ON CHILLED WATER SYSTEM STATUS REPORT
(Hamilton, 25 August 2006)

Name: ________________ **Job Position:** ____________

Evaluation of Current Chilled Water Status Report

At first glance...

1. What are the report features that catch your attention at first sight? (i.e. graphs, colors, text, combination of all of them).

2. Do you think that your attention is drawn to the right place? (i.e. do these prominent aspects of the report lead you to immediately find information relevant to you or are they rather distracting?)

   ○ YES ○ NO

3. If you find that some aspects of the report are confusing/distracting, could you please provide an example of that?

4. Are you able to find what you would expect to find?

   ○ YES ○ NO

5. Was it easy to find?

   ○ YES ○ NO

QUESTIONNAIRE ON CHILLED WATER SYSTEM STATUS REPORT
(Hamilton, 25 August 2006)

Report comprehension

6. Was the plant operating well for the week? What features tell you this?

7. Which chiller performed most of the duty for the week? Is this expected?

8. Which chillers were performing well?

Chiller 1: ◯ YES, because...(please explain) ◯ NO, because...(please explain)

Chiller 2: ◯ YES, because...(please explain) ◯

Chiller 3: ◯ YES, because...(please explain) ◯ NO, because...(please explain)

Chiller 4: ◯ YES, because...(please explain) ◯ NO, because...(please explain)

QUESTIONNAIRE ON CHILLED WATER SYSTEM STATUS REPORT
(Hamilton, 25 August 2006)

9. Could you use the report to identify and/or diagnose a problem with the chillers? How?

10. How would you expect the performance of the plant to differ during summer/winter operation? What parts of the report would look different during these times?

11. Is something missing from the report?

12. Is something redundant?

13. Indicate two things you like and two things you do not like about the actual report, giving a brief explanation for your selection.

QUESTIONNAIRE ON CHILLED WATER SYSTEM STATUS REPORT
(Hamilton, 25 August 2006)

Evaluation of Alternative Chilled Water Status Report

Aesthetics, content and layout

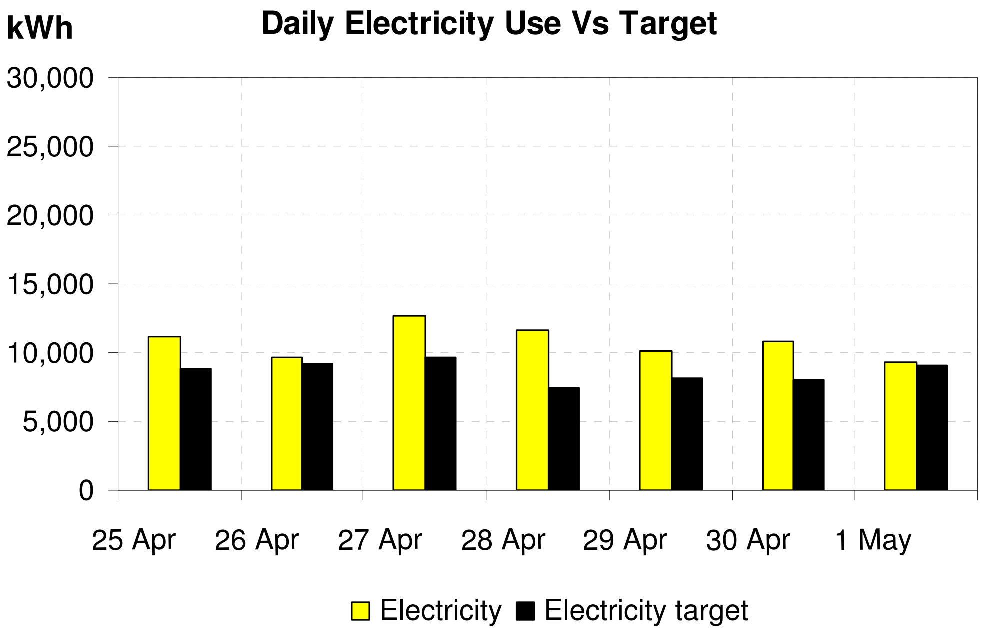
1. Is the color combination appropriate? If you would rather change it, what colors would you use?

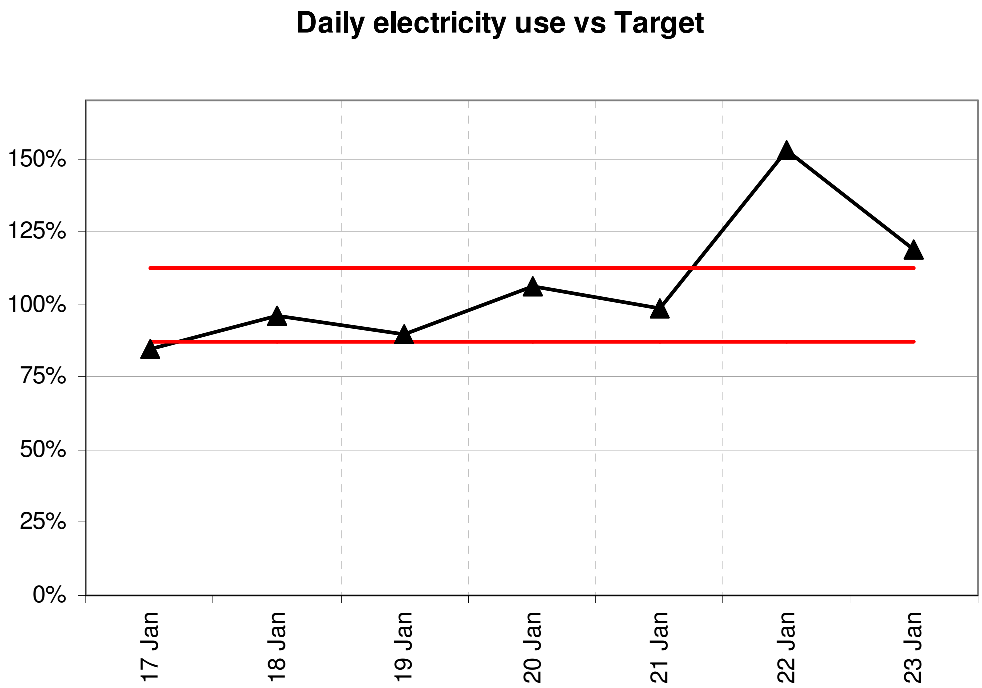
2. Are there too many graphs? If you would rather remove some, which ones would you remove? If you would add some more, what graphs would you add?

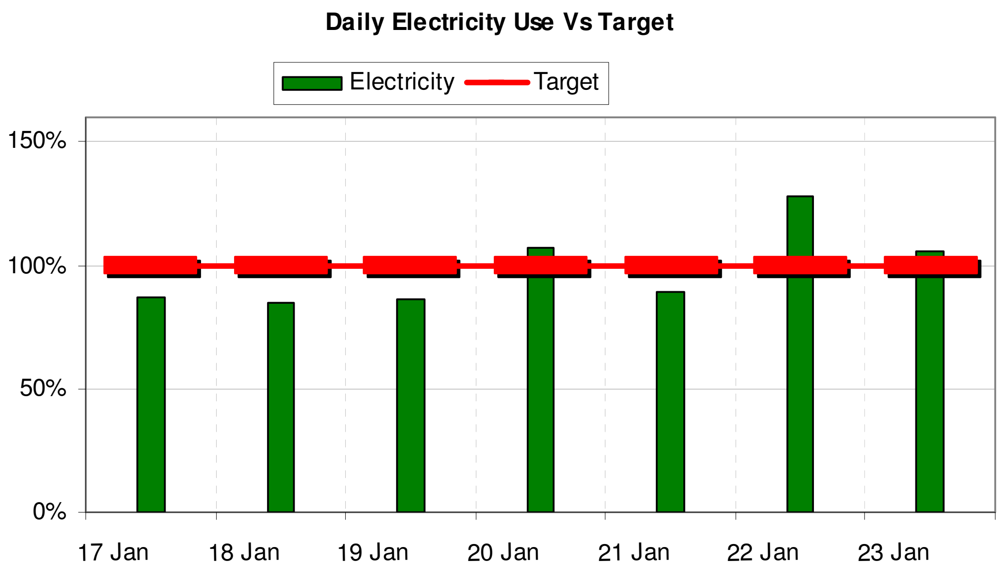
3. Is the text difficult to read? Should it be in different color/font/size?

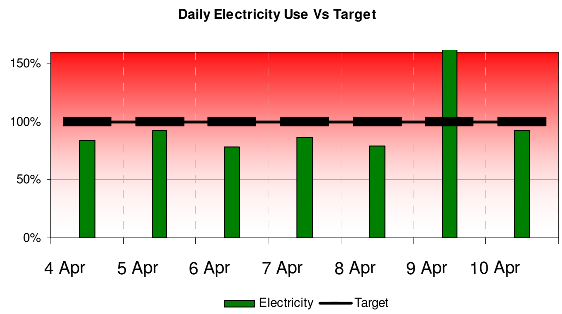
4. What overall changes would you make to the actual report layout and/or content to make it more respondent to your needs?

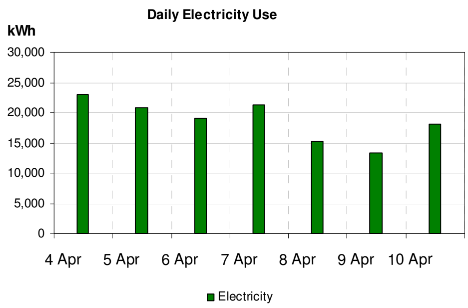
5. Indicate which of the following graphs is, in your view, the most appropriate and explain why.


kWh
Daily Electricity Use Vs Target
30,000
25,000
20,000
15,000
10,000
5,000
0
25 Apr
26 Apr
27 Apr
28 Apr
29 Apr
30 Apr
1 May
Electricity
Electricity target


Daily electricity use vs Target
150%
125%
100%
75%
50%
25%
0%
17 Jan
18 Jan
19 Jan
20 Jan
21 Jan
22 Jan
23 Jan







6. Indicate which is, in your view, the best report between the ones proposed (see "Report Alternative-1" and "Report Alternative-2"). Briefly justify your choice.

APPENDIX B

Refer to the enclosed CD, which contains the following Excel files:

1. Report sample.xls
2. Raw half-hour data.xls

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