Smart reefer system

Modeling Energy Peaks of Reefers connected at terminals and suggesting peak shaving solutions to reduce cost.

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Picture Front Page: A sample model of reefer container (Yang Ming, 2015)

Preface

As a Masters student in Engineering and Policy Analysis (EPA), I am motivated to utilize my technical skills to develop policies for the betterment of society. The area that interests me most is energy management of critical infrastructures like terminals and power plants. This is because of their importance to society coupled with the potential for smart energy management system. This can play a critical role to achieve sustainability targets for a country and ultimately for the entire world. ABB has undertaken port development studies in corporation with TU Delft and Erasmus University of Rotterdam. 'Smart Reefer System', a project under these studies, aims to develop efficient energy management system for terminals. This project provided an ideal opportunity to me to contribute towards a sustainable infrastructure and put into practice, the skills I have developed during my Masters Course.

After six months of work, this report is the physical evidence of my Master Thesis and eventually completes the EPA program at Delft University of Technology. The report begins with introduction of reefer containers followed by its role in the terminal operations. These operations along with the seasonality of trade and the growth in market share of such containers have led to high power peaks in energy consumption which adds to the energy costs. Thus an energy consumption model is developed, for a system of reefers operating at the terminals. Finally peak shaving opportunities are explored and presented which leads to savings in energy costs. Thus, this report provides technical solutions which are commercially profitable.

Doing this project has been an exhilarating journey for me. Whether it was doing big data analysis, developing different energy models or interviewing different stakeholders, each of these aspects required combination of dedication, innovation and iterations. For this, I would like to thank my graduation committee, consisting of Prof Alexander Verbraeck, Dr. Ron van Duin, Dr. Michel Oey and Mr. Patrick Vloemans. Your constant feedbacks, innovative propositions, valuable insights and enhanced networking enabled me to think critically and beyond the regular horizons of the thesis. I am also grateful to Olle de Geest, my colleague during the project, for providing me enhanced perspectives of the system along with the indispensable help regarding the Dutch Language. Next I would like to thank Prof. Harry Geerlings from Erasmus University of Rotterdam, Mr. Peter Schoonen from Port of Rotterdam, Roland Kolijn from Reefer Care and Mr. Patrick Surmount from Thermoking for taking time off their busy schedule to provide deeper understanding of the reefer operations at terminals.

Lastly, this thesis would not be possible without the constant support of my family who are always a part of journey. I am also thankful to my friends whose little help made a huge contribution to this project. Thus with great zeal, I present this report as a final part of my graduation at TU Delft.

Tushar Nafde
Delft, July 2015

Summary

The increase in population, high standard of living and rapid urbanization has led to an increasing demand for food across the globe. The global trade has made it possible to meet this demand by enabling transport of different food products from one part of the world to another. In this trade, refrigerated containers or reefers have played an increasingly important role due to their ability to maintain the quality of product throughout the journey. However, this operation of reefers requires constant supply of power throughout the supply chain. This results in energy consumption by reefers. When a large number of reefers are involved, this results in high amount of energy consumption at terminals. Also, the monthly throughput of reefers is not uniform due to the seasonality of food products. Thus, the growth of reefer trade, the seasonality of food trade and the special requirements of reefers has led to an increase in the peak power demand at terminals. Because extra charges are applied for the highest observed peak demand, it is beneficial to keep this demand as low as possible to reduce energy costs.

To investigate the opportunities for container terminals to reduce their peak demand, an energy consumption model is developed after taking into consideration the modus operandi of a reefer, the different terminal operations, additional data requirements and some assumptions. The simulation model visualizes the energy consumption by reefers at container terminals over period of one year and one month. From this, the peak power is determined to be 14831 kW which is beyond the allowed threshold value of 14000 kW. Also, the total energy consumption and energy costs are 12,1 Million kWh and €1,09 Million respectively. From this model, the problem is analyzed and solutions are proposed to reduce peak power demand.

The solutions deal with changes in the operational procedures of terminal to reduce the peak power demand. Two rules of operation are tested to analyze their impact on peak demand:
1) Intermitted distribution of power among reefer racks;
2) Restriction of peak power consumption among operating reefers.

In the first operation, two cases are considered. In the first case, the power is supplied in the timeslots of 15 minutes. This reduces the peak demand to 8266 kW. In the second case, the power is supplied in 5 minutes timeslots. This leads to even further reduction in peak power demand to 2763 kW. In both the cases, the total energy consumption and thereby the energy cost are also reduced. Thus, this solution results in annual savings of up to €1 Million. However, its downside is that it leads to increase in the reefer temperature during the power off mode. This temperature increase is smaller if shorter timeslots are used. Hence, appropriate timeslots can reduce the risk of product damage in the reefers. However, in order to avoid product damage, proper precautions are required during implementation of this solution.

The second operation reduces the peak power demand to 13760 kW. This results in annual savings of more than quarter Million Euros. Furthermore, it has minimal impact of food

temperature due to its operation within the allowed temperature bandwidth. Hence, this solution, though less impactful, is highly reliable.

Finally, the combined operations of these two solution is recommended to effectively reduce the peak power demand by reefers at terminals. This involves using the power distribution solution at less ambient temperature, during the night time and in combination with Reefer Monitoring and Control System. No restrictions are imposed on power restriction solution.

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CAGR: Cumulative Annual Growth Rate

1. Introduction

The thesis deals with reduction of peak power demand by reefers operating at container terminals. This chapter starts with a background information about the per capita food consumption across the globe in section 1.1 followed by how reefers play a pivotal role in the global food trade in section 1.2. In sections 1.3 and 1.4, the global supply chain of a reefers and their associated energy consumption at terminals are discussed. The following section 1.5 deals with the problem statement followed by the research methodology in section 1.6 . The chapter concludes in section 1.7

1.1. Background

In the past 50 years, the human population has witnessed a three-fold increase from 2.4 billion to 7.2 billion (United Nations, 2004). The current population annual growth rate is 1.1% (United Nations, 2011). With this, it is projected to reach 8.2 billion by 2030. Furthermore, a billion people were added to the human count in the span of last 12 years only. Breaking this down on everyday basis, it means addition of 230000 people to the global food demand. Besides this, the urbanized population has also witnessed a tremendous growth from 746 million people in 1950 (34% of total population) to 3.9 billion people in 2014 (54% of total population). This share is expected to increase to 60% by 2030 (United Nations, 2008). The combined effects of population growth and urbanization has a great impact on the per capita income and standard of living of people. Finally, the trinity of population growth, urbanization and high income has a profound impact on the food consumption (kcal per capita per day) across the globe.

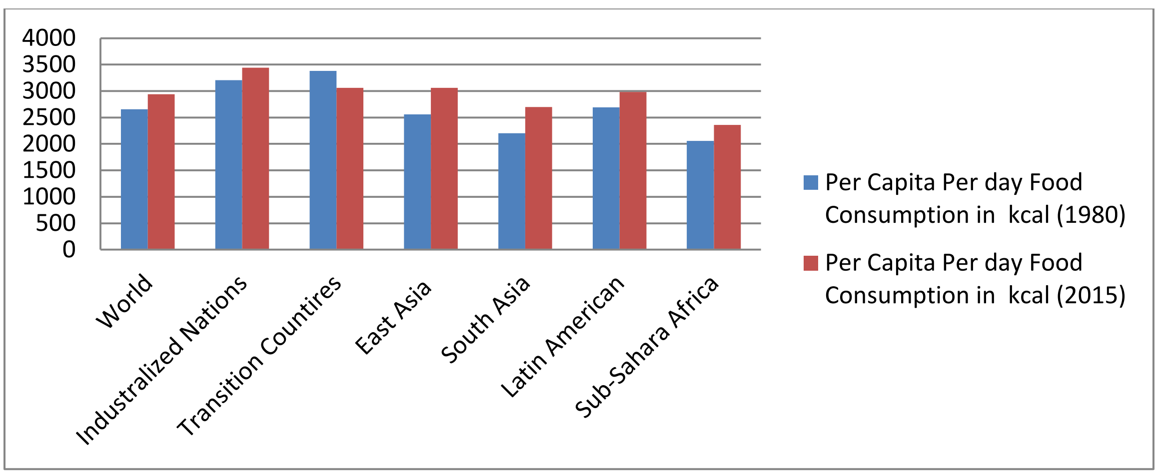

FIGURE 1. FOOD CONSUMPTION ACROSS THE GLOBE (FOOD AND AGRICULTURE ORGANIZATION OF UNITED NATIONS, 2003).

FIGURE 1 shows the growth of per capita food consumption on per day basis across different sections of countries. The industrialized nations have the highest quantity of per capita food consumption. However, the growth in these regions is less compared to the East Asian and South Asian countries. This is because of the rapid economic development in the Asian regions compared to the industrialized countries (United Nations, 2008). The lowest values are observed for the Sub-Sahara countries due to extreme poverty in these regions . Thus from the graph it can been seen that economic prosperity plays a major role in the per capita food consumption of regions around the world.

A person's diet consists of different types of food such as meat, fruits and vegetables. Thus, it is important to consider the diversity of diet when analyzing the food consumption pattern. Four categories of food are considered when analyzing the kilojoules of energy consumed per capita per day. These four categories are as follows:

- Meat (Poultry, Beef, Pork)
- Fruits and Vegetables
- Cereals
- Fish

All products except cereals need a special focus because of high the temperature sensitive of these products (Commonwealth Scientific and Industrial Research Organizaion, 2015). Thus in the following paragraph these special products are discussed.

Meat

The important factor influencing the meat consumption is the per capita income of the country. As shown in FIGURE 2, the meat consumption is highest among the countries with high per capital income. The rich countries like Sweden, Switzerland and USA consume the highest amount of meat. The consumption is also affected by seasonality. It usually increases in the cold weather and this trend is especially observed in the North-Western European countries (Stilley, 2012). Thus, the demand for meat is highest in the countries with high per capita income and this trend is growing in the developing countries as well.

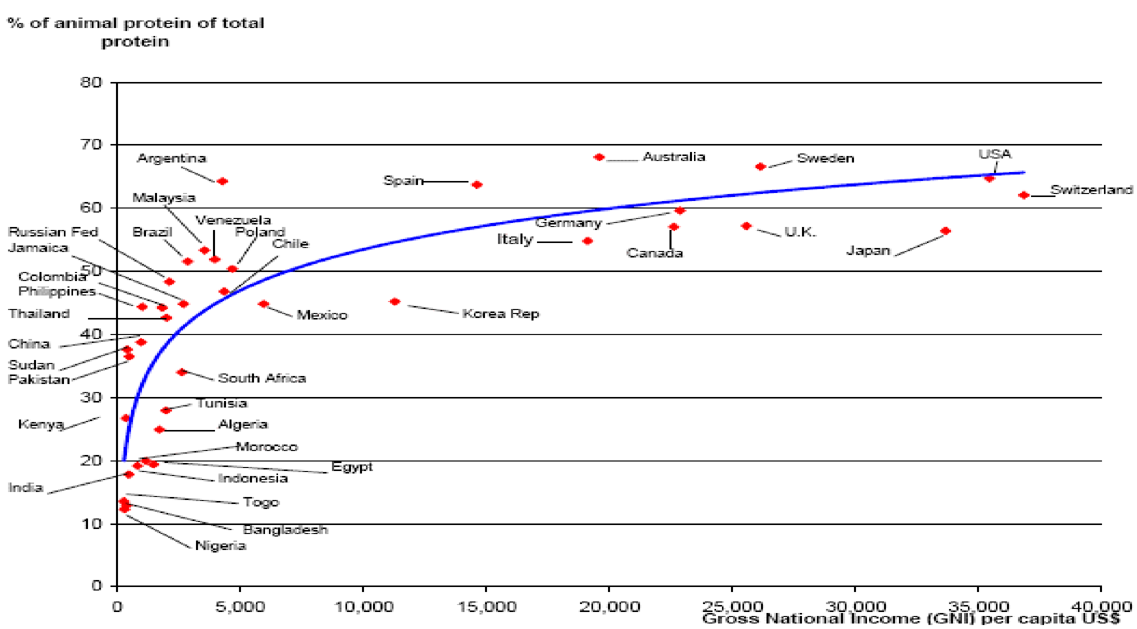

FIGURE 2. MEAT CONSUMPTION AND PER CAPITA INCOME(FOOD AND AGRICULTURE ORGANIZATION OF UNITED NATIONS, 2002)

Fruits and Vegetables

Fruits and vegetables, though not a major part of macronutrient intake, play a major role in the nutritional importance of diet (Weingarten, 2011). A shift towards a healthy food products has contributed towards an increase in consumption of fruits (World Heart Federation, 2015). Also, ,today, the consumer has easy availability of wide variety of fruits from across the globe. This has led to diversification of types of fruits consumed. Global trade has made it possible for a consumer to enjoy exotic fruits grown in other part of the world. Seasonality of fruits also affects its supply and demand pattern. Thus, change in dietary habits, easy availability of different types of fruits and seasonal pattern of fruits trade are the main drivers for increasing consumption of fruits and vegetables. FIGURE 3 shows countries with highest per capita consumption of fruits along with its growth in the span of 3 years. As seen, the Western European countries consume the highest amount of fruits on per capita basis. The trend has also witnessed a steady growth over the past years. Thus, easy availability of variety of exotic fruits and a shift towards a healthy diet are major factors influencing high demand of fruits in Western European Countries.

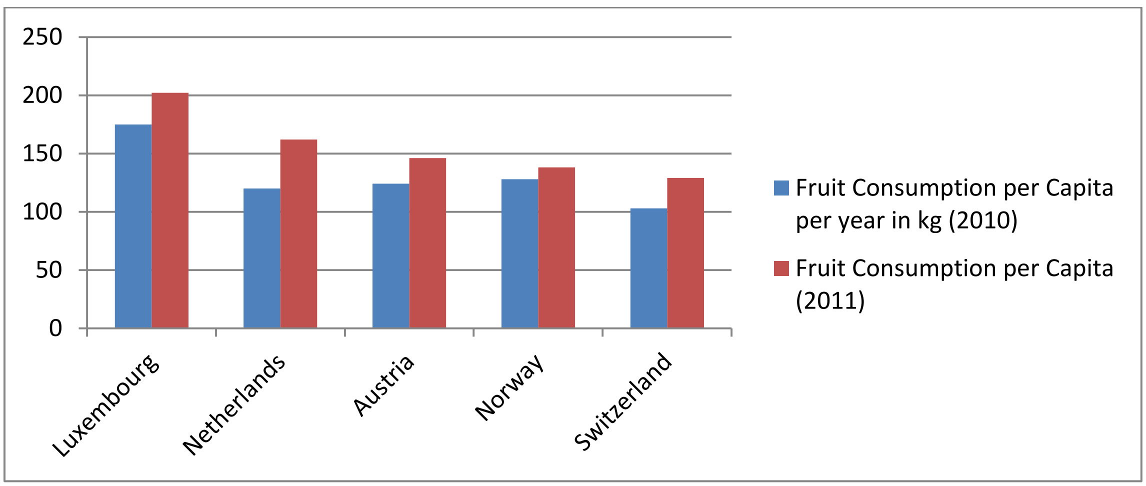

FIGURE 3. COUNTRIES WITH HIGH FRUIT CONSUMPTION (FOOD AND AGRICULTURE ORGANIZATION OF UNITED NATIONS, 2003)

Fish

The consumption of fish forms a major part of diet for many people across the world. Some of the factors influencing the consumption of fish are its product availability in a region, the dietary culture, population density along sea coast and economic factors. Product availability is enhanced if optimal transport and preservation infrastructure are available. Culture determines which species is favored over others. Economic factors include disposable income and the price of different species (Polanco, 2015). The combination of these above factors determine the food consumption across the globe as shown in FIGURE 4.

Asia, by far, consumes the maximum amount of fish in the world. Within Asia, China has the biggest contribution towards fish consumption. Other Asian countries, such as Japan and South

Korea, also have a major share in the fish consumption across the globe. Outside Asia, the major fish consumption occurs in the Mediterranean part of the Europe. Thus, as seen, the highest demand for fish comes from East Asian Countries followed by European Countries along the Mediterranean coast.

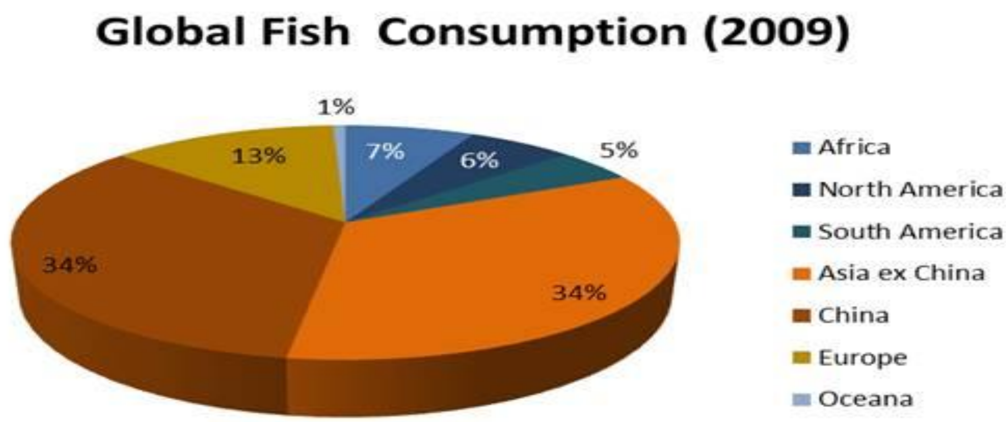

FIGURE 4. FISH CONSUMPTION DISTRIBUTION ACROSS THE WORLD (ADM CAPITAL FOUNDATION, 2013).

1.2. The role of Reefers in Global Trade

The global trade of the above mentioned cargoes requires special requirements due to their temperature sensitivity and high perishable nature. Currently, this trade is carried out by means of refrigerated containers, or "reefers". A reefer is an intermodal container used in the transportation of temperature sensitive cargoes. It plays a crucial role in maintaining the temperature of products in transit. It is capable of controlling temperature ranging from -30 ^{o}C to +30 ^{o}C. It can, thus, maintain the temperature and thereby the quality of frozen (-30 ^{o}C to -10 ^{o}C), chilled (-10 ^{o}C to 15 ^{o}C) and warm (15 ^{o}C to 30 ^{o}C) cargo (Hamburg Sud, 2010). This service by reefers allows consumer to enjoy fresh produce from any part of the world.

Historically, reefer were used in the transportation of bananas and meat (Hamburg Sud, 2010). However, in time, the number of products has diversified and quantity of products has also witnessed a huge growth. As seen in TABLE 1, bananas and meat formed the bulk of the products in 1985. They constituted more than 50% of the total volume of reefer cargo. Over the years, though their volume has increased, their contribution towards the proportion of reefer cargo has decreased significantly. This is mainly due to the addition of exotic fruits, horticulture products to the reefer cargo list. In recent times, the volume of these new products has also grown thereby making a significant contribution to the total volume of reefer trade. Thus, the role of reefers has increased in quantitative and qualitative terms. Thus, it is evident that reefer trade has played a crucial role in transportation of large volume of different kind products.

Product / Year	Bananas	Meat	Citrus	Seasonal Fruit	Exotic Fruit	Fish	Dairy Products	Other	Total
1985	7	4,8	4,2	2,1	-	2,2	1,6	-	**21,9**
1986	13,3	9,7	4,5	3,9	1,3	8,7	1,5	4,1	**47**
2000	14,1	10,7	4,9	4,3	1,5	9,1	1,5	4,9	**51**
2005	15,8	12,2	5,3	4,7	1,7	9,7	1,6	5,8	**56,8**

TABLE 1. QUALITATIVE AND VOLUMETRIC GROWTH OF PRODUCTS IN REEFERS (GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT E.V.(GDV), 2015)
(All Measured in Million Tonnes)

Today, a wide variety of products are transported by means of reefers. Among these, the major products are

- Meat: Beef, Pork and Poultry
- Fruits and Vegetables: Bananas, Citrus (Lemons, Oranges), Deciduous (Apples, peach and Exotic (Strawberries)
- Seafood: Crabs, Fatty Fishes (Herring, Lean Fishes (Cod), Shrimp
- Dairy Products: Butter, Cheese, Milk
- Horticulture Products: Christmas trees, flower bulbs, daffodils
- Pharmaceutical products (Holz, 2012)

FIGURE 5 and FIGURE 6 respectively give the volumetric and percentage distribution of the total reefer trade across the globe in 2012. The total volume of the reefer trade in 2012 was 92,42 million tonnes out of which meat/poultry consisted of 22,98 million tonnes (Dekker, 2014). This formed a quarter of the total reefer trade across the globe. When compared with Table 1, it can be see that meat has overtaken bananas as the dominant product transported by reefers by increasing its share from 21.9% in 1985 to 25% in 2012. Thus, currently, the contribution of meat is maximum in reefer trade across the globe.

The next products to dominate reefer business are the horticulture and the pharmaceutical cargoes (others). Its total volume is 18,77 million tonnes; thereby contributing 20% to the total reefer trade. From virtually non-existent in 1985, this product category has increasingly become an important cargo for reefer business. The next products to contribute substantially to reefer business are the bananas and the seafood with 15,81 and 15,69 million tonnes of products transported respectively. Each of them contributed 17% to the global reefer trade. However, it can be seen that, the contribution of bananas has decreased from 31.9% in 1985 to 17% in 2012. A reverse trend is observed for seafood which has increased its share from 10% in 1985 to 17% in 2012. Thus, the due to diversification of products and constant changes in the demand of consumers, the share of traditional product (banana) transferred by reefer has decreased while the share of other products has increased substantially in the global trade.

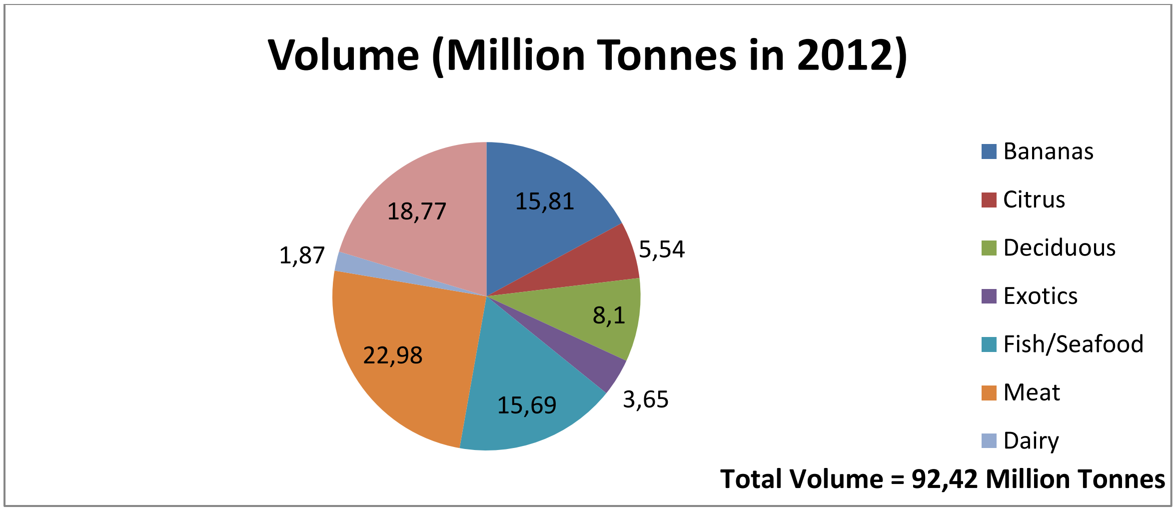

FIGURE 5. GLOBAL REEFER TRADE IN VOLUME (DEKKER, 2014)

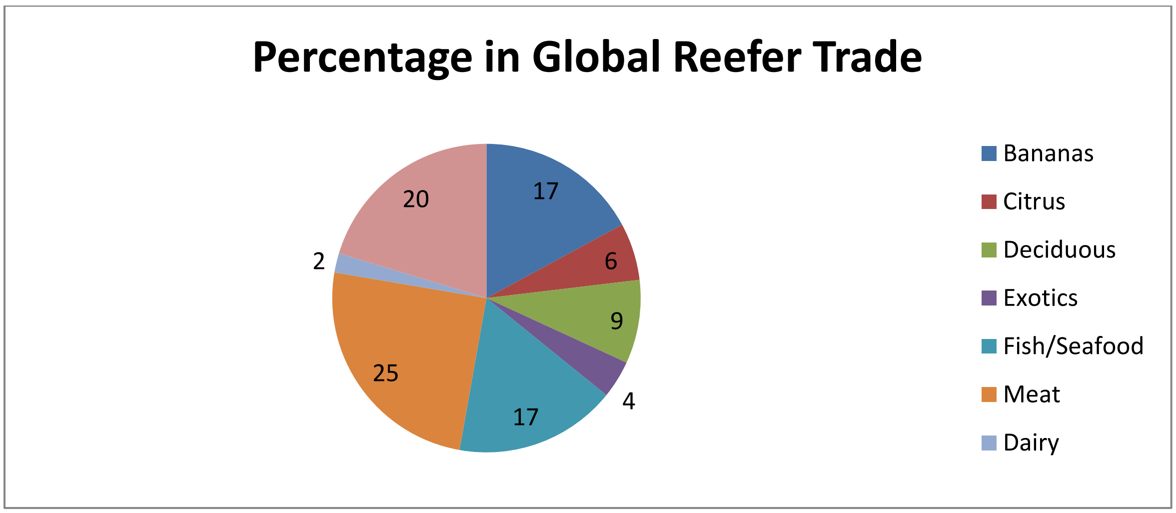

FIGURE 6. GLOBAL REEFER TRADE IN PERCENTAGE (DEKKER, 2014)

Due to the increase in the volume of goods transported by reefers and great demand for diversified food products, the short term future prospectus of reefer market also looks promising. The reefer trade, on volume basis, is expected to rise by 20,5 million tonnes from its value in 2012 (Drewry Maritime Research, 2014). The CAGR over this period amounts to 3.1% (Dekker, 2014). The main products driving this growth will be meat and exotic fruits, with the latter expected to rise 9.3% each year (Drewry Maritime Research, 2014). Thus, the reefer trade will play an increasingly important role in the global shipping business.

A reefer container comes in two standard sizes: 20 feet and 40 feet. TEU and FEU are units used to denote a standard 20 feet container and 40 feet container respectively (1FEU = 2 TEU). Thus, the total number of TEUs denotes the total number of 20 feet equivalent reefers available in that particular year. The importance of reefer containers can also be judged by their cumulative growth over the years.

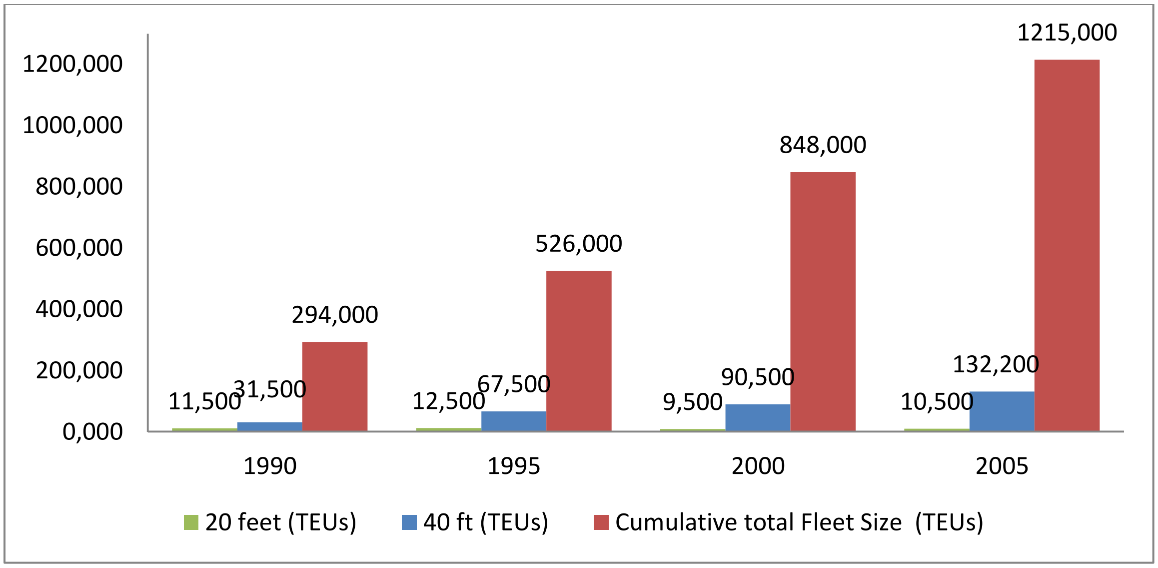

FIGURE 7.PRODUCTION AND CUMULATIVE GROWTH OF REEFER FLEETS (GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT E.V.(GDV), 2015)

FIGURE 7 shows production of 20ft/40ft reefers along with the cumulative growth of the reefer fleet over a period from 1990 to 2005. In 1990, 20ft reefers formed 26% of the total reefer production business. However, in the subsequent years, their quantity of production remained more or less constant. This decreased their share in the total production business. In the same time, the production of 40 ft reefers dramatically increased from 31500 TEUs in 1990 to 132,200 TEUs in 2005. This increased their contribution in reefer production business from 74% in 1990 to 93% in 2005. This was mainly due to the increased cargo carrying capacity of the 40 ft reefers when compared to 20 ft reefers. Thus, the growing demand of food coupled with the increasing need to scale up the cargo carrying capacity of reefers affected the production of 20 ft reefers. Thereby, the reefer manufacturers focused more on the production of 40ft reefers.

This increased production of 40 ft reefers fueled the cumulative reefer fleet available in any particular year. This fleet increased from 294,000 TEUs in 1990 to 1,215,000 TEUs in 2005 signifying a growth of 313% over this period. By January 2012, this figure had reached 2,1 million TEUs. This rapid growth of reefer fleet has increased the market share of reefers in the total container fleet from 7% of in 2012 to 11% in the 2012 (World Shipping Council, 2011). The increase in reefer fleet size and growth in its market share has a huge impact on the supply chain of reefers across the globe.

1.3. The Supply Chain of Reefers

The supply chain of reefers is driven by the global demand for different types of food products. The geographical variation in demand for food is discussed in the previous section. The global reefer trade is in correspondence with this demand. This is shown in FIGURE 8.

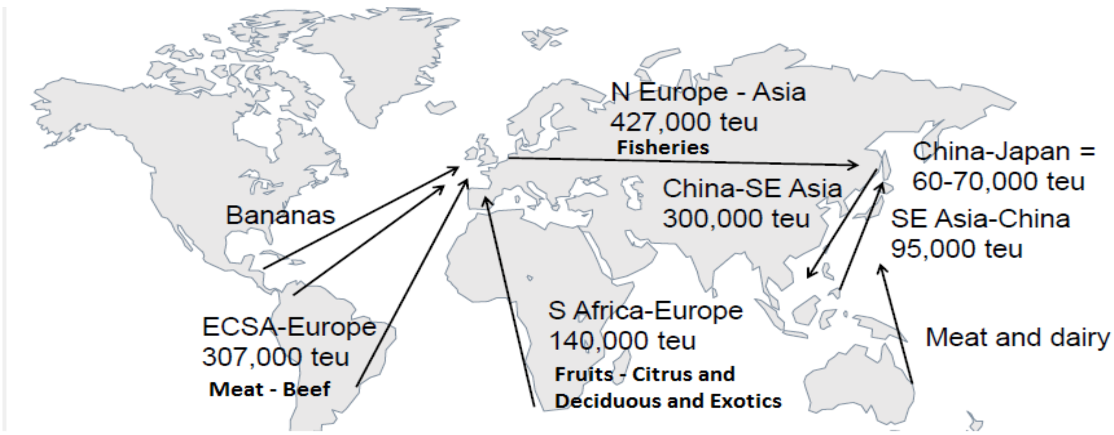

FIGURE 8.GLOBAL TRADE OF REEFER FLEETS (DEKKER, 2014).

The major routes for the reefer trade are the ECSA-Europe, South Africa-Europe, Northern Europe Asia and China-South East Asia. The focus is on the first two routes due to the availability of data. The major products transported on these routes are meat and fruits respectively. This is because, as discussed in section 1.1., Europe has the highest per capita consumption of these products. The following paragraph provides a brief description of reefer trade along these routes.

South America - Europe Route

The majority of the products exported along this route are meat and bananas. Meat makes up to 45% of the total quantity of products transported. This is equivalent to 125,000 TEUs of reefer fleets. The quantity of meat export has been maintained over the years (Lorimer, 2014). The next product to dominate the export are fruits especially Bananas from Ecuador. This is because Ecuador is one of the largest producers of bananas in the world (ChartsBin, 2015). Besides the types and quantity of products exported, it is important to analyze the seasonality of trade especially for meat products and bananas. The export seasonality of meat products is shown in FIGURE 9.

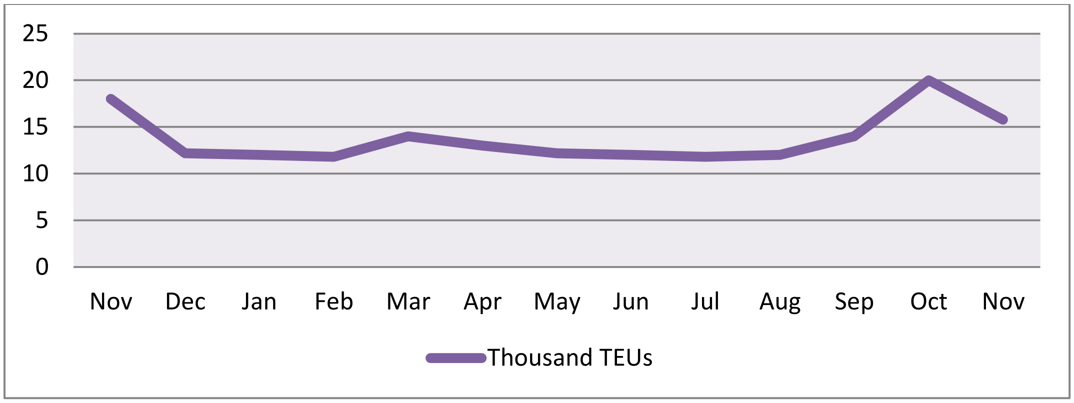

FIGURE 9. SEASONALITY OF MEAT EXPORT(VAGLE, 2013)

The maximum quantity of meat is exported in the three month period of September-October-November with the peak in October (20000 TEUs). As discussed in section 1.1., this is because of the higher demand for meat from European countries during the winter season. The exports reach a minimum during the summer period in Europe. In the case of bananas, they are exported throughout the year with minimum seasonal variations (Vagle, 2013). Thus, besides the quantity and type of goods transported, the seasonality of exports play a crucial role in reefer trade.

South Africa - Europe Route

The overwhelming majority of products transported along this route are the different categories of fruits - Citrus, Deciduous and Exotic. The seasonality of these fruits categories plays a crucial in determining their number of cartons exported to Europe[1]. Hence, the following section deals with seasonality of these products and its impact on reefer trade.

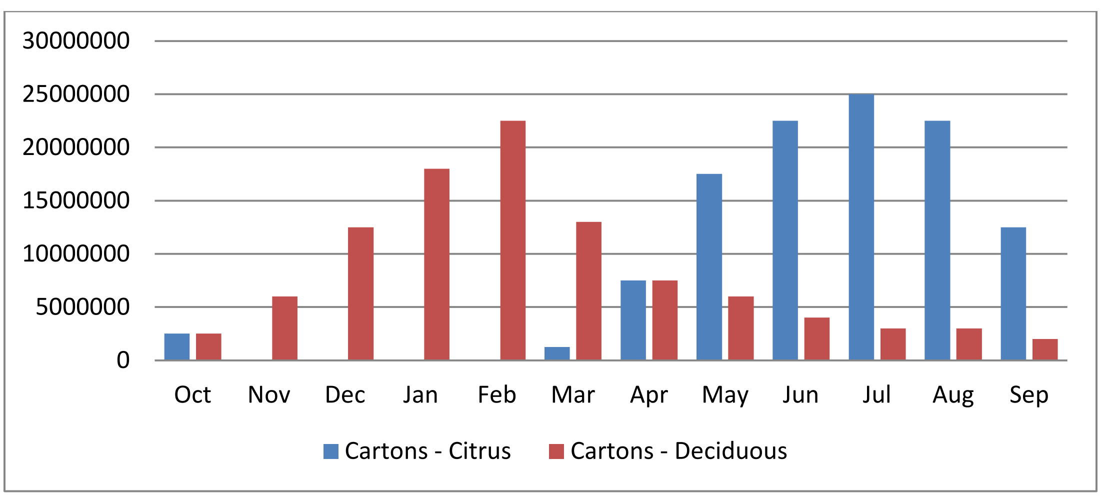

FIGURE 10. EXPORT SEASONALITY OF CITRUS AND DECIDUOUS FRUITS (VRIES, 2015)

[1] For Details, refer to Appendix A.

FIGURE 10 shows the seasonal export pattern of citrus and deciduous fruits. For citrus fruits, the maximum quantity of cartons are exported in the period from June to August with the peak reaching in July (2,5 Million cartons). However, in the period from Nov to Feb, almost negligible quantity of cirtus fruits are exported. This decrease in quantity of citrus fruits is compensated by the high quantity of exports of deciduous fruits. In the period from Dec to Feb, deciduous fruits dominate the export trade. They reach their peak export in the month of February (2,25 Million cartons) (Vries, 2015). FIGURE 11 shows the seasonal export pattern of exotic fruits. Maximum quantity of seasonal fruits are exported in the period of April and May while during, the rest of the year, the exports of these fruits is minimum However, the quantity of these fruits exported is less compared to citrus and deciduous fruits. Hence, majority of the export along this route consists of citrus and deciduous fruits with exotic fruits forming a small portion. In conclusion, besides the quantity,the seasonality of fruits also play an important role in the logistics of the reefer trade.

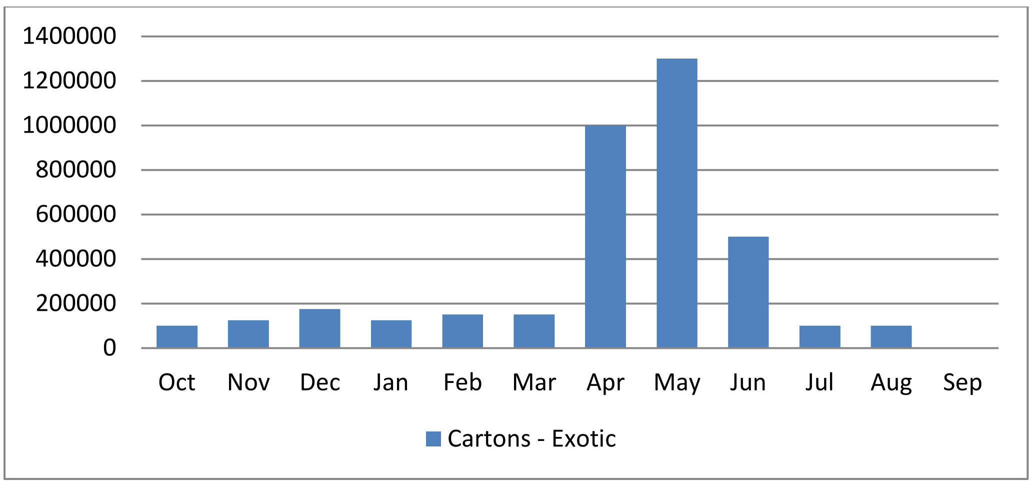

FIGURE 11. EXPORT SEASONALITY OF EXOTIC FRUITS (VRIES, 2015)

The previous paragraphs discussed the reefer trade on global basis. However, to have better understanding, it is important to study the detailed logistics of a reefer container. This will provide insights into the various processes a reefer undergoes. Hence, the following paragraph provides a detailed description of the cold chain logistics.

A cold chain involves the transportation of temperature sensitive products from the site of production to the place of consumption. The temperature is controlled throughout the supply chain by means of enhanced thermal and packaging methods. This requires logistical planning to protect the integrity of products. An unbroken cold chain is an uninterrupted series of storage and distribution activities while maintaining the required temperature range. It consists of several stages of moving and servicing the reefer containers throughout the route (Rodrigue, 2013). FIGURE 12 shows the cold chain logistics of reefers consisting of ten different stages. Each of these stages is described in the following paragraph.

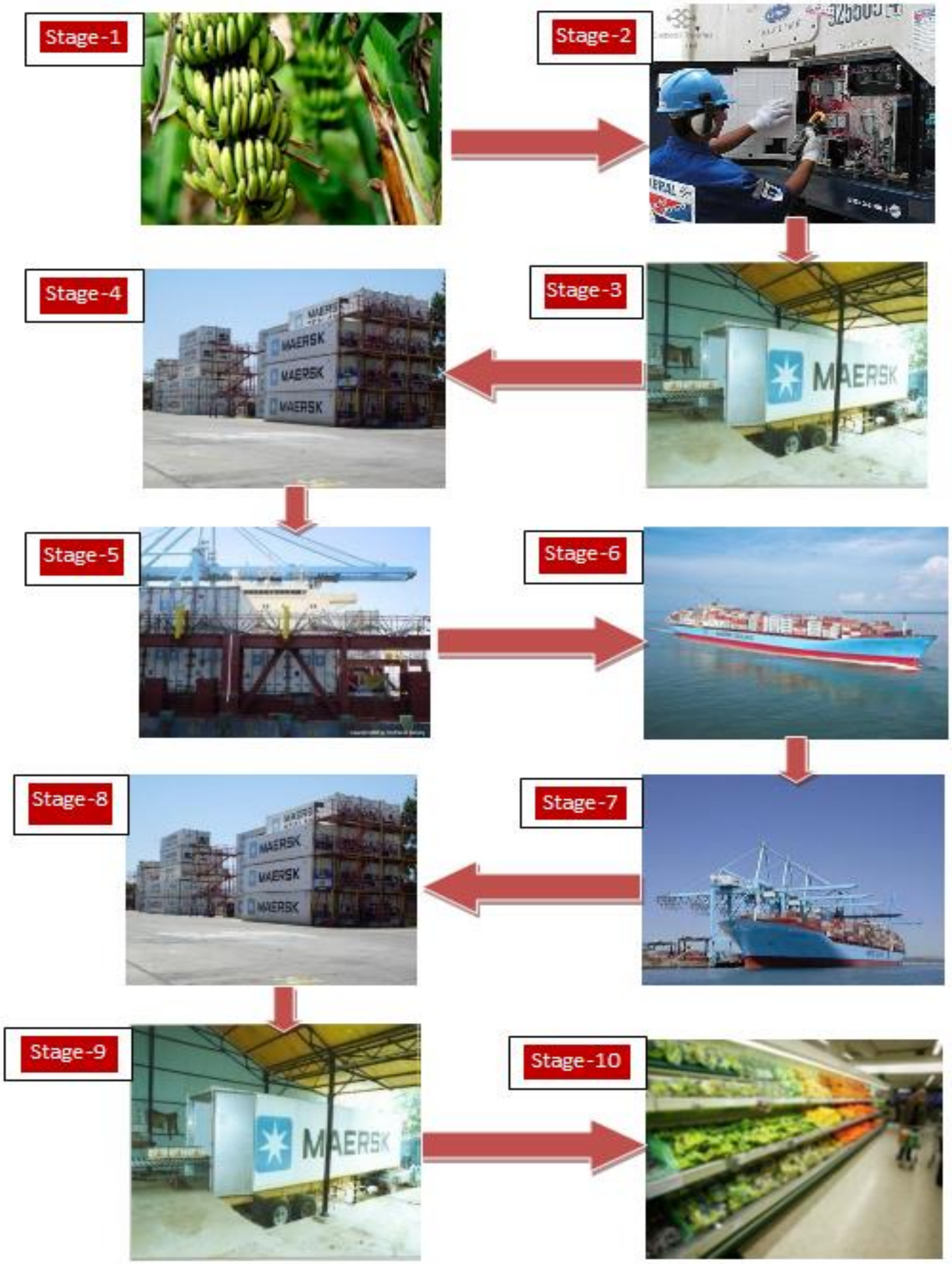

FIGURE 12. COLD LOGISTICS OF REEFER PRODUCTS AND CONTAINER. (MAERSK LINE, 2010)

FIGURE 6 illustrated the different categories of products transported in reefer containers. These categories have several products within them. Each of these products requires a pre-detemined cargo storing temperature, humidity level and air exchange rate (Hamburg Sud, 2015). Also, each of them have different sensitive to temperature fluctuations. This makes it difficult to generalize the product categories according to the storage temperature and sensitivity to temperature fluctuations However, for simplicity, Rodrigue has made the classification of products based on the temperature class as shown in TABLE 2:

Product	**Temperature range (°C)**	**Temeprature fluctuation Sensitivity (°C)**
Deep-Frozen: Seafood, Ice-cream	- 30 to - 28	Low (±2)
Frozen: Frozen fish, meat	- 20 to - 16	Low (±2)
Chilled: Fruits and Vegetables	- 5 to 5	High (±0.5)
Pharmaceuticals	2 to 8	High
Bananas	12 – 14	Very High (±0.2)
Musical instruments, paintaings	18 - 21	Low

TABLE 2. TEMPERATURE CLASSIFICATION OF PRODUCTS AND THEIR RESPECTIVE TEMPERATURE SENSITIVITY (RODRIGUE, 2014)

In a cold chain, the quality of the products with different temperature requirements has to be maintained from the point of production to the point of consumption. The safety of the products has to be ensured at each stage. Hence after, the production of different types of cargoes (Stage - 1), the producer brings them to their respective storage temperature (Stage - 2) before loading them into the reefer container (Stage - 3). The reefers are, thus, loaded with the pre-cooled cargo (Hamburg Sud, 2015).

As reefers carry valuable cargoes with limited shelf life, they are required to maintain nearly constant temperature, humidity level and air exchange rate. Unkeeping of the storage condition degrades the quality of the products. This additional operation requires a permanent connection of reefers to an electricity supply which is unlike the conventional containers. On container trucks, this is achieved by means of gen sets (Generator Sets) which power the individual reefer (Hamburg Sud, 2015). Several such reefer carrying trucks, trains and feeder ships converge at a container termnal for the products to be exported. Here, the reefer are stored for their respective dwell time (Stage - 4). During this, terminal is responsile for maintaining the cargo conditions inside a reefer. It achieves this by constant electric power supply to each individual reefer stored in reefer rack. Due to the simultaneous operations of large quantities of different types of reefer, a huge amount of electrical energy is consumed by the terminal .
After its scheduled dwell time, a reefer container is loaded onto the container ship with the help of automated cranes (Stage - 5). During the transit, the reefer temperature conditions are maintained by means of reefer slots available on the ship (Stage - 6). After the ship arrives at its intended port of destination, the reefers are unloaded from ships (Stage - 7) by means of cranes

and stored on the destination terminal again for their respective dwell time (Stage - 8). Here, too, the reefer undergoes the same as on the terminal of departure. Hence, here also a huge amount of energy is consumed by the terminal. Finally, a reefer is transported by the consigee to its intended supermarket destination by means of trucks, trains or other means of transport. Hence, in the way, fresh products from one part of the world are available to consumers in other part without any quality degration.

1.4. Energy Consumption of Reefers at Terminals

As discussed in the previous paragraph, a large amount of energy is consumer at terminal due to reefer operations. The following paragraph deals with this energy consumptiuon.

In a common container terminal, electrical energy consumption is, on average, distributed as follows: (a) reefer containers, i.e. refrigerated containers carrying deep-frozen or chilled cargo (40%), (b) ship to shore cranes (40%), (c) terminal lighting (12%), and (d) administration buildings and workshops (8%) (Wilmsmeier et al., 2014). A separate reefer stack is provided at terminals for stacking reefer containers. Reefer handling also requires additional handling and logistics costs. Thus, reefer operations puts extra pressure on the logistics and energy infrastructure of terminals.

The above distribution of energy consumption varies considerably throughout the year as shown in FIGURE 13. It depends on the share of reefer trade and the monthly throughput of reefers. The reefer throughput directly corresponds with the variation in the energy consumption at terminals. During the peak fruit and meat season, energy share by reefers can easily rise to up to 65% of the total energy consumption of a terminal (Marks, 2012). This seasonality in trade causes significant variations and peaks in energy consumption, with the peaks determining the number of reefer plugs required for an efficient operation at the terminal. Thus, the energy consumption at terminals corresponds with the share and seasonality of reefer trade

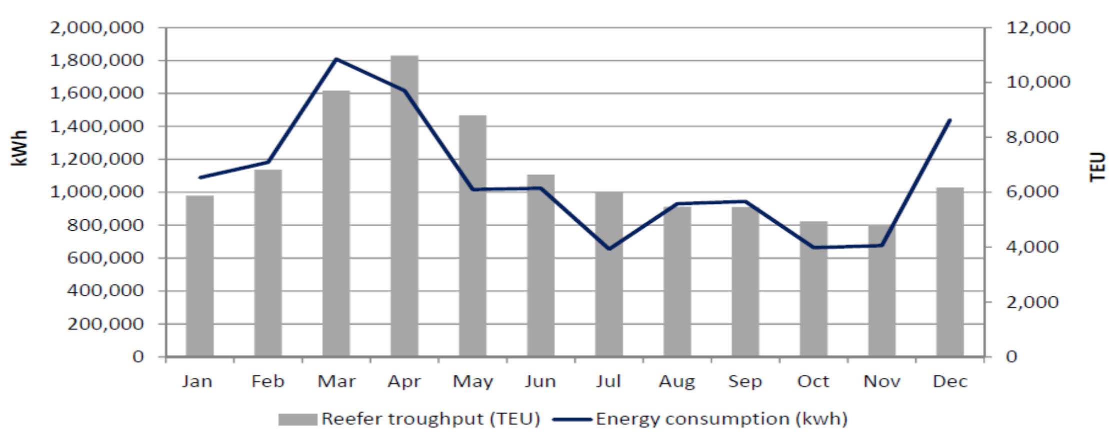

FIGURE 13. REEFER THROUGHPUT AND ASSOCIATED ENERGY CONSUMPTION (WILMSMEIER, 2015)

A characteristic of reefer cargo is that it is not uniform and, as mentioned above, requires differentiation among the different temperature controlled cargoes. The cooling capacity of reefer varies according to set point temperature. This variation in cooling capacity is shown in TABLE 3. It is evident that, greater the set point temperature of a reefer, higher is its cooling capacity and thus faster is cooling process.

Required Set Point Temperature	Cooling Capacity (kW)
21 °C	13.7
2 °C	9.9
-18 °C	5.7
-29 °C	3.8

TABLE 3. SET POINT TEMPERATURE AND CORRESPONDING COOLING CAPACITY (GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT E.V.(GDV), 2015)

(Values for Thermoking Smart Reefer at 37.8 °C external temperature and 60 Hz electric power)

Thus, the combination of the increasing reefer trade, seasonality of reefers and variation in reefers containers leads to high energy consumption and potential power peaks at terminals.

Operating Cost of Reefers at Terminals'

Reefer services on terminals mainly include stacking of reefers by cranes, power supply for temperature maintenance and other additional services. Out of these, the power consumption is the most important operating cost for a reefer. For example, Long Beach port in California has annual electricity bill of $50 million out of which $7,5 million is due to the power used by reefers (Nall, 2013). Thus, reefer power consumption makes up to 15% of energy bill at this port and for some other ports it can be as high as 65%. In addition to this, there are several activity based charges for reefers as shown in TABLE 4.

Activities		Charges
Dwell Time	1-3 days extra after expiration of free time	$335 per container per day
	4 days and above	$490 per container per day
Electricity consumption	Additional charge after expiration of allowed time	$45 per container per day
Manual	Reefer Plug/Unplug	$54 per container

TABLE 4. ACTIVITY BASED CHARGES FOR REEFER CONTAINER (MAHER TERMINALS LLC, 2014)

Of all these activities, the mandatory is the manual plugging/unplugging of reefer from sockets.
Additional labor costs is involved in this activity. Besides this, penalty charges are levied on a terminal for any deviation from scheduled plan of a reefer. Thus, as seen, though reefer

handling involves additional costs, its power consumption forms a major part of operating costs at terminals.

Electricity Prices

Since more and more terminal processes are being electrified, the electricity consumption of terminals has risen. The electricity related costs are made up of two aspects
1) Installation charges for connecting the terminal to the power network and
2) Consumption charges which consists of Energy Consumption and Peak Demand
In this research, only consumption charges for power supply are considered because installation charges are one time investment while consumption costs vary periodically. The consumption charges has two components. One for morning time (9 - 21 h) and other for night time (21 - 9 h) (We Energies, 2015). Each of these component measures the actual energy usage in kWh. The price is charged per kWh of energy used. These charges are shown in FIGURE 14. The variable costs relate to the highest peak demand (€/kW) (We Energies, 2015). The following section provides how peak prices are calculated.

The container terminals are charged for the highest peak demand that is observed over a year (kWmax year). This peak is the highest capacity required during the given billing period which is typically a 15-minute interval during the billing cycle. A demand charge is a charge based on price per kW, mostly the peak kW of the billing period (We Energies, 2015). Officially the peak is charged per month, but the policy of the grid exploiters is to charge peaks not only for the month in which it occurred, but to charge it for the next twelve months. To illustrate this: if in January the highest peak exceed the threshold value by 200 kW, the terminal will have to pay 200 times the peak demand charge per kW (=27 €/kW) for the rest of that year (12 Months). So, the terminal has to pay additionally pay €200*27*12 due peak demand charges. In this way, energy suppliers are charging companies for their peak demand because this demand is almost always higher than the requested contractual demand (i.e. $kWmax > kWcontracted$), which means that the energy suppliers could not prepare their energy production for this extra power (Heij, 2015).

Hence, the main challenge for container terminals is to reduce their peak demand as much as possible (especially because the highest peak is charged for the next twelve months). This lower peak demand may not lead to a lower total energy consumption or lower emissions, but will save costs due to the pricing of peak demand.

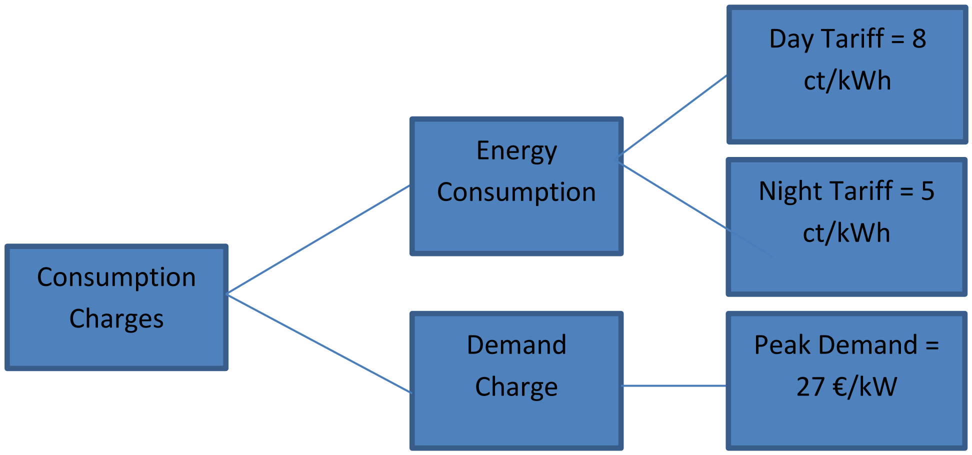

FIGURE 14. BREAKDOWN OF ELECTRICITY TARIFFS (FRONTIER ECONOMICS, 2011; GRAVE ET AL., 2015; HEIJ, 2015)

1.5. Research Design

Problem Statement

The previous sections dealt with the growth in the demand of reefers to transport different types of products to meet the food consumption demand across the globe. This has led to a tremendous increase in the number of reefer fleets. The seasonality of food products further affects the movement of these fleets. Many of these products have different temperature requirements leading to variation in power requirements of reefers. Furthermore, they are also highly sensitive to temperature variations leaving little bandwidth time to switch them off. The combination of above has led to large amount of energy consumption on terminals.

On these terminals, electricity is primary source of energy used for reefer operations. This electricity is provided by an energy utility company. Due to seasonality of reefers, their energy demand over terminals is very volatile. This volatility is the energy demand pattern by reefers leads to a peak power demand as shown in FIGURE 15. Peak power in energy demand management is a period in which electrical power is expected to be provided for a sustained period at a significantly higher than average supply level. Peak power fluctuations may occur on daily, monthly, seasonal and yearly cycles. This leads to excessive energy costs due to additional peak charges applied by utility companies. Despite, these peak power and excessive energy costs, energy efficiency measures and strategies are rarely present in ports and terminals (Wilmsmeier & Zotz, 2014)

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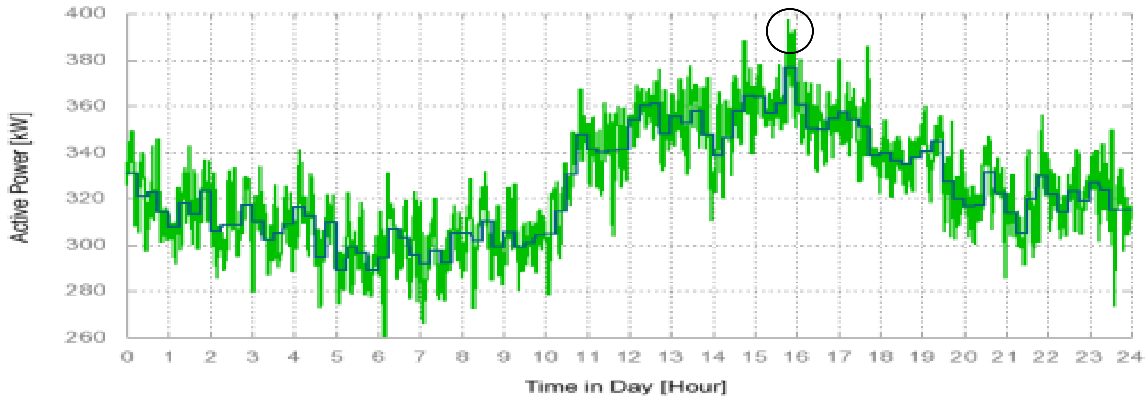

FIGURE 15. VOLATILITY IN ENERGY DEMAND OF REEFERS AT TERMINALS (TAO ET AL. , 2014)

Furthermore, a terminal operator has no knowledge about the modus operandi of the shipping lines and other modes of transport. It does not have any say in the plug-out time of reefers on ships, the arrival/departure schedule of ships and manner of handling of reefers by other actors. Hence, this bounded rationality creates an additional pressure on the terminal to have an efficient energy management system for reefers. Thus, there is urgent need for terminals to innovate and become more energy efficient by implementing new rules of operation for reefers to lower the peak power and save money in energy costs.

Research objective

The research objective describes the goal of the research and is derived from the problem statement in the previous paragraph. The growth in the demand of reefers has led to diversification of terminals. Efficient handling of reefers provides a unique selling point and a competitive advantage to them. However, reefer cooling process also leads to an increase electricity costs due the volatility in power demands by reefers. The stringent norms on product quality and the bounded rationality faced by terminal operators further add to the complexity of efficient energy management of reefers.

Thus, efforts are needed to reduce the energy costs by lowering the peak power consumption of reefers while ensuring the stringent temperature requirement of products inside reefers.

The research objective is therefore:

"To investigate the possibilities for peak shaving the electricity demand at reefer stack by applying new rules of operation for modus operandi of reefers, while monitoring its impact on the reefer temperature"

Thus, the research aims to reduce the peak power demand of reefers from the point P1 to lower point P2 as shown in FIGURE 16.

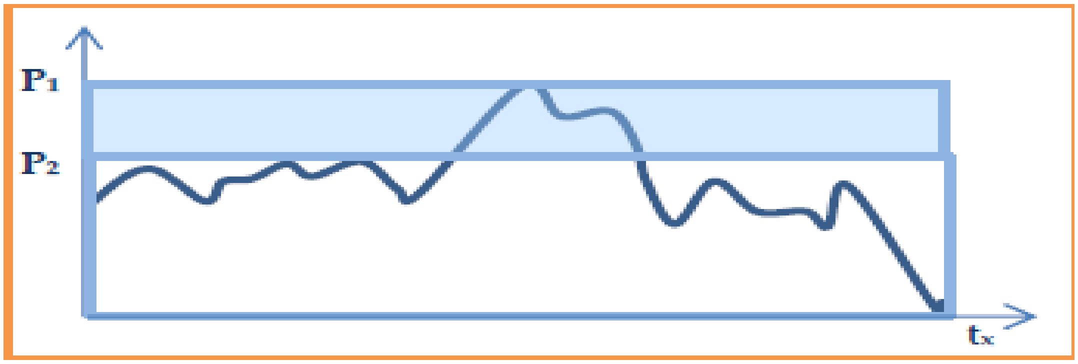

FIGURE 16. PEAK POWER REDUCTION OF REEFERS AT TERMINALS (WE ENERGIES, 2015)

Scientific relevance

In last few years, many studies have been undertaken to understand the working of individual reefers resulting in models that suggest the reduction of its power consumption. These models are available with the help of technical terms such as 'power consumption of reefer', 'reefer control system model' and energy consumption by reefer'. Models have also been developed to study various terminal operations to increase their productivity. These models are included in the various operations research journals such as OR Spectrum and port productivity studies by groups such as JOC, PwC. However, there is no study available that presents a model that determines the energy consumption of a system of reefers operating over a period of time at terminals, then analyzes the peak power demand and finally suggests peak shaving opportunities. The first contribution to science is, therefore, the development of insights into the energy consumption of reefers followed by visualization of this consumption over time. This model is not only valid for reefer containers but also for other temperature sensitive equipment such as thermostats. After developing the model, algorithmic changes can be implemented to test the possibilities of peak power reduction in areas besides the container terminals. The second contribution is, therefore, to present rules of operation that contribute towards the reduction of peak power demand at areas using temperature sensitive equipment.

Business relevance

Today's state-of-the-art container terminals are moving towards full electrification of terminal operations. With the growth of reefer fleets, the use of electricity rises. The pricing of electricity has shown the high costs due to peak power demand. A lower peak demand could, therefore, save a terminal millions of euros per year. New rules of operation could contribute to reduce these peaks and would made container terminals aware of this problem. This can lead to competitive advantage in terminal operations.

Research Questions

Based on the main research objective the research question formulated is as follows:
What are the possibilities for reducing the peak demand (peak shaving) of electricity consuming reefer stack in order to reduce the electricity related energy cost?

Sub questions:

1. What are the key input variables for affecting the energy consumption of reefers?
2. How to incorporate these variables to develop an energy consumption simulation model?
3. How to simulation the energy consumption of a system of reefers?
4. How is the energy profile of reefers based on the simulation model?
5. What are the reasons for the power peaks in the energy profile?
6. What solutions can be implemented to reduce peak power consumption at reefer stack?
7. How much is the energy saving and costs saving for the terminals with the new modus operandi of reefers/reefer stack?

Boundary Conditions

The research involves the modeling of peak power demand and energy consumption of 40 ft reefers operating on terminals. Thus, the modeling of reefer energy consumption during transportation by ships or other mode is out of scope for this research.

1.6. Research Methodology

In order to answer the research questions, a systematic approach is followed. Based on the research approach, the thesis is designed. The research approach and the thesis design are discussed in the following section.

Research Approach

FIGURE 17 expresses the basic Sargent modeling process, the problem entity, the conceptual model and the computerized model (Sargent, 1999). A triangle connects these three main parts of the modeling process. The problem entity is the real system and condition, which is complicated or hard to gain insights into, so modeling is necessary and helpful to get these insights and, thereby, get the characteristic of the real situation. The conceptual model is the logical expression of the problem entity, which is developed for a particular research, to represent the relationship and the process of the model elements, and it is the fundamental of the final model. The computerized model is the implementation phase of the modeling process, which is conducted using a computer programming language, and the experimentation with the problem entity.

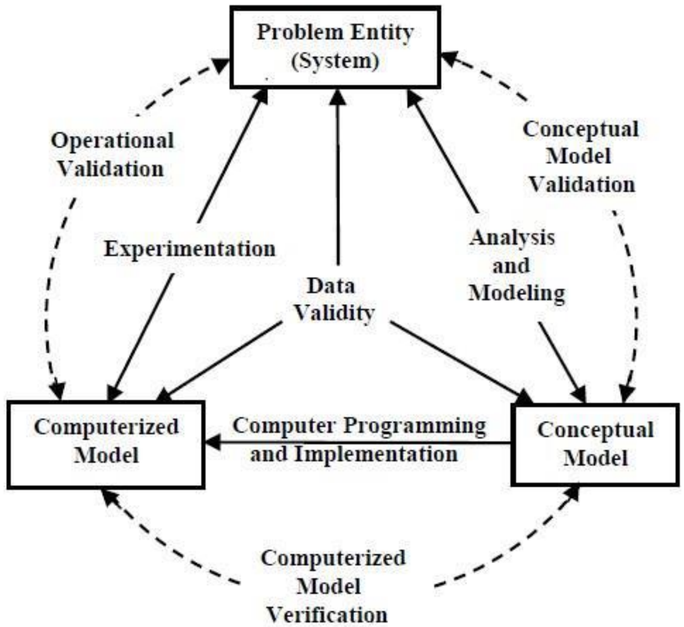

FIGURE 17. SARGENT MODEL FOR RESEARCH APPROACH (SARGENT, 1999)

In this master thesis research, the Sargent modeling process will be used to develop the peak power demand and energy consumption of reefer containers at terminal. The first step is to analyze the working of reefers (system). This will help answer the key variables affecting energy consumption of reefers (Sub-qestion-1). Then, the knowledge gap is identified from the current energy saving models. This is followed by a conceptual model whose working is validate by literature study. Based on the data collected and conceptual model, a simulation model is developed for a system of reefers (Sub-question 2 & 3). Its result will give energy profile of system of reefers over the period of time (Sub-question-4). This energy profile is again validated based on expert opinions. It will then be analyzed to diagnose the problem (Sub-question-5). Finally, peak shaving solution are be implemented resulting in reduction of peaks and saving in energy costs (Sub-questions 6 & 7). The research is finally concluded by summarizing the results, giving recommendations, providing directions for further research and by reflecting on the current research.

Thesis Outline

Based on the research methodology, this master thesis is structured in six chapters. Chapter 1 provides information on research topic, followed by the problem definition and research question. Chapter 2 provides a brief description of the working of a reefer and the current energy saving models followed by the knowledge gap In Chapter 3, following the description of reefer operations, the conceptual model for energy consumption of reefers is developed. This model is implemented and simulated for a system of reefer to generate the energy profile. Finally, the results are obtained from the simulation model and the problem is analyzed. In Chapter 4, peak shaving opportunities will be discussed followed by their analysis and implications. Conclusions and recommendations are given in chapter 5 and the reflection is given in chapter 6. The FIGURE 18 shows the relationship among each of the chapters:

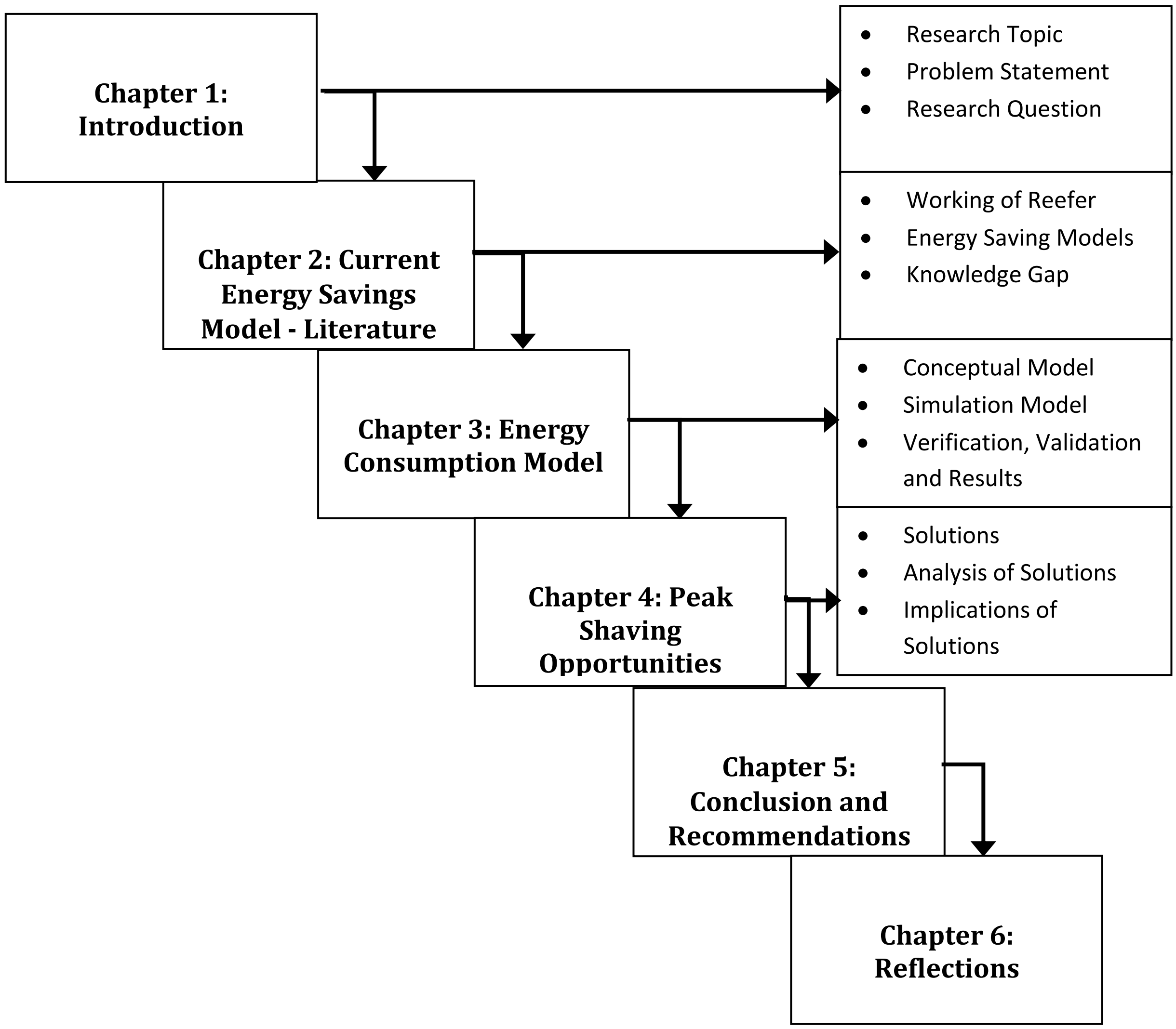

FIGURE 18. THESIS OUTLINE

The approaches considered in Chapters 3 follows the Sargent modeling process as outlined above. In the beginning of this chapters, the problem entities for energy modeling of reefers are identified; after that, the energy consumption model is developed based on the problem entities followed by verification of the model. Thus, a systematic approach will be followed to develop the computerized model.

1.7. Conclusion

The increase in the standard of living has led to higher food consumption per capita. Reefers plays a major in transporting different types of these food products by keeping them fresh throughout the entire supply chain. However, this mode of operation of reefers and the seasonality of food products has led more reefers operating simultaneously in cooling mode at terminals. This causes high power peaks resulting in large amount of energy costs for terminals. Hence, there is a need to reduce peak power leading to saving of millions of Euros in energy costs.

However, an energy-related cost reduction for a terminal operating reefers cannot afford to compromise of the quality of food products inside reefers. Hence, to identify the energy-saving solutions, a deeper understanding of the working of reefer is required. Based, on this the current energy-saving models can be discussed. These things are address in Chapter 2.

2. Current Energy Savings models – Literature Review

The main research objective to explore the possibilities to reduce peak power demand by reefers operating on terminals. This requires understanding of the modus operandi of reefers and the important variables affecting its energy consumption.

This chapter begins by explaining the working of reefer in section 2.1. After that, the important variables that impact its energy consumption discussed in section 2.2. This is followed by a literature review of the current energy saving models for reefers, the reefer monitoring tool available at terminals and some peak shaving techniques in section 2.3. Finally, based on this, the knowledge gap is formulated is section 2.4. The chapter concludes in chapter 2.5.

2.1. Description of working of a reefer container

A reefer is a portable refrigeration unit. Though it is complex unit, it is important to have basic understand of its working in order to develop the energy model. This will provide the foundation for building the base case model. A simple diagrammatic representation of different working units in reefer is shown in FIGURE 19.

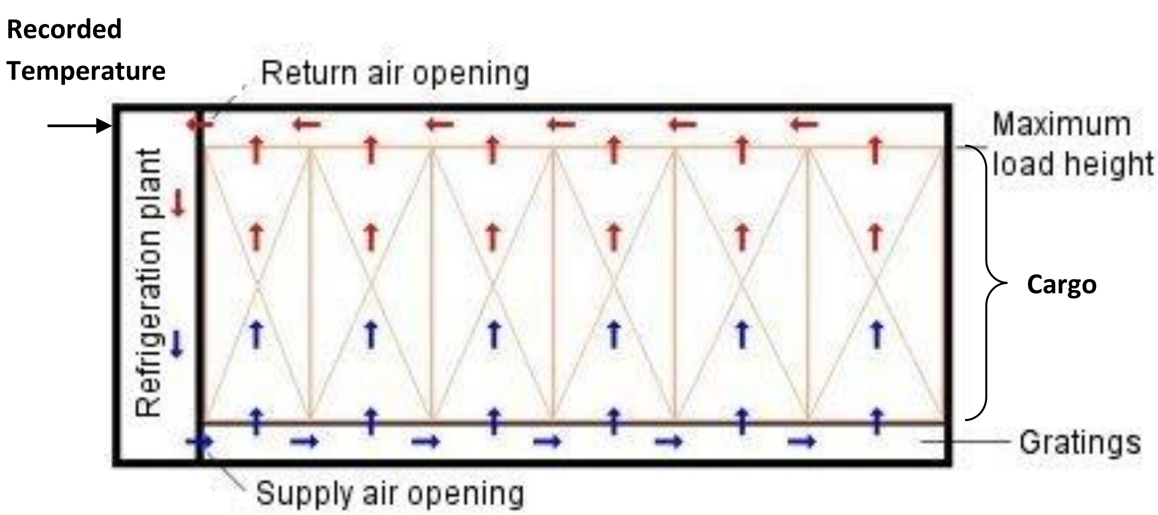

FIGURE 19. SCHEMATIC REPRESENTATION OF A REEFER (GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT E.V.(GDV), 2015)

Cold supply air is blown from the bottom of the reefer container. It flows through and around the goods through the gratings in the floor. During this process, heat exchange takes places between the cold air and the cargo. If the difference between the supply air temperature and cargo temperature is high, the hot return air is drawn off from below the container ceiling. The circulating fans in the refrigeration part then forces the returned air through the air cooler, which also acts as the evaporator in the cold circuit, and back through the gratings into the cargo.

In order to enable proper heat exchange, the goods must be stowed in the container in such a way that the air flow is not interrupted. Hence, it is necessary to stow the cargo below the red load limit line. Also, proper packaging must be ensured to avoid circulation bypasses of the supply air.

When operating, small fluctuations in temperature are insignificant. The degree to which these fluctuations are allowed depends on the type of products. The cooling compressor used to regulate the temperature switches on and off to save energy. In the switched off mode, only the circulating fans operate by means of auxiliary power. Thus, the temperature is allowed to rise/fall till the allowed bandwidth. Power consumption, in this mode, is reduced by a factor of 6. After the temperature has reached the bandwidth, cooling power is applied to bring it back to the set point temperature. This cycle is repeated till the entire dwell time of a reefer. As it is difficult for reefer handlers to determine the actual cargo temperature, *return air temperature*, i.e. the temperature of the air coming out of the cargo is used as an indication of the cargo temperature. If the return air temperature is very high compared to set point temperature, the cargo requires rapid cooling/heating thus utilizes both the auxiliary and the cooling power. And when the return air temperature has reached the set point temperature, the reefer operates in on/off mode alternating between auxiliary power and auxiliary plus cooling power. Thus, return air temperature is used as indicator to regulate the working of reefers (Gesamtverband der Deutschen Versicherungswirtschaft E.V.(GDV), 2015).

2.2. Factor Affecting Energy Consumption of Reefer

Based on the working of reefers, the energy consumption of reefers depends on following factors:

- Nature of cargo

The type of cargo determines the required set point temperature. The rate of heat exchange between the cargo and the supplied air depends on the specific heat and mass of the cargo. It is given by the equation

$$\mathbf{Q = M * C_p * \Delta T / \tau}$$

EQUATION 1. COOLING POWER OF REEFER (TRAN, 2012)

Where Q = Cooling/Heating Power (kW)
M = Mass of cargo (kg)
C_p = Specific heat of cargo (kJ/kg.^{o}C)
ΔT = Temperature Difference (^{o}C)
T = Cooling time (Seconds)

- Ambient temperature and Sun radiation

A reefer with a long time without power supply, exposed to high ambient temperature and sun intensity can lead to a potential problem known as ‘hot box’. It is a reefer whose return air temperature is beyond the allowed bandwidth when delivered to a container terminal. This reefer needs an excessive electric power to first bring down its temperature to the set point.

- Reefer Characteristics

Reefer size, its area and its thermal insulation are some of the factors that affect the energy consumption of reefers.

- Reefer technology

The technology used in the refrigeration unit plays a crucial role in determining the energy consumption of reefers. Most of the research to improve the energy efficiency of reefer focuses on the improving this technology.

- External factors

Reefer status including the airtightness of doors and the ventilation openings and clean ventilator systems have a major impact on the energy consumption of reefers. Their malfunctioning leads excessive power consumption by a reefer (Kieschnick , 2015).

2.3. Current Energy Saving Model

A reefer unit consists of hardware components such as thermal insulation, gratings and software component such as technology used for refrigeration. Two developments concerned with improving the energy efficiency of reefer units are: hardware improvements and software solutions.

Hardware Improvements

Zsembinszki et al. (2014) have carried out numerical model evaluation of the reefer which uses phase change material as a cooling component in the compressor. The major input variable considered in addition to container size is the thermal conductivity of the material of the container. Further research involves the proposition to use carbon nanotubes as insulation for reefers. However, hardware solutions have reached their potential limit, unless a major breakthrough occurs in material science.

Software Solutions

Majority of the energy saving models in reefers deal with optimizing the software running the refrigeration unit.

Sorenson (2013) has investigated the potential for reduction in energy consumption on a sample Star Cool reefer by the introduction of modern control methods, without compromising the quality of the transported goods. He has developed a non-linear dynamic simulation with the implementation of controller unit. He, finally, a presents a control structure consisting of a linearizing inner loop and an energy optimizing outer loop. The outer loop of the controller saves energy through adaptation to daily variations in ambient temperature and a grating ventilation rate that is varied to fit the actual demand. He uses the combination of thermal inertia of cargo and ventilation rate of grating to determine the actual demand for potential reduction in energy consumption of reefers.

However, the most commercially successful energy saving model for reefers has been developed by Wageningen University in Netherlands. This model, called 'QUEST', is currently the most advanced approach and hence it is discussed briefly in the following section.

QUEST

Quest stands for 'Quality and energy efficiency in storage and transport of agro materials'. Quest is a software solution to improve the control of refrigerated marine container (reefer) units with the objective of maximizing the energy efficiency in chilled mode operation without impairing the produce quality (Cuppen, 2015). A brief description of its working is discussed.

A reefer unit is designed to both freeze and cool. Traditional non-Quest control in chilled mode runs the evaporator fans in maximum speed regardless of load. Therefore it works less efficient in part load, such as when cooling less amount of fruit or vegetables. Quest aims to improve chilled mode energy efficiency by optimizing evaporator fan speed with the load, without impairing produce quality. A complex algorithm controls the changing of fan speed between OFF, HALF and MAX. The algorithm is designed to run fans in MAX speed during periods of high load, to alternate fan speed between MAX and HALF at moderate load, and to alternate fan speed between OFF and HALF during periods of very low load. The Quest software design includes carefully designed temperature limits and settings that keep produce at correct temperature, so that the quality is not harmed (Lukasse et al., 2011).

The above two systems are based on the individual working of reefers. It does not take into account a system of reefers operating at terminals. For this, a system named Reefer Monitoring and Control System has been developed. The following section provides a brief overview of this system.

REEFER MONITORING AND CONTROL SYSTEM

It is the automated control system that remotely monitors the conditions of reefer containers – during transportation onboard the containership and during storage at the container terminal. A reefer with a modem communicates its status to controller which sends the signal to the screen via transmission cable (Emerson Climate Technologies, 2014). The screen display the information as shown in FIGURE 20.

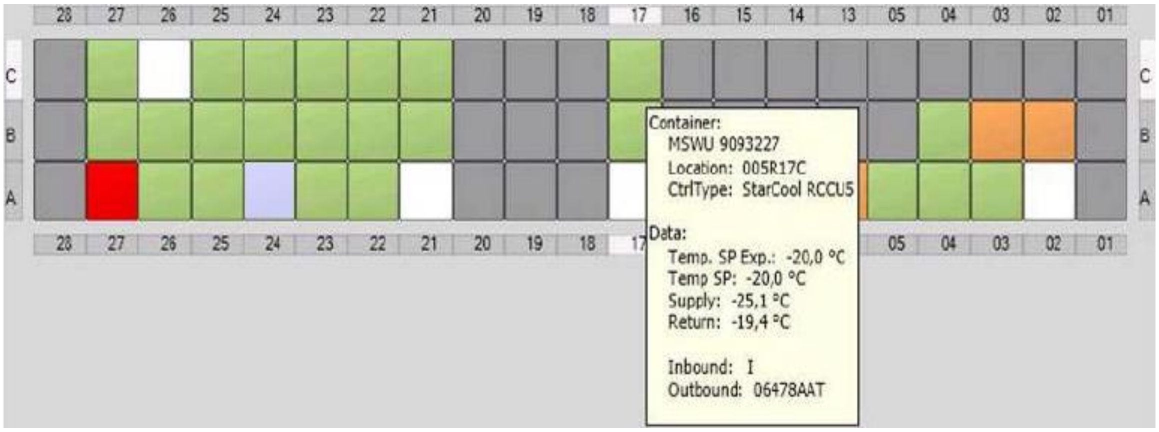

FIGURE 20. INFORMATION DISPLAY FROM REEFER MONITORING AND CONTROL SYSTEM (EMERSON CLIMATE TECHNOLOGIES, 2014)

This most important information displayed on the screen is the temperature indicators esp the return air temperature and set point temperature. A large deviation of return air temperature from set point is notified to the reefer handler who then inspects it.

This system enables safe transportation of cargo and transparency in shipping operations. Automated monitoring improves operational efficiency, reduces operating costs and increases personnel safety. A two-way communication takes place between the operator and every single reefer (Emerson Climate Technologies, 2014).

Peak Shaving Techniques

Peak Shaving is the technique to reduce electrical power consumption during periods of maximum demand on the power utility. Some of the techniques available to reduce peak demand are as follows:

- Load Shedding involves turning off non-critical loads during peak hours or operating non-critical loads only during non-peak hours
- Peak sharing uses a generator to power a portion of the facility electrical load. A generator can also be used to power non-critical loads during peak hours
- Power Sharing involves intermitted supply of power for the cooling operations of reefers.

It is common for a facility utilizing peak shaving techniques to have net energy savings of 10% to 30% of their electricity bill (Baldor Electric Company, 2005)

2.4. Knowledge Gap

Based on the previous paragraphs, the knowledge gaps deals with the dynamic visualization of energy consumption by a system of reefers operating at terminals and appropriate peak shaving techniques to save energy bill. The earlier studies emphasize the energy saving models for a single reefer and a reefer temperature control system at the terminal. It also provides list of different peak shaving techniques. However, it lacks the following elements that form the basis of the knowledge gap:

- Most of the models deal with energy consumption of reefers on individual basis. Reefer Monitoring and Control System, too, provides information mainly about the temperature of system of reefers. Hence, a detailed study is lacking about the energy consumption of a system of reefers connected at terminals. This includes the interconnection between the terminals operations and the temperature increase of reefers. For this, the research deals with the terminal logistics, its impact on reefer temperature and thereby the energy consumption at terminals.

- Existing models do not take into account the sensitivity of various factors discussed in section 2.2 on the energy consumption of reefer. Hence, a sensitivity analysis for a single reefer and for a system of reefers is performed. This will give insight into the key decision variables for determining the energy consumption of a reefer.

- Many studies confirm the occurrence of power peaks at terminals due to reefer operations. Several peak shaving techniques are also available to reduce peak power demand. However, there is a lack of study of how to incorporate these peak shaving solutions the peak power demand by reefers terminals. Hence, this research will provide details of the peak power consumption by reefers followed by the opportunities to reduce these peaks.

- Grid operators calculate the electricity price for container terminals partly based on the peak energy consumption of terminals. The greater the observed peak, the higher the energy costs. The challenge for container terminals is therefore to smoothen their peak demand over time to prevent high peaks leading to saving in energy bill. However, the financial saving due to peak reduction are unknown. This research, thereby, presents the saving by a terminal due to peak power reduction.

2.5. Conclusion

This chapter began with the description of the working of reefers with emphasis on its on/off operations. Furthermore, it discussed the importance of return air temperature in monitoring the status of reefer. The most important variables affecting the energy consumption of reefers are also presented. From the previous research, most of the energy saving models dealt with the refrigeration unit of a single reefer. Reefer Monitoring and Control System, a temperature monitoring software, lacks the visualization of energy consumption by reefers and provides only temperature status of reefer. Hence, there is need to study of this energy consumption by reefers at terminals.

This chapter theoretically described the working of reefers. This working is developed into a conceptual model and final implemented into the simulation model. These models are discussed in Chapter 3.

3. Energy Consumption Model

Chapter 2 identified the knowledge gaps in the current energy saving models of a reefer. It emphasized the development of energy consumption model for a system number of reefers operating on terminals. This chapter presents the development of the conceptual model for energy consumption followed by its implementation in the simulation software and finally the outcome of the simulation.

The chapter begins with identifying the key terminal operations of a reefer. This forms the basis of the conceptual model in the section 3.1. This is followed by the motivation for the appropriate simulation method in section 3.2. The data required and the key assumptions to build the model are discussed in the section 3.3. of model specification. The conceptual model, the required data and key assumptions are incorporated in simulation software to develop the actual model. This is discussed in section 3.4. The verification, validation and the sensitivity analysis of the model are discussed in sections 3.5, 3.6 and 3.7 respectively. The key results and the problem analysis is presented in section 3.8. The chapter concludes in section 3.9.

3.1. Development of Conceptual Model

In order to determine the relation between terminal logistics and reefers, it is important to identify all the terminal processes. FIGURE 21 gives an overview of the different terminal operation a reefer undergoes. The operations are divided into three phases: Incoming, Dwell Time and Outgoing. In the incoming phase, the ship carrying reefer containers arrives on the quay side. The reefers are, then, unplugged on ships and transported on the terminals by means of quay cranes. During the dwell time phase, they are stored in special reefer racks. Continuous supply of electricity is ensured by plugging them into electrical sockets for their respective dwell time. Finally in the last phase, they are plugged out of sockets, loaded onto trucks, trains or barges and transported to hinterland.

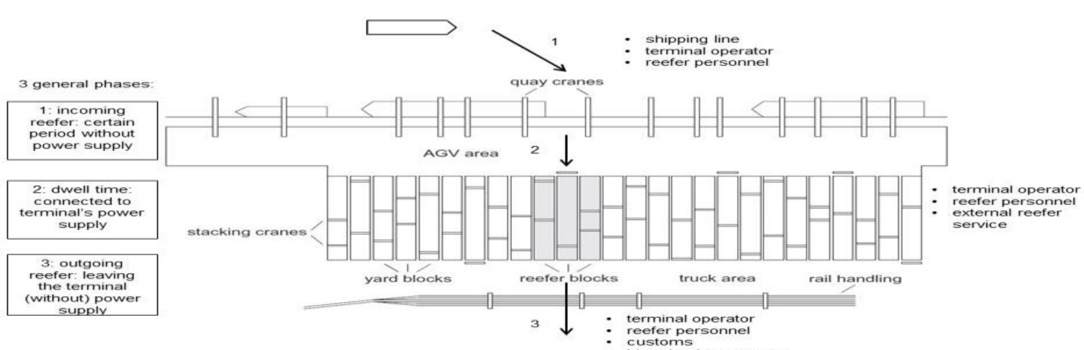

FIGURE 21. TERMINAL OPERATIONS OF A REEFER (HARTMANN, 2013)

However, in order to have an in depth understanding of terminal operations and its impact on temperature fluctuation in reefer, IDEF0 (Integrated Definition) diagram is constructed. The next paragraph gives overview of the IDEF0 process and the IDEF0 diagram for reefer operations.

IDEF0

IDEFO scheme is often used in systems engineering to represent its functions and its ICOMs: Inputs, Controls, Outputs and Mechanisms (Sage & Armstrong, 2000). FIGURE 22 shows the schematic representation of IDEF0 diagram. On the left side of the scheme, an input enters the function/process box. The controls that are needed for the process (e.g. data/information) are labeled on the top side of the box. The mechanisms (entering from below) are the means (e.g. machines or operators) needed for executing the process. After the execution, the output leaves from the right hand side.

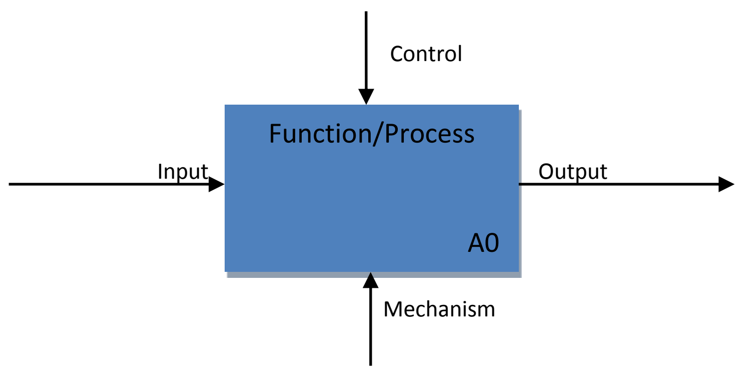

FIGURE 22. IDEF0 PROCESS SCHEME

The highest representation of all container terminals handling reefers is presented by A0 scheme in FIGURE 23. Here all the control and mechanisms of handling a reefer can be visualized. The controls refer to different types of instructions or activation signals, whereas the mechanisms show the means to achieve these instructions or signals.

The containerships, trains and trucks entering the container terminal form the input of the reefer handling process. They are often loaded with reefer containers. With the help of terminal equipment (visualized below the A0-box), the containers are stacked in reefer racks, plugged into electrical sockets and checked for its temperature setting according to the bill of lading information supplied by the shipping line (Radu & Kruse, 2009). After dwell time of reefers, they are plug-out and loaded onto the containerships, trucks and trains to depart from terminal. The constant power supply of reefers results in energy consumption at terminals.

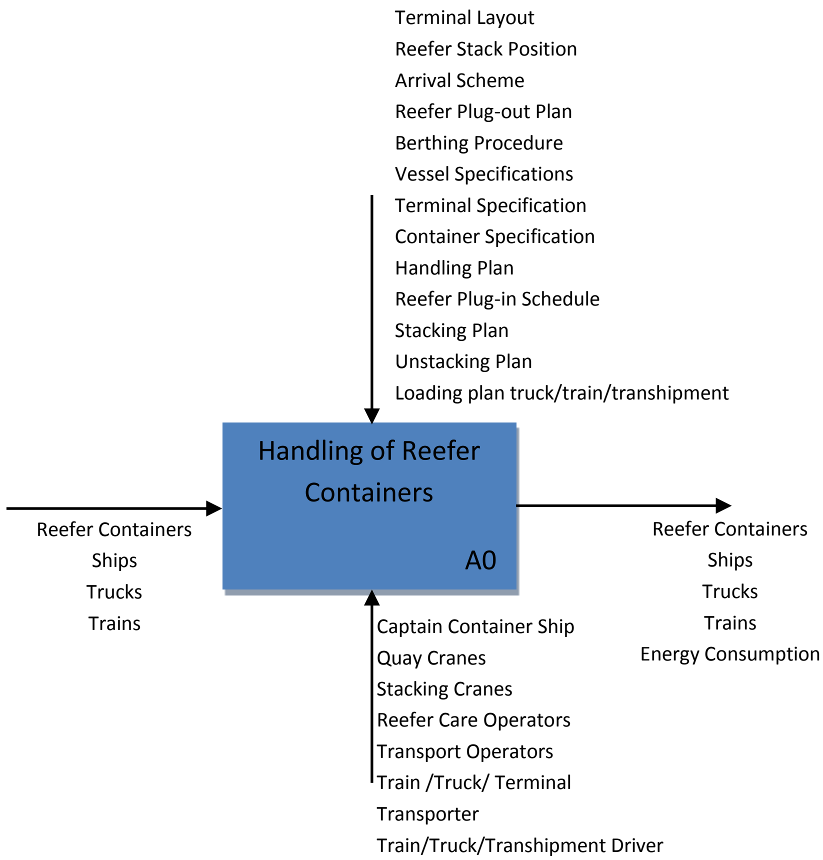

FIGURE 23. A0 SCHEME FOR CONTAINER TERMINAL HANDLING REEFER

The low level IDEF0 diagram in FIGURE 23 is further decomposed into deeper levels[2]. This provides a detailed understanding of the reefer handling operations at terminal. Because energy is consumed by reefers only between its plug-in and plug-out time, the other terminal processes mainly impact its temperature. First part of the conceptual model mainly deals with this impact.

Conceptualization of reefer model during its unplugged time

The IDEF0-schemes have identified all the terminal processes, concerning the handling of reefers. It is important to study the impact of these processes on the reefer temperature. This will help determine its temperature fluctuations. These fluctuations have great impact on the its initial power requirement. FIGURE 24 gives a sample temperature profile for the transport of fishes from Iceland to France. As seen, as the ship arrives on the terminal and a reefer is plugged out, there is a rapid temperature increase. This is because there is a certain time period where a reefer is without power supply (Unplugged time) which affects its temperature. In this case, the temperature of reefer increased from 0.5 ^{o}C to 6 ^{o}C for a period of eight hours without power supply,. The next section deals with the modeling of this temperature fluctuation.

[2] For Details, Refer Appendix C.

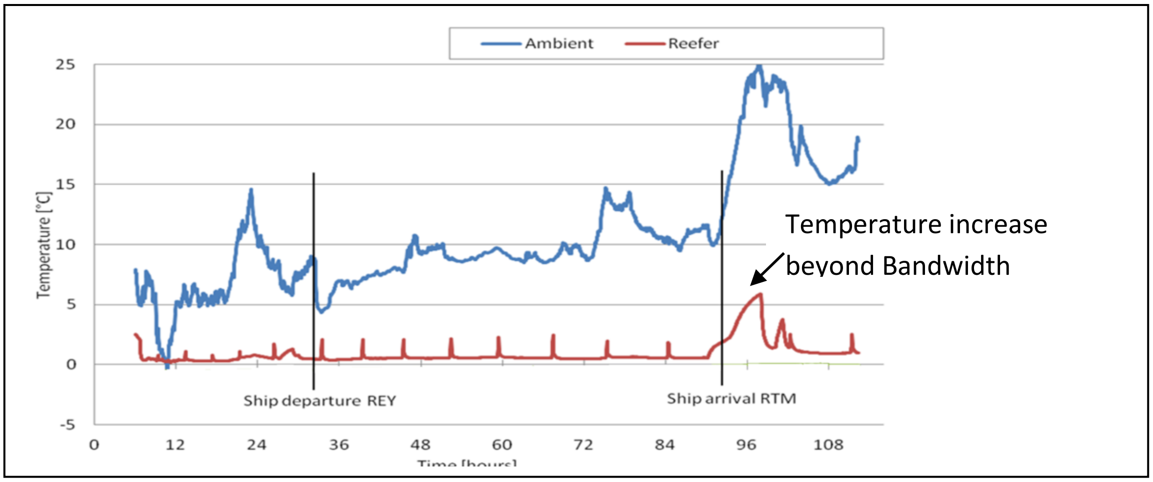

FIGURE 24. TEMPERATURE PROFILE OF REEFER (ELÍASSON, MARGEIRSSON, & ARASON, 2013)

Based on the literature study, the most comprehensive equation to model the temperature increase is as follows

$$\Delta T(t) = \Delta T - \Delta T * \exp(-(A*k*t*(1+S)/(m*Cp)$$

EQUATION 2.TEMPERATURE INCREASE OF REEFER (TRAN, 2012)

Where

$\Delta T(t)$ = Temperature Effect in Time (^{o}C);
ΔT = Ambient Temperature - Return Air Temperature (^{o}C);
A = Surface Area of Reefer (m^2);
K = Thermal Insulation of Reefer ($W/m^2.^{o}C$);
t = Time before plugging in at reefer stack (Seconds);
S = Exposed sun intensity (Dimensionless);
m = Mass of Cargo (kg);
Cp = Specific heat of cargo ($kJ/kg.^{o}C$).

As seen, EQUATION 2 covers different types of variables affecting the energy consumption of a reefer (Section 2.2), Hence, this equation is in line with variables affecting the working of a reefer.

This equation gives the temperature rise of reefers during its unplugged time. Once, the reefer arrives in stack, it is plugged it and the temperature settings are checked. The reefer starts consuming energy from this moment. The working of the reefer during this time is discussed in section 2.1. Based on this, the conceptual model for energy consumption of reefer is developed and shown in the FIGURE 25. The next paragraph provides the description of the conceptual model.

Conceptualization of reefer model during its plugged-in time

From EQUATION 2, the temperature fluctuation of a reefer before its plugged-in is determined. The return air temperature of reefer rises correspondingly during this period. Once a reefer arrives in stack and it is plugged it, the return air temperature may show deviation from the recommended set point temperature. The first check occurs whether due to temperature fluctuation, the return air temperature has crossed the allowed bandwidth. This point is shown in FIGURE24. Based on this two conditions are possible:

- Return air temperature is beyond the allowed bandwidth
- Return air temperature is within the allowed the bandwidth

Case 1: Return air temperature is beyond the allowed bandwidth

Within this case, there are again two possibilities:

- Return air temperature is beyond the upper limit of bandwidth

In this case, there is great risk of product damage due to overheating (Miller, 2012). Thus, there is urgency to bring the reefer back to its set point temperature. Hence, rapid cooling occurs to bring down its temperature. During this process, in addition to usual auxiliary power, maximum amount of cooling power is applied. The applied cooling power is given as follows:

$$\mathbf{Q = M*C_p*\Delta T/t}$$

EQUATION 3. COOLING POWER OF REEFER

This equation is same as EQUATION 1. The combined use of auxiliary and cooling power causes an initial power pulse. This pulse is applied till the temperature has reached the set point. After this, the reefer operates in its usual on/off mode. Therefore, in this case, there is an initial power pulse of auxiliary plus cooling power to bring down the reefer temperature.

- Return air temperature is beyond the lower limit of bandwidth

In this scenario, there is a high risk of formation of crystals especially in the meat products (Frozen food Handling and Merchandising Alliance, 2015). Hence, again there is an urgency to bring back the temperature to its set point. Hence, heating occurs in reefers till the set point is reached. Like previous scenario, there is an initial power pulse till the set point temperature is reached. Then the reefer operates in its usual on/off mode.

Case 2: Return air temperature is within the allowed the bandwidth

In this case, the return air temperature at the time of plug in is within its allowed bandwidth. Hence, the reefer operates in usual on/off mode. Auxiliary power is used till the temperature has reached the upper limit/lower limit in case temperature rise/fall. After this, cooling/heating power is additional used to bring down(up) the reefer to its set point.

Based on the above description, the conceptual model is developed. This model is shown in FIGURE 25.

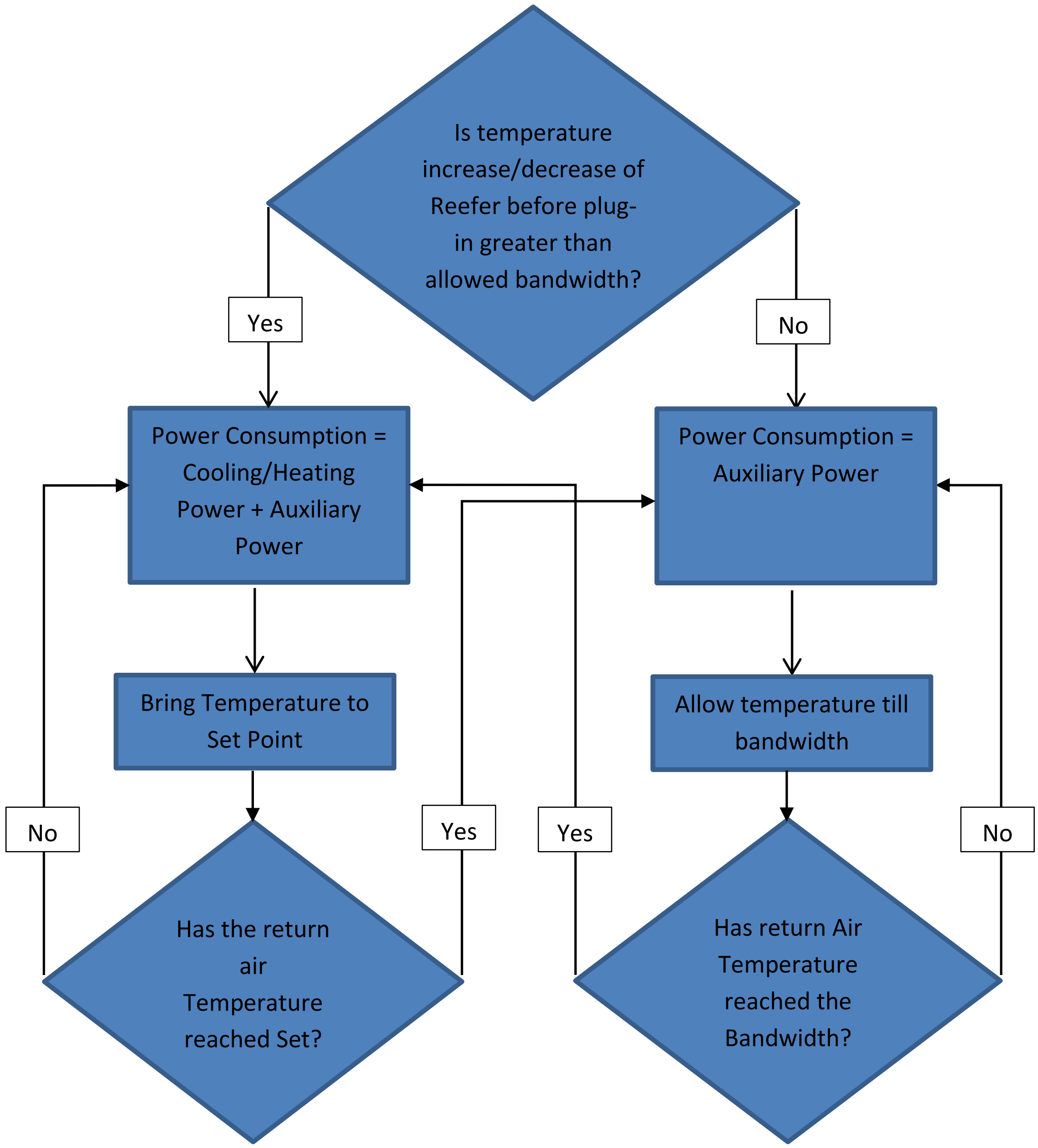

FIGURE 25. CONCEPTUAL MODEL OF POWER CONSUMPTION OF REEFER

Discrete Simulation is used to build this conceptual model. The following section provides the motivation to use this modeling technique.

3.2. Simulation Approach

Model is a representation of the construction and working of a system of interest. It is similar to but simpler than the system it represents. Hence, it is used to solve complex problems, especially when real experiments are too costly or cannot be executed easily. A good model is a judicious tradeoff between a real system and the simplified one. The motivation to carry out computer generated simulation models is understand the complex dynamic processes. These models help to identify potential bottlenecks in the system and can aid as a decision support tool (Hartmann, 2013). Other advantages of these models are ease of adaptability, the ease of representation and simplified understanding. It also enables analyst to predict the effect of changes in the system. Thus, models can be used as a policy-support tool for managers (Idener, 2015).

As reefer is a complex unit, different modeling techniques have been used to understand its mode of operation. The following paragraph deals with the techniques used for modeling an individual reefer.

Simulation models for energy consumption of reefers

Modeling is being used to aid the design and optimization of refrigeration systems**.** Over the years, many models have been developed to understand the working of a reefer and thereby develop energy saving solutions. The fundamental concept of these models is the basic energy balance equation. Using this as a foundation, several approaches such as spatial temperature difference models, heat flux models have been developed to gain an in depth understanding of the reefer system(James et al., 2006).

Though there are several techniques available for determining the energy consumption, the methodology adopted in this research is simulation modeling. This is because, it is a cost-effective means to understand the current system, identify the bottlenecks and suggest solutions to improve the current system. Simulation also provides design tools capable enough to generate real life atmosphere. It is often a preferred choice when the system is complex with many interacting variables, the relation among the variables is nonlinear and output has to be visualized in interactive way. These factors make simulation modeling the preferred choice for studying reefer system (Fishwick, 1995).

In simulation modeling, Computational Fluid Dynamics (CFD) has been the most widely used technique for modeling energy consumption of a reefer (James et al., 2006). Jedermann et al.,(2013), however, follows a different approach. He has used linear dynamic differential equations in Matlab software to study its energy consumption. Sorenson (2013) has used simulation environment such as TRNSYS, Matlab and Simulink to model the complex refrigeration system of an isolated reefer. These models, however, are too individualistic and thereby fail to determine the impact of energy consumption of system of reefers operating on a terminal.

Like a reefer, terminal is also an extremely complex system consisting of different types of equipment and their operations. Many models have been developed to understand the terminal process. Some of the modeling techniques are discussed in the following paragraph

Simulation models for terminals

Several simulation models have been developed to understand the complex terminals operation. Lutjen et al. (2012) has used network model to study the interactions between different agents of logistics such as vendors, distributors and ware houses. The model consists of nodes and transport relations among these agents. Hartmann (2013) has used discrete-event based simulation to understand the container logistics for the entire terminal. The model is built in the emPlant simulation software. The model captures the dynamics of logistics of the containers between different physical resources. These simulation models include the frequency and transport related parameters along with the container parameters. Operations research (OR) models are used to determine the optimal fleet size and optimal operation schedules. However, the focus of these models is on the logistics side and it ignores the energy consumption of reefers.

Simulation models have also been developed to study the energy consumption at terminals. Saanen et al. (2015) have used heat mapping technique to simulate the CO_2 emissions of a terminal. This is especially helpful to understand the energy and environmental impacts of different terminal operation in much detail. However, this model though extremely useful, deals with only large objects and focusses more on the CO_2 emission. Abadi et al. (2009) have used an object-oriented simulation system developed in C# programming language to develop an macroscopic model of terminal. It consists of objects such as the terminal itself, trucks, trains and ships. Other minor objects such as various yards, different types of canes are contained within the terminal object. However, this model does not track the movement of these individual objects. The summary of the above modeling techniques is given in TABLE 5.

Simulation Purpose	Simulation Technique	Advantage	Disadvantage
Energy consumption of reefers	Energy Balance, Fluid Dynamics, Differntial Equations	Detailed Understanding of Refrigeration System	Lack of Systems perspective between terminal and reefers
Terminal Operations	Network Model, Operations Research	Interaction among different actors, Enhanced Operations	Lack of Focus on Energy consumption by eefers
Energy Consumption at Terminals	Heat Mapping, OOPs	Emission by equipment, Interaction among objects	Lack of dynamic representation of peak power demand by reefers

TABLE 5. SIMULATION MODELING TECHNIQUES

Choice of Modeling Technique

From the above shortcomings, it is important to identify a simulation technique which interrelates the terminal operations with the energy consumption of reefers. The modeling approach should be feasible to represent the dynamic energy consumption of reefers. It should enable the modeler to adjust the system easily for testing different scenarios. This is suitable only in discrete event simulation.

In this simulation, the state of the system changes at discrete points in time called events. Hence, a state will only alter when there are events such as operational change in reefer, arrival/departure of reefers. This simulation technique follows an object oriented approach with each system treated as a separate object. Also, each objects can be described by entities that take over the object's attributes and behavior. Each of these entities can also have its own attributes and behavior (Maria, 1997). The electrical billing period, as discussed in section 1.4, occurs in discrete time steps of 15 minutes. With this simulation, it is possible to determine peak power demand in this time step. Thus, this simulation can model individual operation of reefers, the interaction between terminal and reefers, the dynamic energy consumption at terminals and provide accurate results for energy consumption.

Therefore, the conclusion is to use the discrete-event approache for constructing the simulation model. For this purpose the Simio simulation software package of Simio LLC is used (Simio LLC, 2015). Nevertheless, as discussed above, different approaches and software packages, with their own advantages and disadvantages, can be used to model energy consumption of reefers at container terminals.

3.3. Model Specifications

After discussing the conceptual model and the simulation approach, the data requirements for the simulation model are presented in the following section

The main data required is divided into the following categories:

- Reefer Logistics on Terminal

This provides information about the arrival and departure schemes of the large number of reefers at a terminal. ABB has provides this data for a sample terminal in Port of Rotterdam for the period from 01/01/2014 to 29/01/2015. This data sheet also includes individual reefer related information such as the type of cargo in reefer, mass of cargo, the set point temperature and the number of reefer plugs.

- Terminal specification

In this, the important data required is the delay time before a reefer is plugged-in because this affects the temperature fluctuations of a reefer. The delay time depends on whether a reefer is for import or export purpose. In case on import, the layout of reefers on the ship is an important factor determining their delay time. A quay crane and a stacking crane takes 10 minutes to bring the reefer from ship to reefer rack. On average, a container ship has 800 reefer plugs. Hence, in this case, it takes 2 hours for the last reefer to arrive in reefer rack. Once a reefer arrives in a rack, a job is sent to reefer operator on terminal to plug it in within one hour. However, in some extreme circumstances, a reefer might be plugged out for more than 6 hours. For an export reefer, the delay time is less due to the arrival of small quantity of reefers.

- Characteristic Reefer data

Based on EQUATION 1, EQUATION 2 and the conceptual model, the following reefer related data is required for simulation.

Thermal Insulation

This data is important to determine the temperature increase of reefer in the unplugged and auxiliary power state. Based on the literature, lower the value of thermal insulation of reefer, better is its resistance to temperature increase (Geysen & Verbeeck, 2011). This value mainly depends on the age of reefers. The average lifetime expectancy for a reefer is 12 years (Sorensen, 2015). Thus, as the reefer becomes older, its thermal insulation value increases. The table gives the relation between the age of reefer and its thermal insulation value.

Age (years)	Thermal Insulation Value ($W/m^2.^oC$)
0 - 4	0.5
5 - 8	0.6 - 0.7
9-12	0.8
>12	0.9

TABLE 6. VARIATION OF THERMAL INSULATION OF REEFER WITH ITS AGE (GEYSEN & VERBEECK, 2011)

Surface Area

The dimension of reefer varies slightly according to the manufacturers. However, for this research the following dimensions are adopted.

Dimension	Size
Length	12 m
Width	2.3 m
Height	2.6 m
Area	130 m^2

TABLE 7. DIMENSIONS OF A REEFER (CMA CGM, 2015)

- Electric Power Data

The electric power of a reefer consists of auxiliary and cooling power. Based on literature, 2.5 kW of power is required by a reefer to run its basic components such as fans (Tran, 2012). The cooling power depends on the set point temperature (see section 1.4). The cooling capacity varies slightly according to the manufactures and ambient temperature.

- Cargo Data

The important cargo data required for modeling are the specific heat of cargo and the allowed temperature bandwidth

Specific Heat of Cargo

In the model, the specific heat of cargo is determined from the set point temperature. This, is because the terminal operator has no knowledge of the type of cargo inside a reefer.

Allowed bandwidth for cargo

This data depends on the type of cargo inside the reefer. In general, frozen cargo has higher allowed bandwidth compared to chilled cargo. The simulation model is built on the same principle.

Mass of Cargo

Mass of cargo is equal to the quantity of product stuffed in reefers.

External Atmospheric Data

Hourly ambient temperature and sun intensity data of Rotterdam is used in the simulation model. The ambient temperature is directly taken from the weather data for Rotterdam. Sun Intensity, however, is modeled as a relative term ranging from 0 (No Sun Intensity) to 1 (Maximum Sun Intensity). It has value '0' during the night time and value '1' during the peak summer period. For the rest of the duration, its value fluctuates between '0' and '1'.

Scope and time span

The scope of the simulation model deals with energy consuming reefer operations at a terminal. For this, a systems approach has been followed describing the important terminal operation, the characteristic reefer data, the important details of cargo inside reefers and the necessary external variables. In this systems approach, emphasis has been on the energy consumption algorithm of a reefer.

The energy consumption is modeled for of 61321 reefers arriving and departing at the sample terminal over a period from 01/01/2014 to 29/01/2015. These reefers arrive in different periods of the year, have their distinguishable characteristic data, carry various types of cargoes, each of these cargo have different weights. For detailed data analysis, see appendix[3].

The run length of the simulation period is one year and one month, which is 9480 hours. The longest cycle time within the simulation model is the reefer with highest dwell time. This value

[3] For details, refer Appendix D.

from the data analysis is 12 days including the loading/unloading time. A rule of thumb is that the runtime of the model should be at least three times the longest cycle time (Kelton, 2000). This precondition is satisfied in the simulation model, since the run time is 33 times the longest cycle time. A time step of 1 minutes is used to simulate the temperature increase/decrease function. For peak power calculations, 15 min time step is used. No warm-up period is used, because the plug time of reefers are based on a data table.

Model assumptions

For constructing the simulation model some assumptions have to be made due to the lack of precise data or to simplify the (sub) processes of some complex terminal operations. The assumptions are divided according to system parameters.

- Terminal Operations

A container ship has varying number of reefer plugs depending on its size. The number of reefer plugs vary from 100 on a small ship to over 1000 on a large ship (Dekker, 2014). The number of reefer plugs has impact on the time taken by the last reefer to reach the reefer rack. In the model , a ship with 800 reefer plugs is assumed. Also, 10 min time period is assumed between the plug out time on ship to arrival of first reefer in the rack. This value may be lower or higher depending on the terminal, crane operations and other factors. To determine its impact, a sensitive analysis is performed.

The time period between arrival of successive reefers in reefer racks in considered as 15 seconds. This is due to the movement of quay cranes from one reefer to another. Its impact is considered minimal as in this time period, the temperature increase of a reefer is negligible.

Once a reefer arrives in rack, it takes 1 hour for the terminal operator to reach the rack and plug-in the reefer. This is the maximum time allowed. Hence, in the model the worst case scenario is already considered.

- Reefer Characteristics

The dimensions of the reefer vary slightly according to manufacturers. However, a constant surface area is assumed for all the reefers. Its impact is considered a minimal as the variation in area among the reefers is negligible.

In the model, a mixture of different thermal insulation values is considered. The four thermal values of 0.5,0.6,0.7,0.8 are divided equally among all the reefers. To determine the impact of a group of very old reefers on energy consumption, sensitivity analysis is performed.

For a particular set point temperature, the cooling capacity of reefers vary slightly according to ambient temperature. In the model, a uniform cooling capacity is assumed for a particular set point temperature. A detailed sensitivity analysis has to performed to determine of varying cooling capacity of total power consumption at terminal. This is currently beyond the scope of this research.

- Cargo

In the model, temperature is solely used to monitor the state of cargo. This is because only temperature status is available to the terminal operator. Also, other cargo condition checklist such microbial growth, gas exchange and crystallization mainly depend on the temperature of reefer. These processes and different cargo conditions checklist are not considered in this model

Other cargo related data such as packaging, spatial temperature difference are beyond the scope of this research.

- Electrical Data

Electrical contracts between the utility company and terminal is confidential information. Hence, a general electricity tariffs for industries in Netherlands are used for calculation of energy costs. Within this tariffs, day, night and peak prices are only used. Other costs such as installation costs, maintenance costs are not considered. Thus, the final result will provide additional cost due to peak power demand, day and night time energy costs and total energy costs.

In the model, the time step to calculate power peak is 15 minutes. This is usually determined in the contract between the utility company and the terminal operator and varies as per terminal.

Based on the conceptual model, model specifications and the above assumptions, the simulation model is developed. This simulation model is discussed in the following section

3.4. Description of Model

The FIGURE 26 shows the structure of the energy consumption model of a single reefer. When the containership carrying reefers arrives, the reefer is plugged out from its power source. It is then lifted by quay cranes and stacked into the reefer racks. Here, it is again plugged into power source. In between this time, the reefer is without power supply. Hence, depending on the conditions, its temperature may rise/fall to varying degrees. Once the reefer is plugged in, it operated in its usual on/off mode.

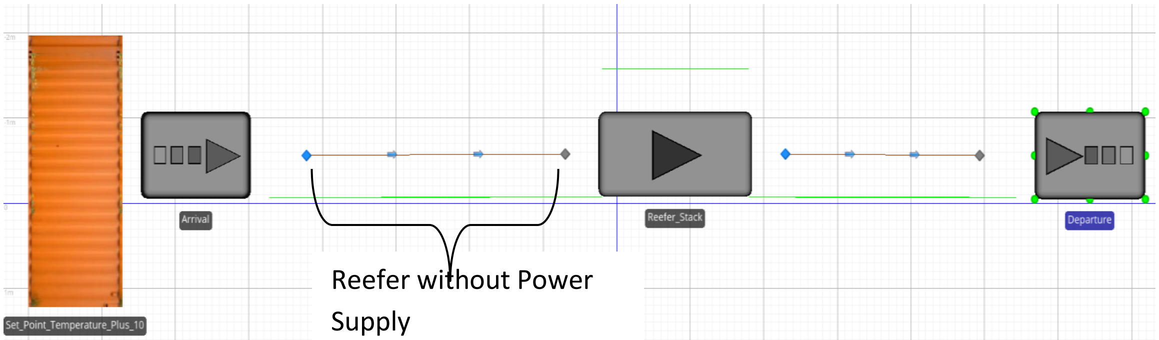

FIGURE 26. ENERGY CONSUMPTION MODEL - SINGLE REEFER

Reefers with different set point temperature arrive at the terminal. Hence, the above model is replicated for the different temperature classes of reefers available from the data sheet. These temperature classes consists of several individual entities. For all these entities, the only common attributes are surface area and their auxiliary power. Rest of the data from the model specification varies for each entity. Hence, every entity (Reefer) is unique in its own way. This assignment of different attributes to each entity is summarized in FIGURE 27.

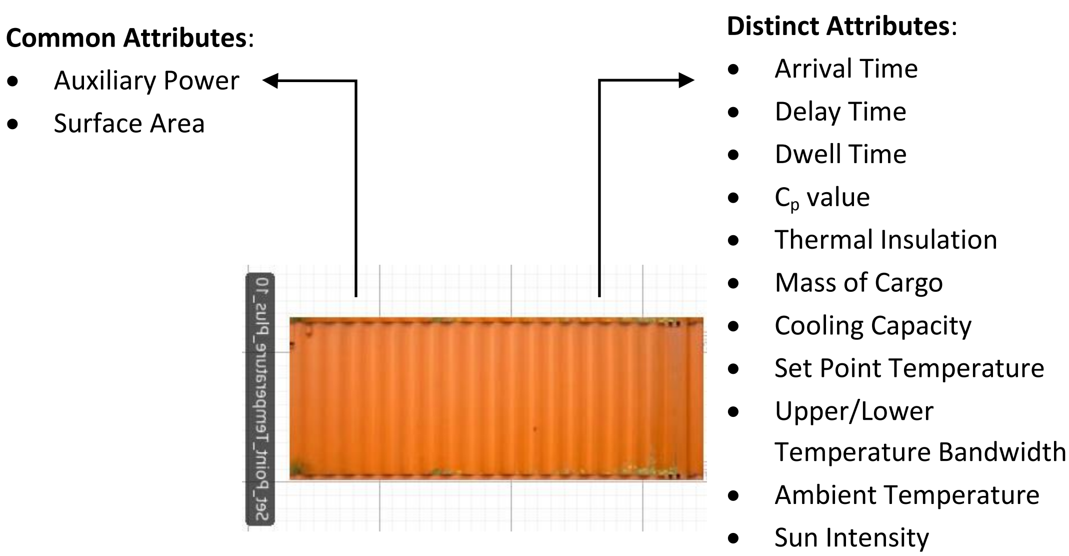

FIGURE 27. DIFFERENT ATTRIBUTES OF A REEFER

After assigning these attributes to each of the 61321 entities, the working algorithm of the reefer is developed. This algorithm is shown in FIGURE 28. Its working is based on the conceptual model discussed in FIGURE 25 and is applicable for all the entities.

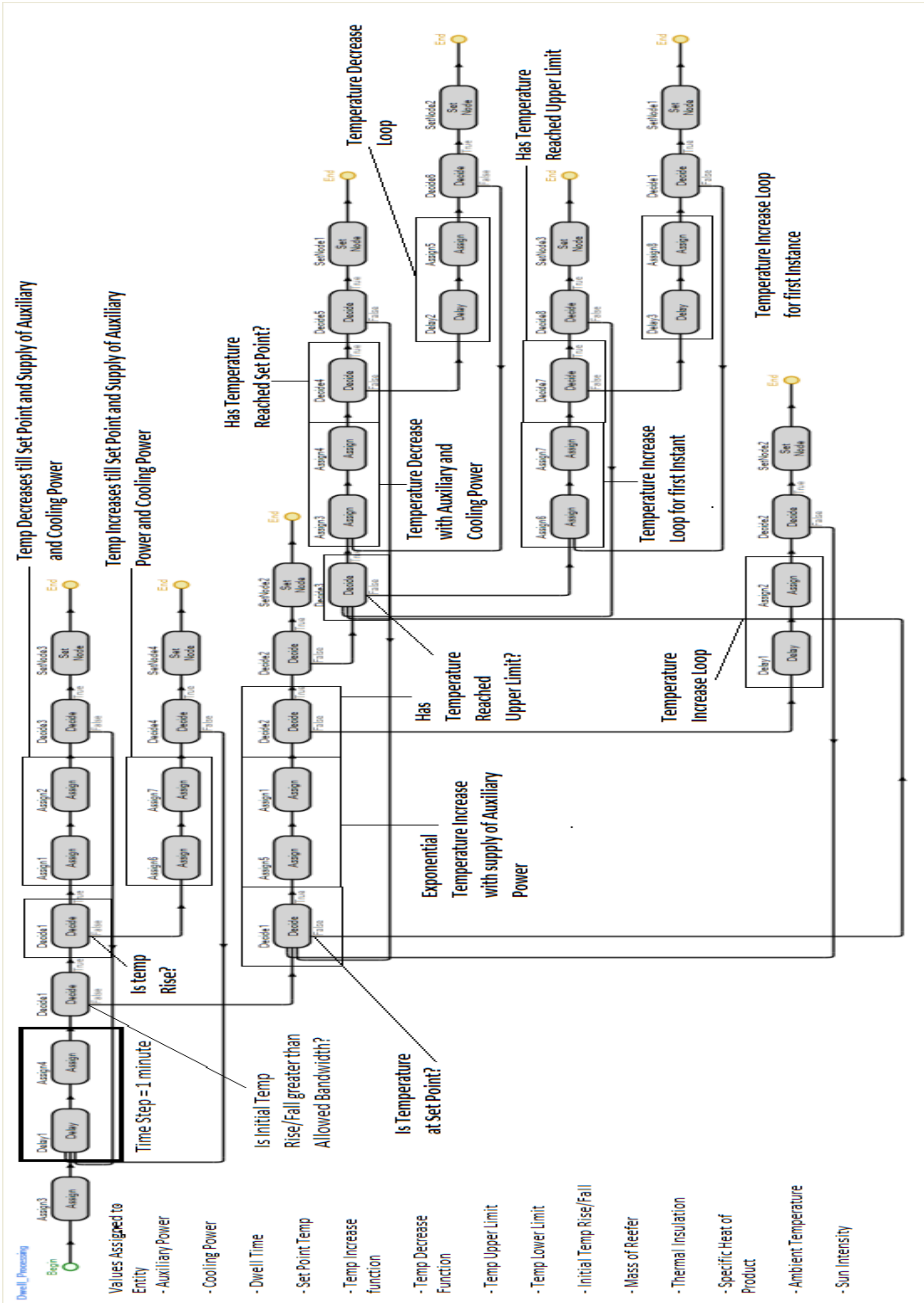

FIGURE 28. OPERATING ALGORITHM OF A REEFER

The working algorithm is then incorporated into the simulation model shown in FIGURE 29. The entities are divided on the basis of temperature class as frozen (Black) and chilled (Orange).

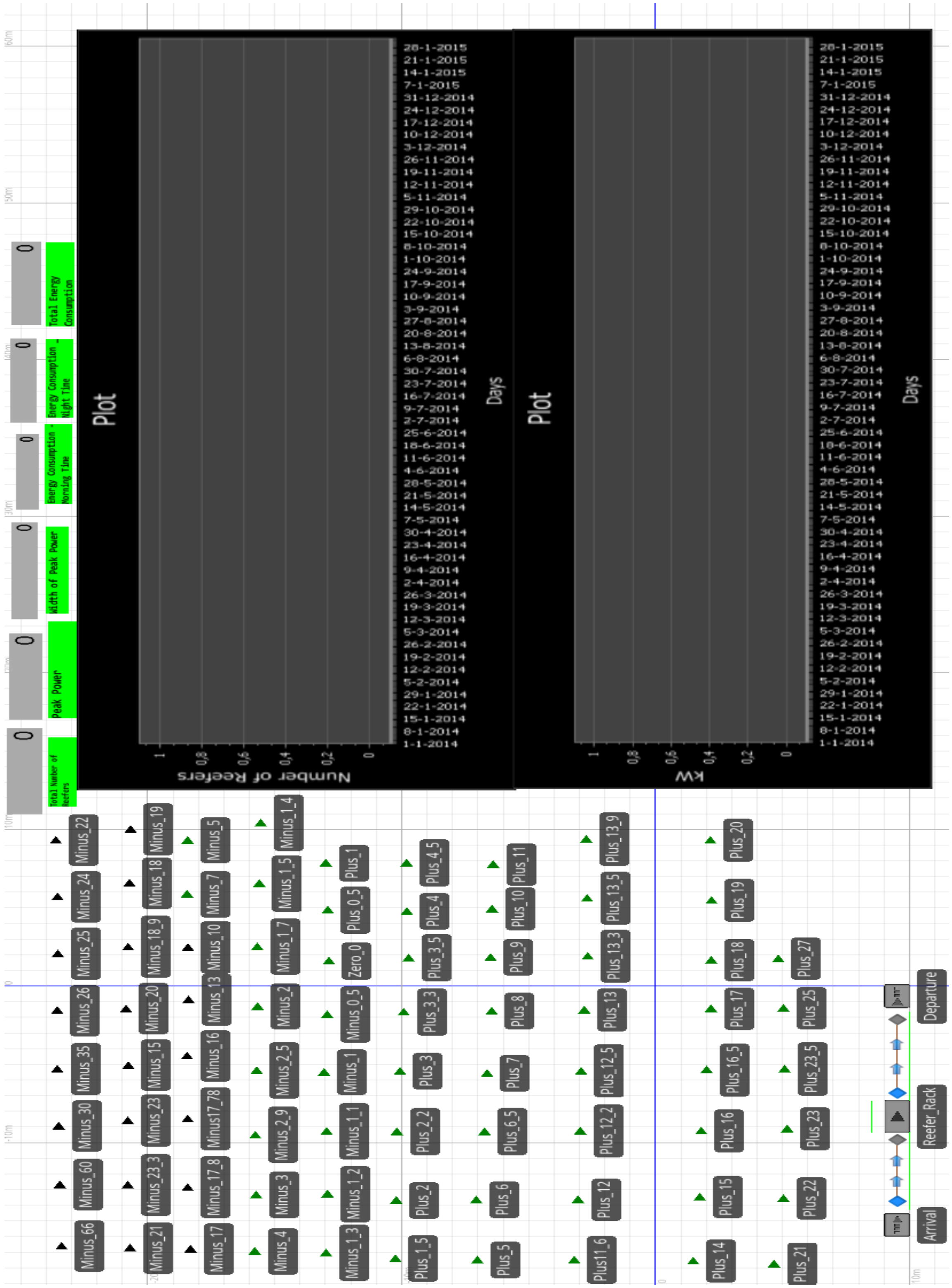

FIGURE 29. COMPLETE SIMULATION MODEL

As seen above, the model is able to generate the following output:

- Number of reefers connected at any moment in time;
- Utilization of Reefer Plugs (%);
- Power consumption over time graph ;
- Peak power demand (kW);
- Average Power Consumption (kW);
- Number of Peaks;
- Time period of peak power (Minutes);
- Total energy consumed at Morning time (kWh);
- Total Energy consumer at Night Time (kWh);
- Total Energy Consumption (kWh).

Thus the model is able to generate the all the required and relevant information.

3.5. Verification

A verification test is conducted to check whether the model is working correctly. It aims to remove errors and unwanted behavior. It cannot be proven that the model is 100% correct. However, extensive testing can give a good view whether the model works in a correct way (Kelton, Smith, & Sturrock, 2011). Following tests are executed on the model:

- Test-1
  - For a reefer with only small temperature fluctuations allowed, there should be many power pulses within a time period. However, the duration of these pulses should be small. The data shown in TABLE 8 is used for verification purpose.

Dimensions	Values
Initial Temperature Before Plug-in	10.2 ^oC
Set Point	10 ^oC
Allowed temperature Upper Limit	10.5 ^oC
Allowed temperature Lower Limit	9.5 ^oC
Auxiliary Power	2.5 kW
Cooling Power	10 kW

TABLE 8. SAMPLE DATA FOR VERIFICATION TEST-1

Result

The temperature of this sample reefer fluctuates between the upper limit and the set point as shown in FIGURE 30. As the allowed bandwidth for temperature fluctuation is small, the cooling process occurs many times. Every time a cooling process occurs, a power pulse is created. The energy profile for this temperature fluctuation is illustrated in FIGURE 31.

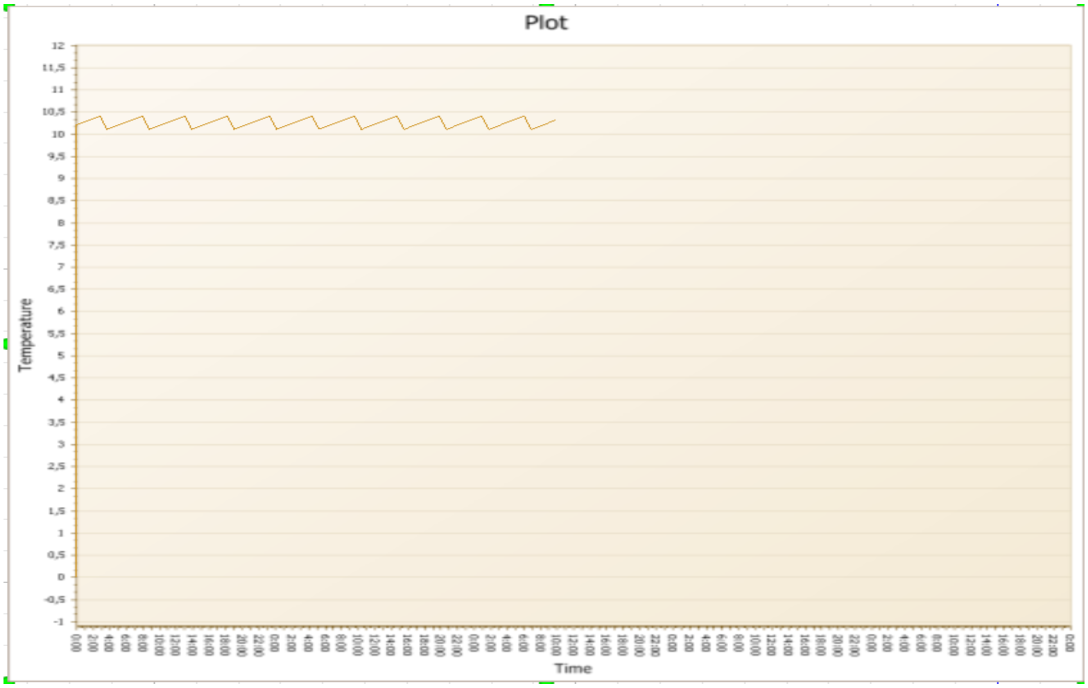

FIGURE 30. TEMPERATURE FLUCTUATION FOR VERIFICATION TEST-1

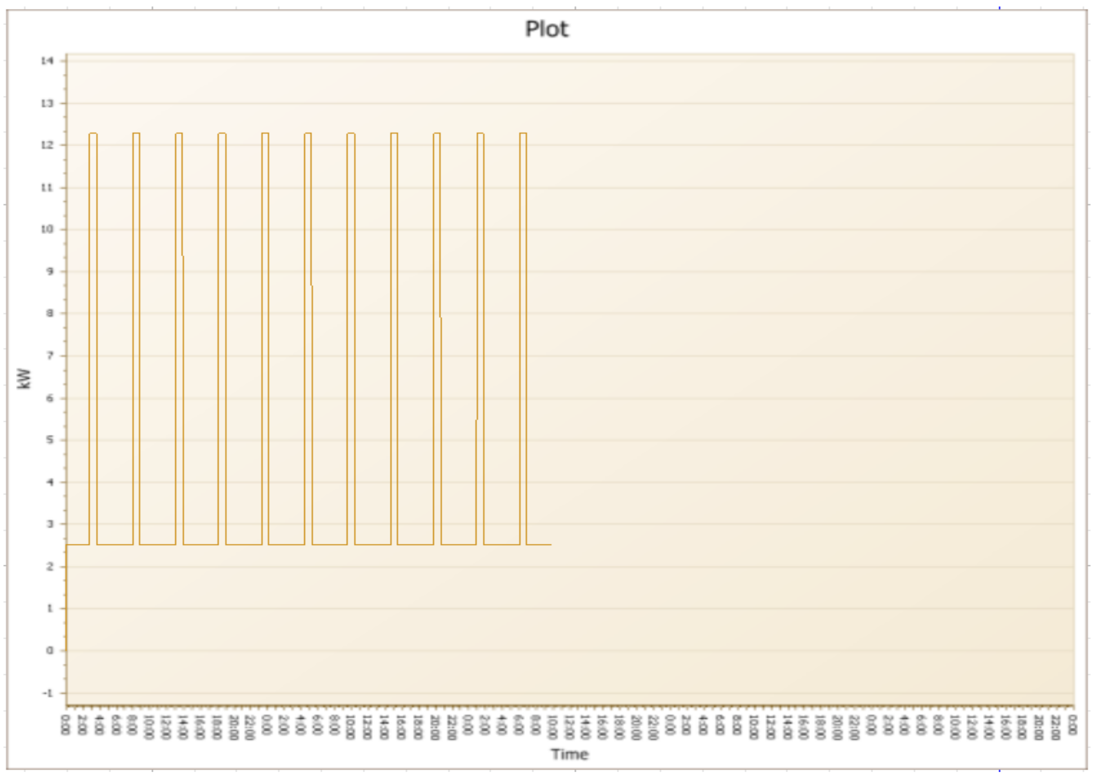

FIGURE 31. ENERGY PROFILE FOR VERIFICATION TEST-1

As discussed before, in this case, the number of power pulses corresponds with the number of cooling process a reefer undergoes. Due to low temperature bandwidth, the cooling process occurs many time within a certain time period and so do the power pulses. However, the width of these pulses is short (shorter time span) as cooling process occurs for short time perios. Hence, the hypothesis for this test is correct.

- Test-2
  - For a reefer with large temperature fluctuations allowed, there should be few power pulses within a time period. However, the duration of these pulses should be large. The sample data shown in TABLE 9 is used for verification purpose.

Dimension	Values
Initial Temperature Before Plug-in	10.2 ^{o}C
Set Point	10 ^{o}C
Allowed temperature Upper Limit	12 ^{o}C
Allowed temperature Lower Limit	8 ^{o}C
Auxiliary Power	2.5 kW
Cooling Power	10 kW

TABLE 9.. SAMPLE DATA VERIFICATION TEST-2

Result

The temperature for this test is shown in FIGURE 32. As seen, the temperature fluctuates between the upper limit and the set point. As the allowed bandwidth for temperature fluctuation is large, the cooling process occurs few times. Every time a cooling process, occurs a power pulse is created. This power profile diagram for this test is shown in FIGURE 33.

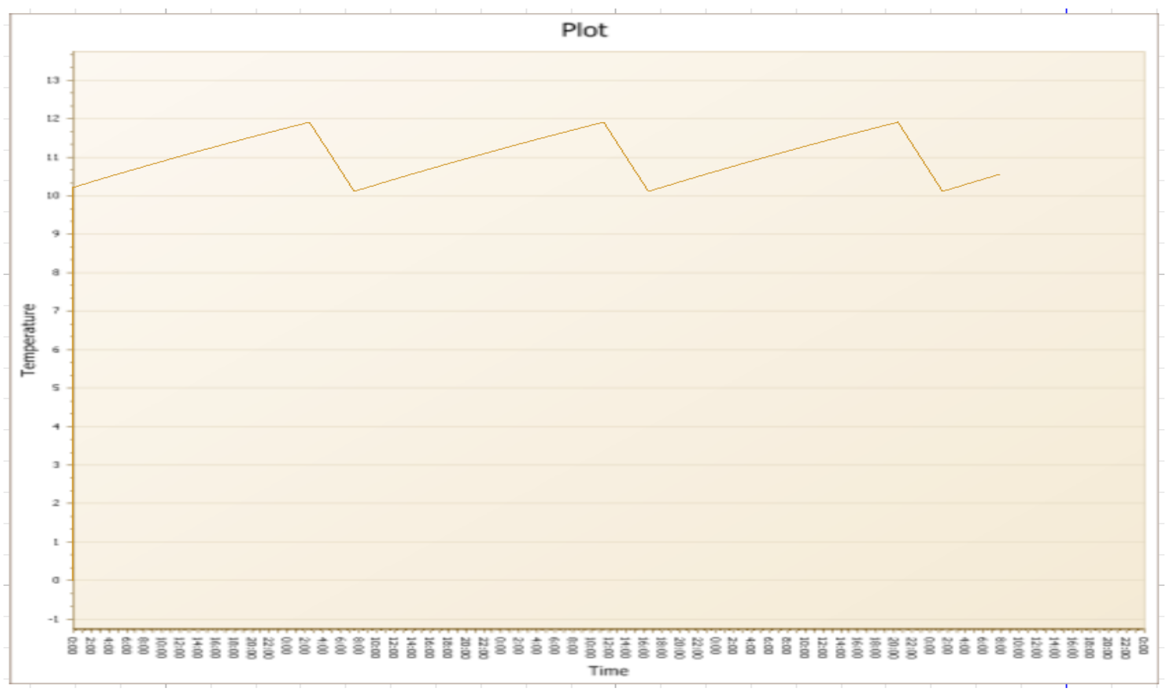

FIGURE 32. TEMPERATURE FLUCTUATION FOR VERIFICATION TEST-2

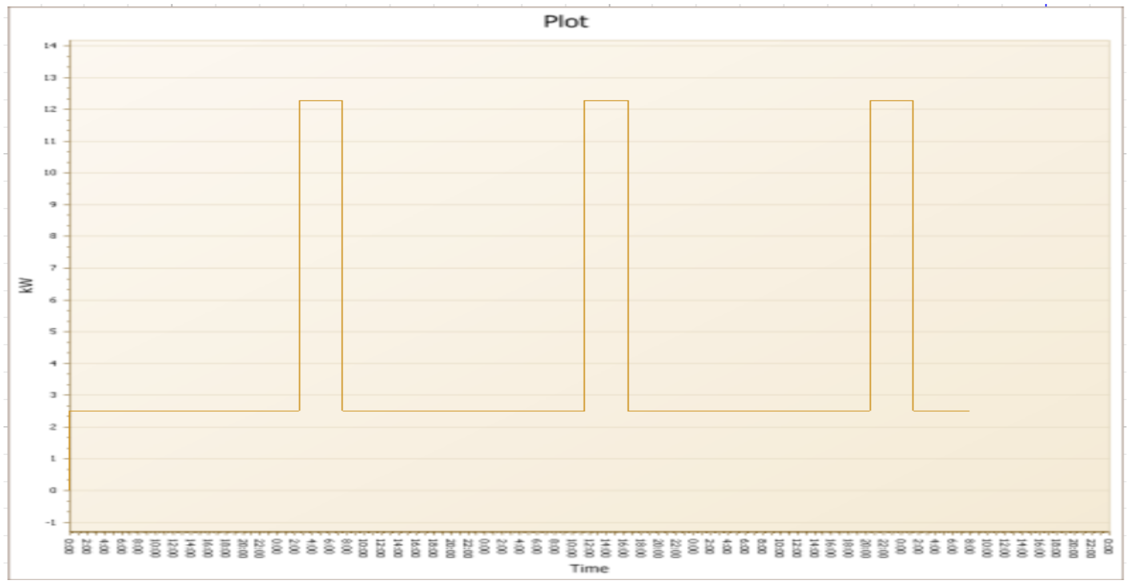

FIGURE 33. ENERGY PROFILE FOR VERIFICATION TEST-2

As discussed before, in this case too, the number of power pulses corresponds with the number of cooling process a reefer undergoes. However, due to high temperature bandwidth allowed, the cooling process occurs few times within a certain time period and so do the power pulses. However, the width of these pulses is long (longer time span) as cooling process occurs for long time. Hence, the hypothesis for this test is correct.

- Test-3
  - For a system of reefers, if the reefer plugs are not working then the power consumed is zero. In the above model, the two graphs does not give any value for this scenario. Hence, this hypothesis is also proved.

- Test-4
  - For a reefer with zero dwell time, no power is consumed. The model shows the corresponding result.

After executing these tests, all hypotheses are proven correct. In this way, the model is working properly.

3.6. Sensitivity Analysis

The sensitivity analysis is initially performed on a single reefer to determine important variables affecting its temperature. The variables taken into consideration are the ones affecting the reefer temperature in Equation 2. Their base values and their corresponding deviations for sensitivity analysis as shown in TABLE 10.

Variable	Constant Value	Sensitivity Analysis
Thermal Insulation	0.7 $W/m^2.^oC$	0.4 to 0.9 $W/m^2.^oC$
Unplugged time	2 hours	6 Hours
Mass	30000 kg	5000 kg to 35000 kg
Sun Intensity	0.6	0 to 1

TABLE 10.. BASE VALUES OF VARIABLES AND THEIR DEVIATIONS FOR SENSITIVITY ANALYSIS

In the above table, constant values are considered for all the variables except for which sensitivity analysis is performed. The following sections discusses the results of sensitivity analysis for each of these variables.

- Sensitivity w.r.t thermal insulation of reefer

Thermal Insulation is one of the factors that determines the temperature increase of a reefer in an unplugged or auxiliary mode state. The thermal insulation value varies from 0.4 $W/m^2.^oC$ for a newly manufactured reefer to 0.9 $W/m^2.^oC$ for a 12 year old reefer (Geysen & Verbeeck, 2011). The following section discusses the results of the sensitivity analysis w.r.t. thermal insulation.

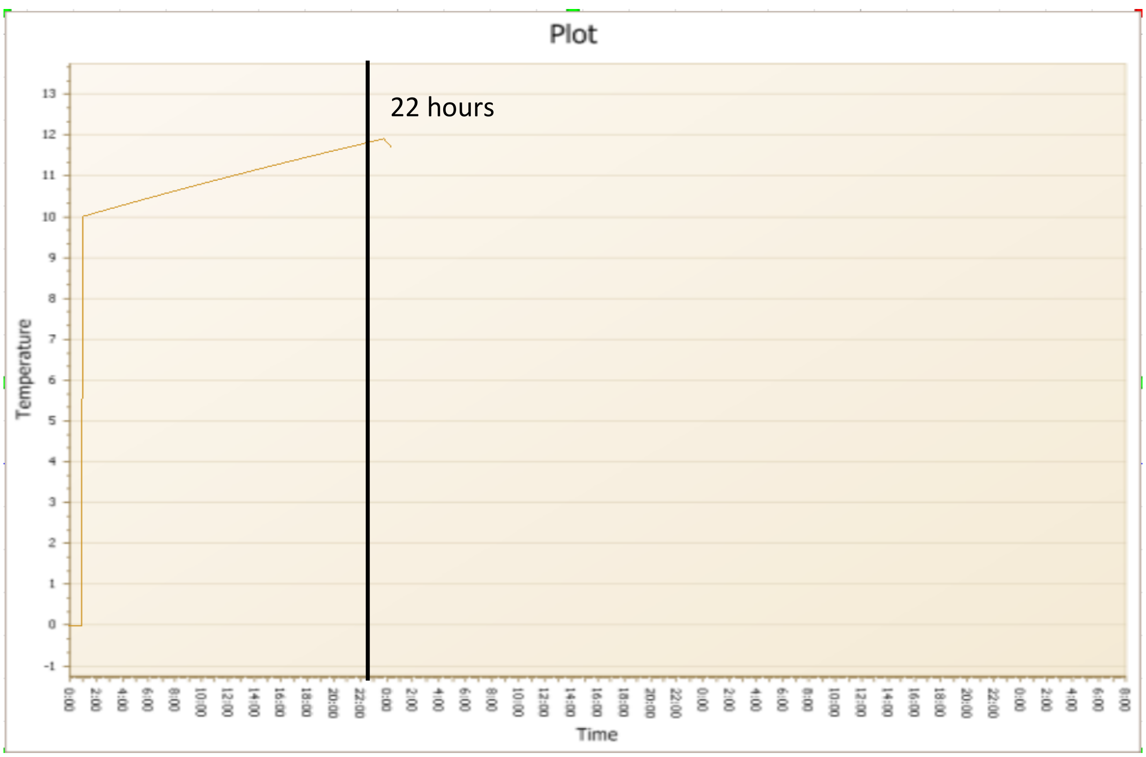

FIGURE 34. TEMPERATURE INCREASE WITH THERMAL INSULATION - 0.9 $W/M^2.^oC$

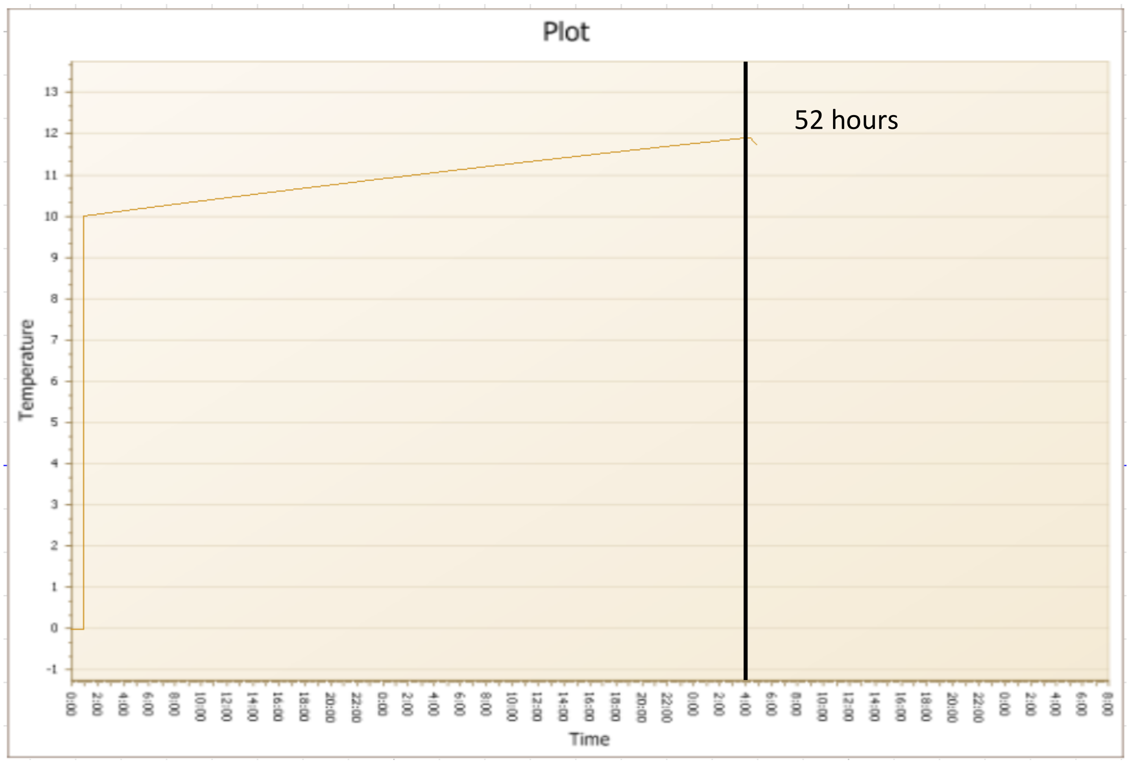

FIGURE 35. TEMPERATURE INCREASE WITH THERMAL INSULATION - 0.4 W/M^2.^{O}C

FIGURE 34 and FIGURE 35 give the temperature increase in a reefer for thermal insulation values of 0.9 W/m^2.^{o}C and 0.4 W/m^2.^{o}C respectively. As seen in Fig. 31, for a temperature rise of 2 ^{o}C , a reefer with poor thermal insulation takes only 22 hours. On the other hand, for the same temperature rise, a reefer with good thermal insulation takes 52 hours. Thus, a reefer with poorer thermal insulation undergoes a faster temperature increase[4].

Faster the temperature increase, higher the number of cooling operations performed for the same dwell time. This high number of cooling operations leads to frequent power pulses within a certain time period. Thus, a poor thermal insulation leads to more cooling operations which causes high number of power pulses in the same time duration. Hence, the thermal insulation plays a crucial role in temperature increase of a reefer and thereby the frequency of power pulses.

- Sensitivity w.r.t unplugged time

Unplugged time is also one of the important factors determining the temperature increase of reefers. A high unplugged time may lead to formation 'Hot Boxes'. Hence, it is important to determine the impact of high plugged time on the reefer temperature.

[4] The accepted rule of thumb is a temperature rise of 1 ^{o}C in 24 hours.

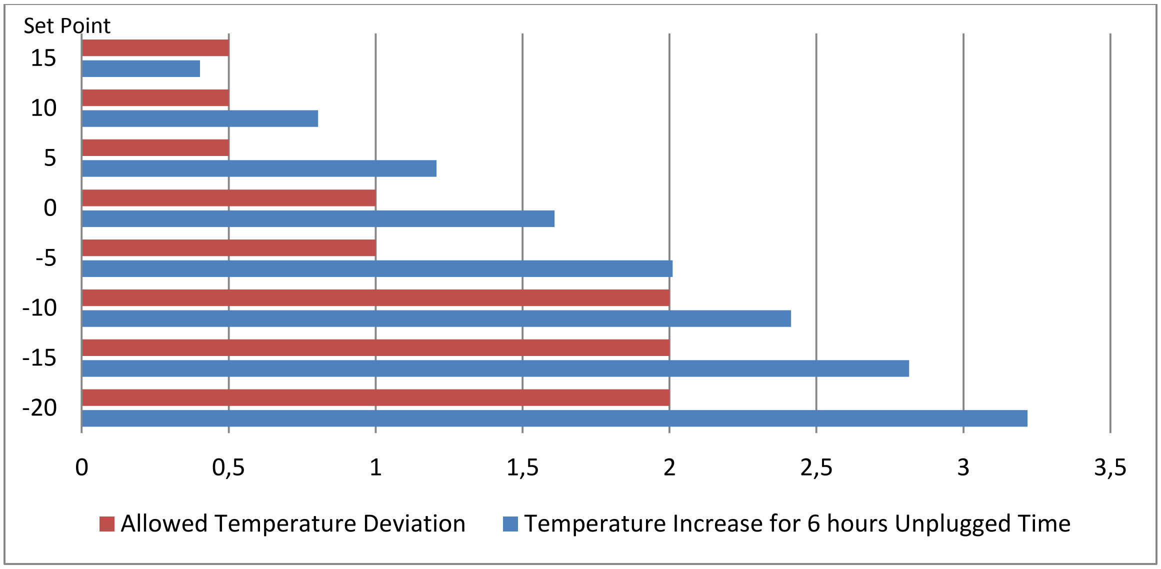

FIGURE 36. TEMPERATURE FLUCTUATION FOR DELAY TIME OF 6 HOURS

The FIGURE 36 shows the impact of worst case unplugged time (6 hours) on reefers with different set point. In most of the cases including frozen cargo, the temperature increase exceeds the allowed bandwidth. This can lead to cargo damage which can be claimed by the insurance company leading to additional costs for terminal operators (Radu & Kruse, 2009). Also, due to this temperature rise , initial power pulse has to be applied to bring it down to the required set point temperature. Hence, a high unplugged time is not only a great risk to the cargo but also leads to an initial excessive power pulse at the terminal[5].

- Sensitivity w.r.t. to mass of cargo

Mass of the cargo determines both the rate of temperature increase and the rate of temperature decrease of a reefer. For temperature increase, it plays role in heat exchange with ambient conditions while for temperature decrease, it determines the rate of heat exchange with the supply air. Hence, it is important to carry out sensitivity with regards to mass.

[5] A reefer should not be left unplugged for more than 4 hours.

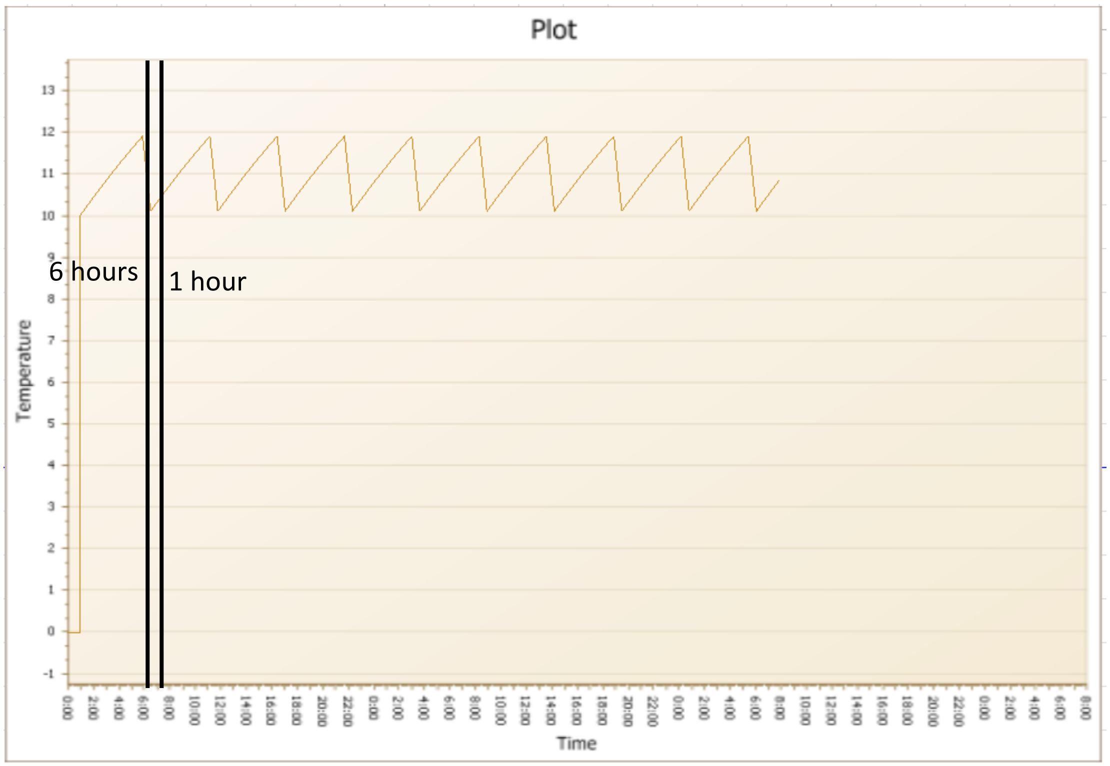

FIGURE 37. TEMPERATURE FLUCTUATION WITH MASS - 5000 KG

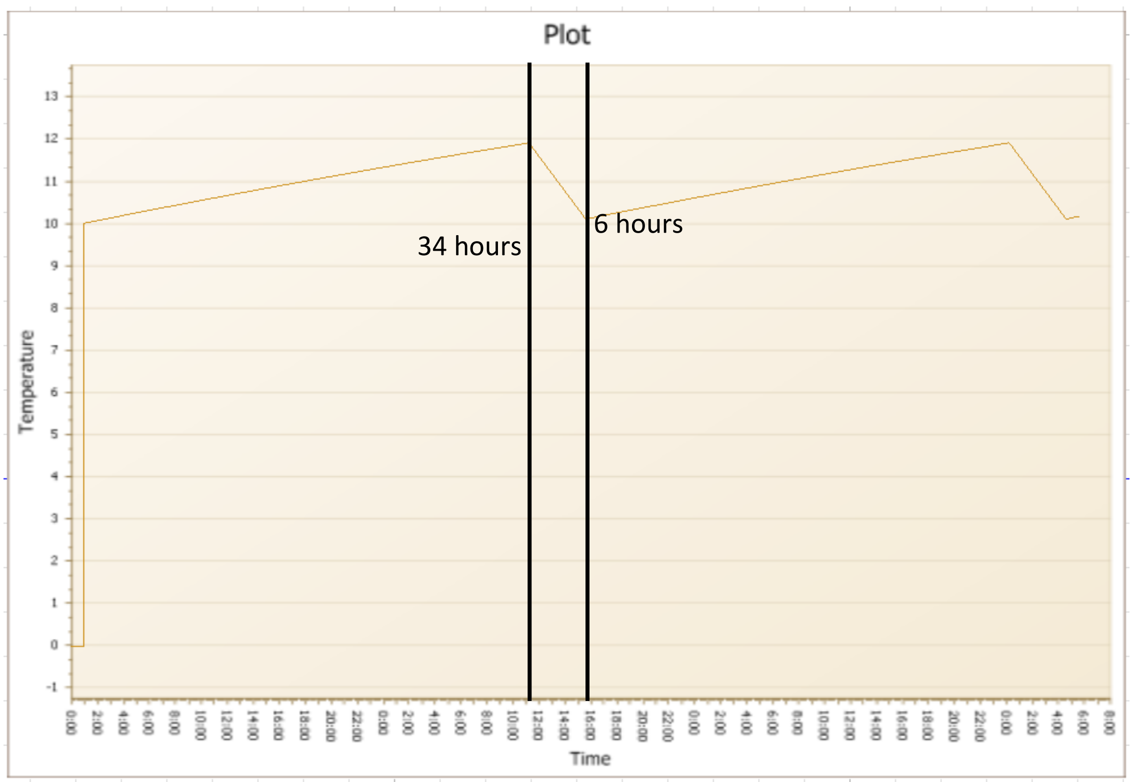

FIGURE 38. TEMPERATURE FLUCTUATION WITH MASS - 35000 KG

The FIGURE 37 and FIGURE 38 show the temperature fluctuation results for the cargo mass of 5000 and 35000 kg respectively. For cargo mass of 5000 kg, the reefer undergoes rapid temperature increase and decrease. The reefer temperature rises by 2 ^{o}C within a period of 6 hours. Due to low cargo mass, there is a lack of thermal inertia offered by cargo (Sorensen, 2013). The temperature decrease for this cargo mass is also rapid (1 hour). EQUATION 1 showed that there is a direct correlation between the mass of cargo and the time to cool down the cargo. Hence, lower the mass, the shorter the time it takes to cool it down. For cargo mass of 35000 kg, the case is reverse. Here, both the temperature increase and the temperature decrease are slow (34 hours and 6 hours respectively). Hence, from the sensitivity test, it is evident that low cargo mass leads to rapid temperature fluctuation in a reefer.

From energy perspective, low cargo mass is not preferred. This is because the reefer demands large number of short duration power pulses. For cargo with high mass, the case is exactly opposite. In this case, the reefer demands fewer power pulses though of longer duration. Hence, reefers with low cargo mass has high probability of causing power peaks at terminal.

- Sensitivity w.r.t. to Sun Intensity

The researchers agree that sun intensity is an important factor in determining the temperature rise of reefer. However, there is no quantitative proof of its impact on a reefer. This sensitivity analysis is the first step towards quantification of impact of high sun intensity on reefer temperature.

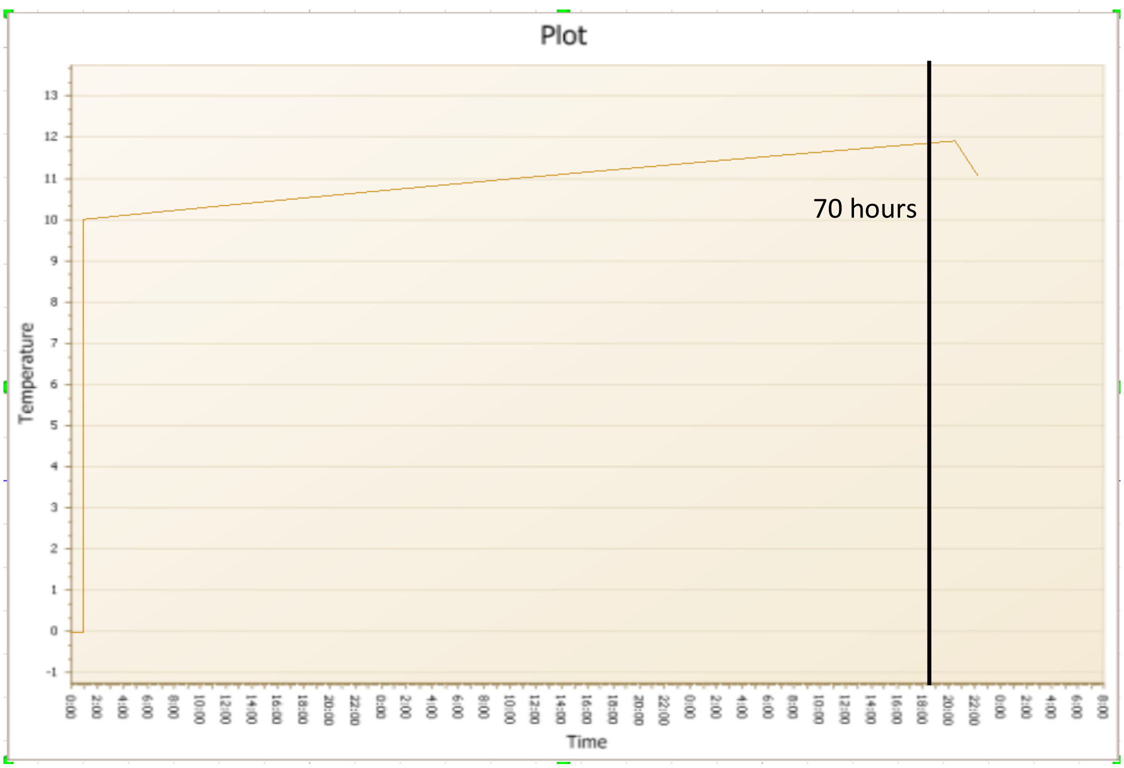

FIGURE 39. TEMPERATURE INCREASE WITHOUT SUN INTENSITY

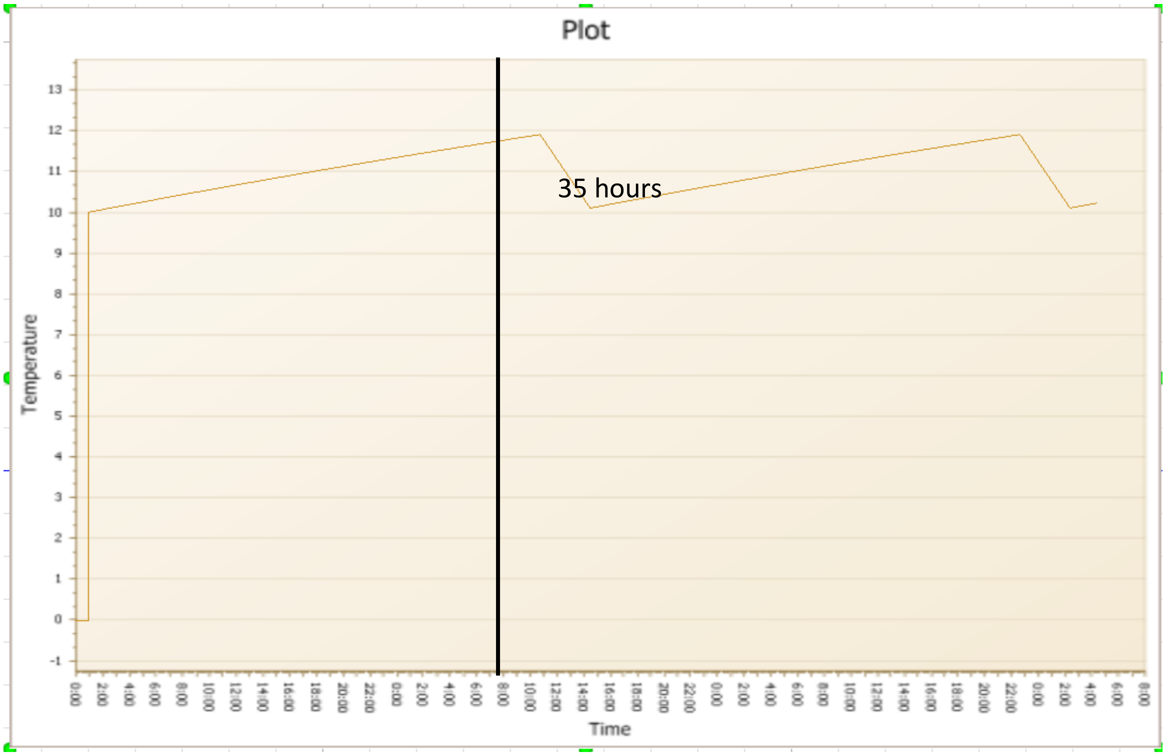

FIGURE 40. TEMPERATURE INCREASE WITH SUN INTENSITY

The FIGURE 39 and FIGURE 40 quantifies the impact of sun intensity on a reefer. In first instant , a reefer is not exposed to any sun intensity. In this case, the temperature rise of 2 ^{o}C occurs in 70 hours with all the other variables remaining the same. On the other hand, in a reefer exposed to maximum sun intensity, the same temperature rises in 35 hours. Hence, higher the sun intensity faster the temperature increase of a reefer.

The sensitivity analysis highlighted the most important variables impacting the temperature fluctuations in a reefer. This fluctuation determines its power cycle. A rapid fluctuation of temperature causes large number of short timed power pulses. However, a delayed fluctuation leads to small number of long timed power pulse. Hence, by changing these variables, the power consumption pattern of a reefer can be impacted. Based on the sensitivity analysis, the following conclusions can be made.

The mass of the cargo in reefer is the most important factor affecting the temperature fluctuation of a reefer. However, it is difficult for the terminal operator to have control over this factor. The next important variables affecting the reefer temperature are the thermal insulation of a reefer. The temperature of an aged reefer rises more rapidly than compared to newly manufactured reefer. Sun Intensity also plays an important role in the temperature increase of a reefer. In conclusion, efforts should be made to minimize the impact of sensitive variables on reefer temperature.

Based on the above sensitivity analysis of an individual reefer, key decision making factor is the thermal insulation of reefer. Hence, using this factor, sensitivity analysis is performed on the entire system of reefers. The results of the sensitivity analysis are discussed below.

All reefers with Poor Thermal Insulation

In this case, all the reefer have thermal insulation value of 0.9 $W/m^2.^oC$. Based, on this, the peak power consumption is 17128.7 kW and average power consumption is 1372 kW.

All reefers with Strong Thermal Insulation

In this case, all the reefers have thermal insulation value of 0.4 $W/m^2.^oC$. Based on this, the peak power consumption is 14612 kW and the average power is 1216 kW.

Thus, from the sensitivity analysis, it can be seen that reefers with poor thermal insulation leads to higher amount of peak power (17%) and average power consumption (12%) when compared to reefers with strong thermal insulation. Thus, this factor, plays a crucial role in the variation of peak power and average power consumption.

3.7. Validation

Validation of the model deals with its accurate representation of the real system. It is mainly concerned with building the right model. A variety of methods are used to validate the simulation models. Some of these methods are discussed below.

Comparison to other models

Researchers have modeled the individual working of reefer to gain deeper insights into its energy consumption pattern. They have used these models to optimize the refrigeration unit in reefer to reduce its energy consumption. Sorensen (2013) is one of the leading researchers in the modeling of refrigeration unit of reefer.

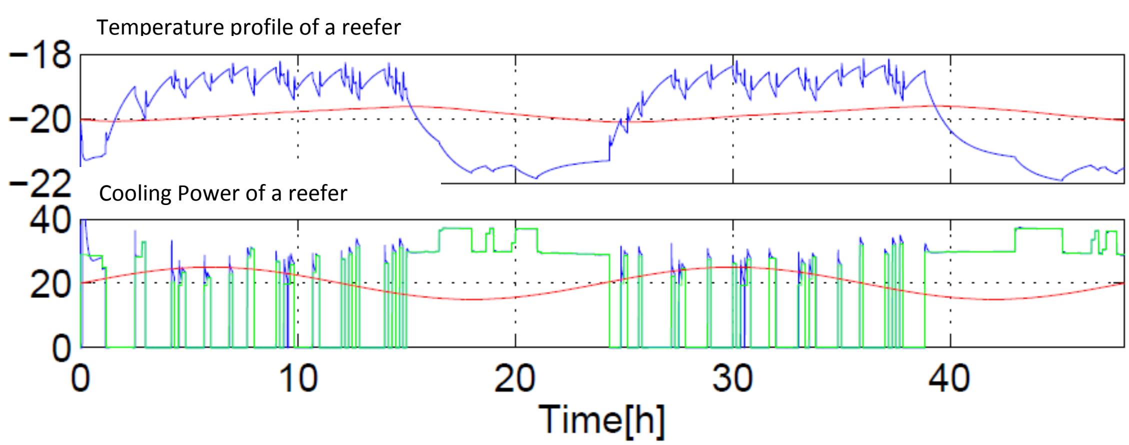

FIGURE 41. A SAMPLE WORKING OF REEFER FOR VALIDATION (SORENSEN, 2013)

A sample working model from his research is shown in FIGURE 41. The set point of the sample reefer is -20 °C. Hence, when the cooling power is not applied, the temperature of the reefer rises till it has reached to allowed upper limit bandwidth. Once, it reached this temperature, the corresponding cooling power is applied to bring the temperature back to its required set point. Thus, temperature fluctuates between the upper limit and the set point. This fluctuation gives rises to cooling power pulses. The current model also works in the same fashion as above. Hence, it can be concluded that model corresponds with the working of the real system.

Face Validation

To make validation comprehensive, expert opinion is also taken into account. The current simulation model is validated from experts in ABB and reefer operators from Port of Rotterdam.

Hence, after thorough validation, it can be concluded that the model highly corresponds with the working of the real system. Thus, after confirmation of the model, its results are discussed in the following section.

3.8. Results of Simulation Model

After running the Simulation model for the period of 9480 hours (One year and one moth), several important results are obtained. Valuable insights are gained from the analysis of these results. Each of these important results are discussed in the following section.

Throughput of Reefers

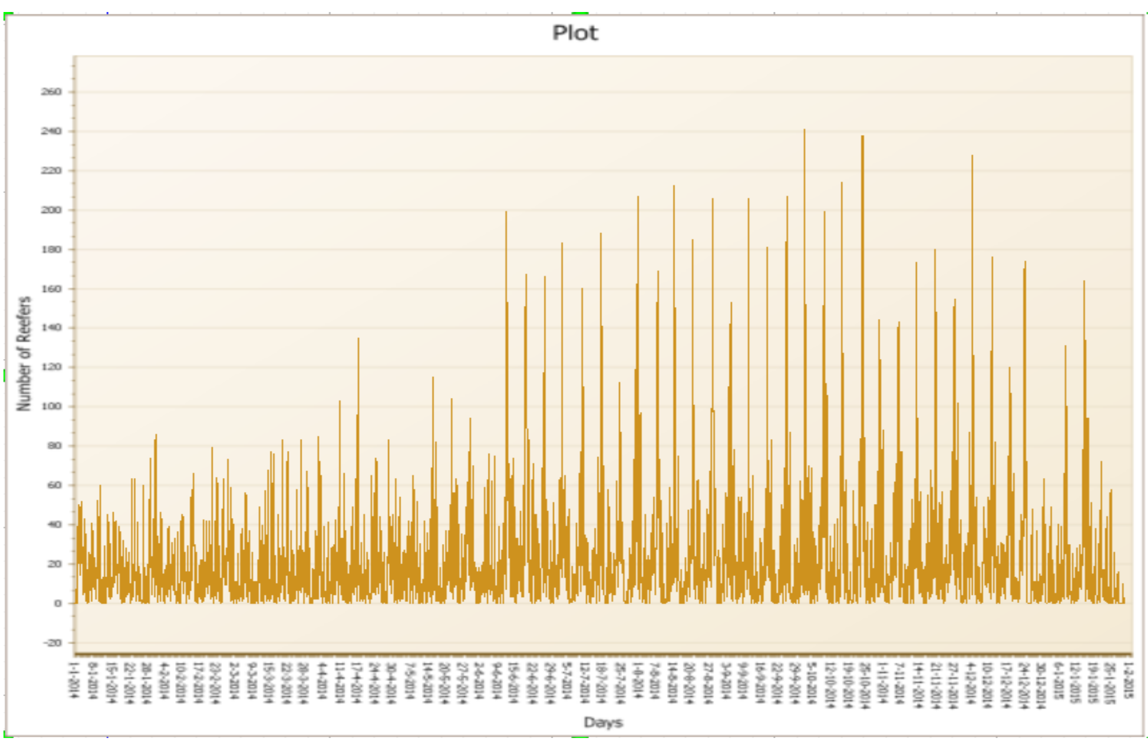

FIGURE 42. THROUGHPUT OF REEFERS

The FIGURE 42 gives the number of reefers simultaneously connected to reefer plugs at the sample terminal for the entire simulation period. The throughput of the number of reefers during this period is 61321 out of which 45923 carried frozen products while the rest carried chilled products. In the first quarter of 2014, the less chilled and frozen reefers arrived at the terminal. This is due to the seasonality of reefer trade towards Western European Countries. Hence, small no. of reefers are simultaneously connected to reefer plugs leading to diminutive height of the spikes

In the month of April, large quantity of chilled products arrive at the terminal. This can be attributed to the seasonal arrival pattern of deciduous fruits from South Africa. However, the quantity of frozen reefers arrived in the same period is still small due to lack of sufficient cargo trade between South America and Western Europe. Thus, though the arrival of large number of chilled reefers increases the height of the spike, it is still small due to lack of sufficient number of frozen reefers.

The largest consignment of chilled and frozen products arrive in the period from Jun to Nov. For chilled products, this is due to seasonal export pattern of citrus fruits from South Africa and frozen products, it the seasonality of meat trade between South America and Western Europe. Their combined effect leads to large number of reefers being simultaneously connected at terminal. This causes large number of very high spikes. Hence, a peak power demand and high energy consumption is expected in this period.

The spikes in the FIGURE 42 also depend on the dwell time of individual reefers. In general, the frozen products have a higher dwell time compared to the chilled products. This is because of their less sensitive nature to temperature variations. The combined effects of arrival of large quantities of different types of reefers and their respective dwell time has a huge impact on the energy consumption of the terminal. This energy consumption is discussed in the following section

Energy Consumption by reefers

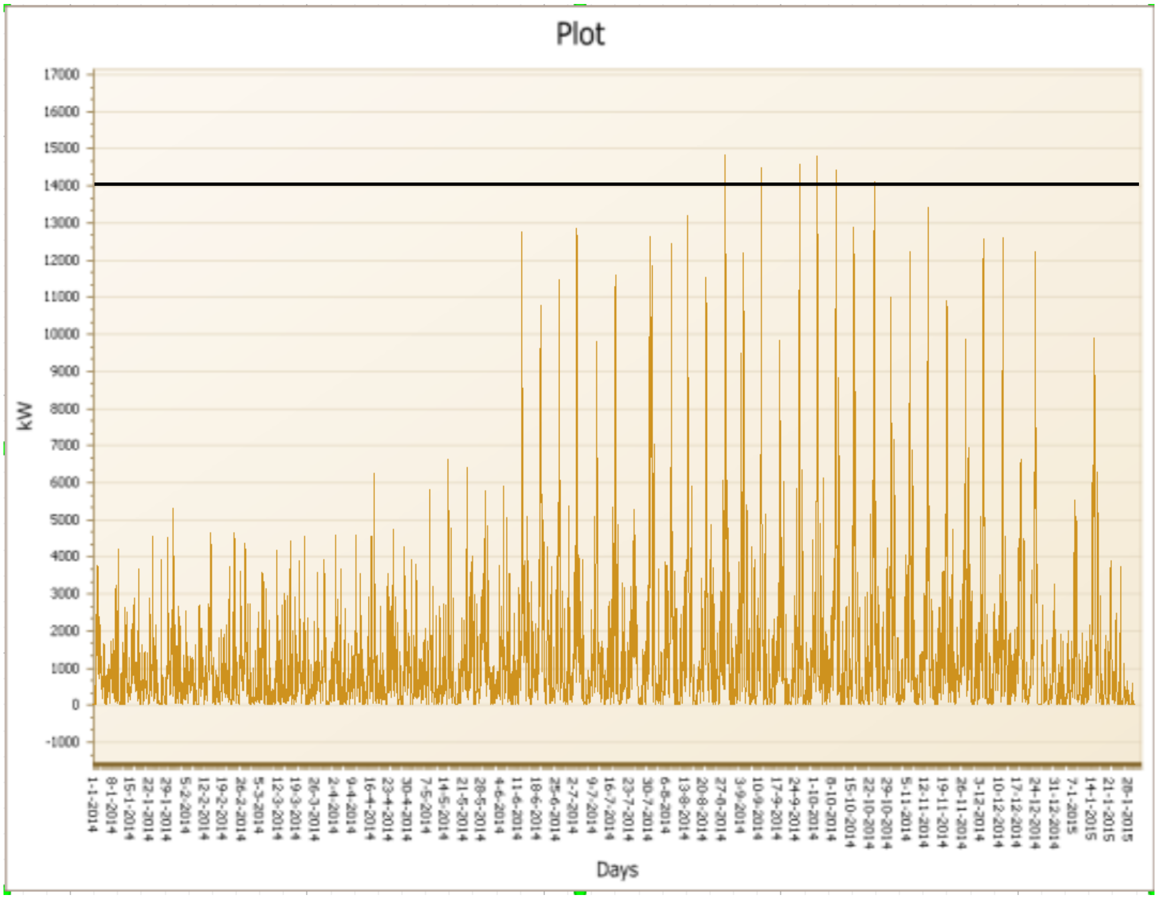

FIGURE 43. ENERGY CONSUMPTION BY REEFERS - BASE CASE

The FIGURE 43 shows the corresponding energy consumption at the sample terminal for the reefers discussed above. The consumption pattern highly corresponds with the arrival pattern of reefers. In the first quarter of 2014, there are no high power peaks mainly due to the arrival of small quantity of reefers at the terminal. The pattern shows a drastic change from second half of 2014. Large number of high power peaks occurs during this period. However, the focus is on those peaks which cross the threshold peak limit of 14000kW. From the FIGURE 43, it is seen that limit is crossed six times mainly in three month period of August-September-October. The reasons for high peaks in this season are as follows:

- Arrival of large no. of chilled reefers which require cycles of high cooling power.
- Arrival of extremely large quantity of frozen reefer. Though these reefers require less cooling power, their high numbers contribute towards peak power.
- Exposure of large quantity of reefer to high ambient temperature and maximum sun intensity condition[6]. This leads to have extreme temperature rise for the unplugged time.

[6] Summer Period in Rotterdam

- Simultaneous cooling power demand by large quantity of reefers. The stacking of power pulses of individual reefers contribute towards the peak power consumption.

Furthermore, based on FIGURE 43 , additional valuable information is obtained.

Monthly Energy Consumption

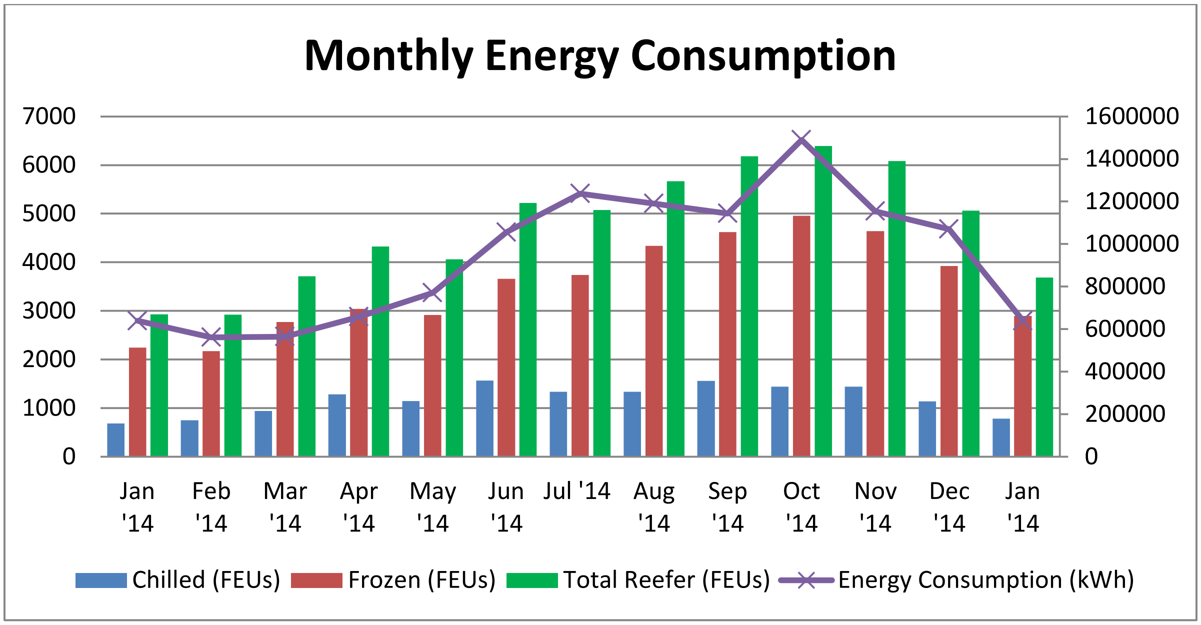

FIGURE 44. REEFER ARRIVAL AND MONTHLY ENERGY CONSUMPTION - BASE CASE

The FIGURE 44. shows the correspondence between the reefer arrival and the monthly energy consumption. As seen, the monthly energy consumption in the first quarter of 2014 is less due to the low quantity of reefer arrival. This consumption increase with the rise in the reefer arrival. Large amount of energy is consumed in the three month period of August-September-October with the peak energy consumption in October. This is because maximum number of reefers are connected in this month (6711). Hence, the monthly energy consumption also corresponds with the arrival pattern of reefers.

Based on peak power demand and monthly energy consumption, the energy costs are calculated. This is discussed in the following section.

Energy Costs

Output	Value
Maximum Power Consumption	14831 kW ± 16.5 kW[7]
Width of Peak power	5.89 Minutes
Average Power Consumption	1275 kW ± 0.17 kW
Total Energy Consumption	12,1 Million kWh
Peak Energy Costs	€250000 - €300000
Total Energy Costs	€1,09 Million[8]

TABLE 11. KEY OUTPUTS FROM ENERGY CONSUMPTION OF REEFERS

The TABLE 11 shows the values of the key outputs from the energy consumption of reefers. The peak power consumption is 14831 kW with half width of 16.5 kW and its lasts for duration of 5.89 minutes. Thus, peak power exceed the threshold by 840 kW. The average height of the power consumption for the entire period is 1275 kW with half width of only 0.17 kW. Thus, the peak power demand is 11.5 times the average power demand. Total energy consumption in this period is 12.1 million kWh. The electricity energy consumption of the sample terminal in 2006 was 47 million kWh (Geerlings & Duin, 2010). Hence, it can be seen that energy consumption by reefers forms a significant percentage of the total energy consumption at terminals. The energy costs for this share of energy consumption is equal to €1,09 Million from which the peak power demand contributes between €250000 - €300000 which is 20% to 30% of the energy costs. Hence, it is essential to have an efficient energy management at terminals to reduce peak power demand by reefers resulting in saving of energy costs.

From the above paragraphs, the peak power demand and monthly energy consumption pattern depend on the arrival pattern of reefer, the seasonality of reefer trade and simultaneous cooling operation of reefer containers. Out of these, the terminal operator has little control over the first two factors. The arrival pattern of reefers highly depends on the seasonality of food products. Hence, the focus of peak reduction is on the proper management of simultaneous cooling operations of large quantity of reefers. For this, two modes of operation can be considered:

- Intermitted power supply to reefer racks
- Spreading of peak power pulses over time

[7] For Details, Refer Appendix E.

[8] Cost based on only highest peak. For details refer Appendix F.

Based, on this two modes of operation, the simulation model can be summarized in FIGURE 45.

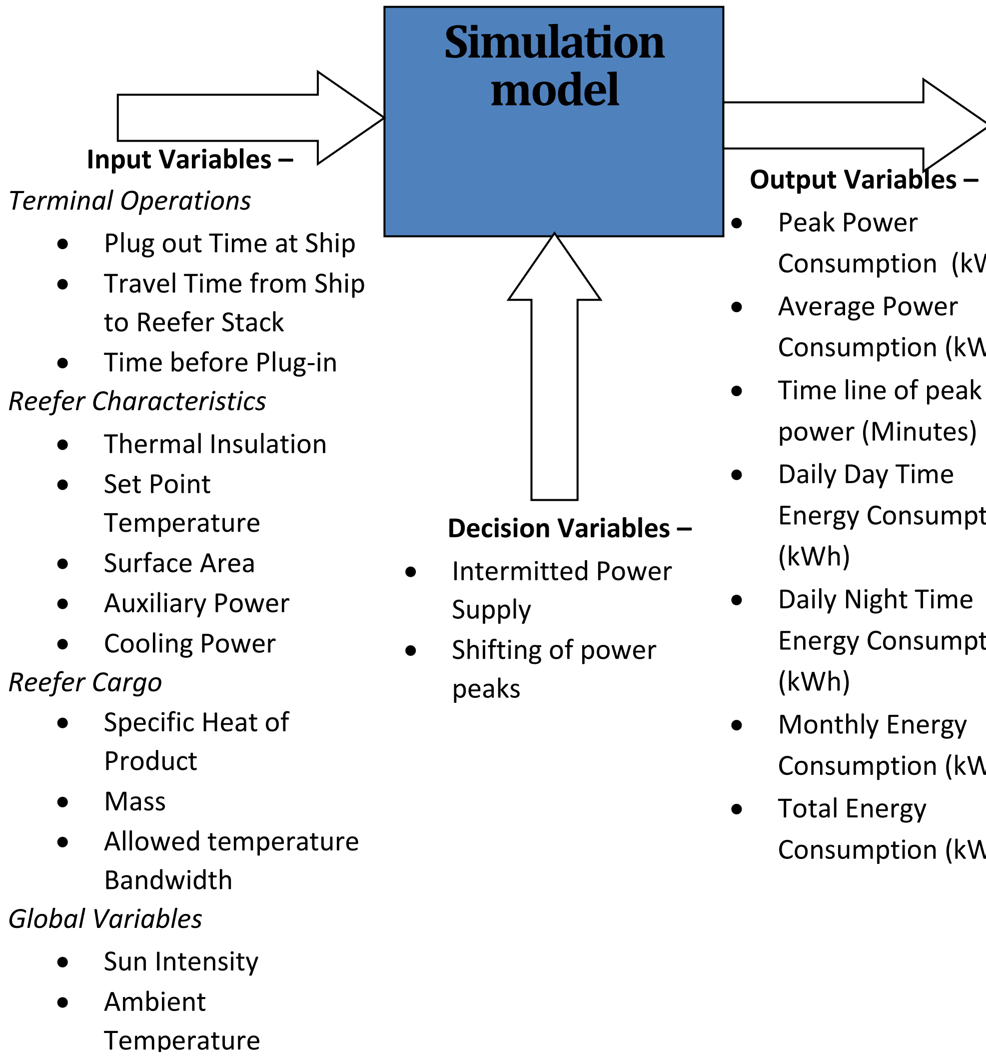

FIGURE 45. SUMMARY OF SIMULATION MODEL

3.9. Conclusion

For determining the energy consumption by reefers on terminal, the current models are not adequate. This is because they focus primarily on an individual reefer or determine energy consumption at terminals by heavy equipment. Thus, these models lack the focus of energy consumption by reefers on terminals. To determine the relation between the terminal operations and reefer, an IDEF0 diagram is presented in the beginning. Based, on this, the conceptual model for determining the energy consumption of systems of reefers operating simultaneously is developed. The energy consumption can be calculated after the availability of following information.

- Reefer Logistics at Terminal

- Terminal Logistics
- Characteristics data of reefer
- Reefer Cargo Data
- External Conditions

This answers the research sub-question of what are the input variables required to model the energy consumption of large number of reefers at terminal.

An extensive and a reliable data is required for the simulation model. However, when data is not available, assumptions need to be made in order to make an approximation of the energy consumption. These assumptions might affect the accuracy of the model and the preciseness of the model results.

For developing the energy consumption model for the case-study for an existing terminal, discrete event simulation is used. This is because its ability to assign unique attributes to different objects and also to entities within these objects. Besides this, the event-based character of discrete simulation is another reason for using it. After developing the model using discrete simulation, a sensitivity analysis is performed to determine the important variables affecting the temperature of a reefer. Finally, the results of the simulation are analyzed. From the results, the observed peak demand is 14831 kW with a timeline of 5.89 minutes. The total energy consumption is 12,1 Million kWh. The annual energy costs based on peak power and energy consumption is €1,09 Million with the peak alone contributing between €250000 - €300000.

Based on the problem analysis of peak power demand, solution are developed to reduce the this demand below the threshold value of 14000 kW. These solution are discussed in Chapter 4.

4. Peak Shaving Opportunities.

Chapter 3 discussed the energy consumption model of reefers at terminals. It presented the results of the simulation and identified the problem of peak power demand. This chapter addresses how this peak power can be reduced by two rules of operations. It then studies the impact of these operations on the reefer temperature.

First, the two rules of operations are discussed in section 4.1 and section 4.2 respectively. These solutions are then analyzed in section 4.3 on the basis of four important criteria. The next section 4.4. discusses how their combined operation can bring out the best out of the two solutions. Finally, the implications of these solutions on different actors is presented in section 4.5. The chapter concludes in section 4.6.

4.1. Solution - 1: Power Sharing among Reefer Racks

The reefers on terminals are stored in separate reefer racks. A sample reefer rack is shown in FIGURE 46. It consists of 4 rows and each row further has multiple slots to store the reefer containers. Each of these slots is provided with an electrical socket for the operational functioning of reefers.

FIGURE 46. A SAMPLE REEFER RACK (STEVENS, 2015)

Currently, electrical power is made available to a reefer as soon as it is plugged into the slots. Then, the reefer operates in its usual on/off mode. As discussed, a large numbers of reefers cooling simultaneously leads to huge demand of power from the electrical network. This is the primary reason for the crossing threshold allowed peak power. Thus, if the power supply to these reefer racks is divided into appropriate timeslots, the simultaneously overlapping of cooling power can be avoided.

Case - 1: Intermitted Power Supply in 15 minutes timeslots

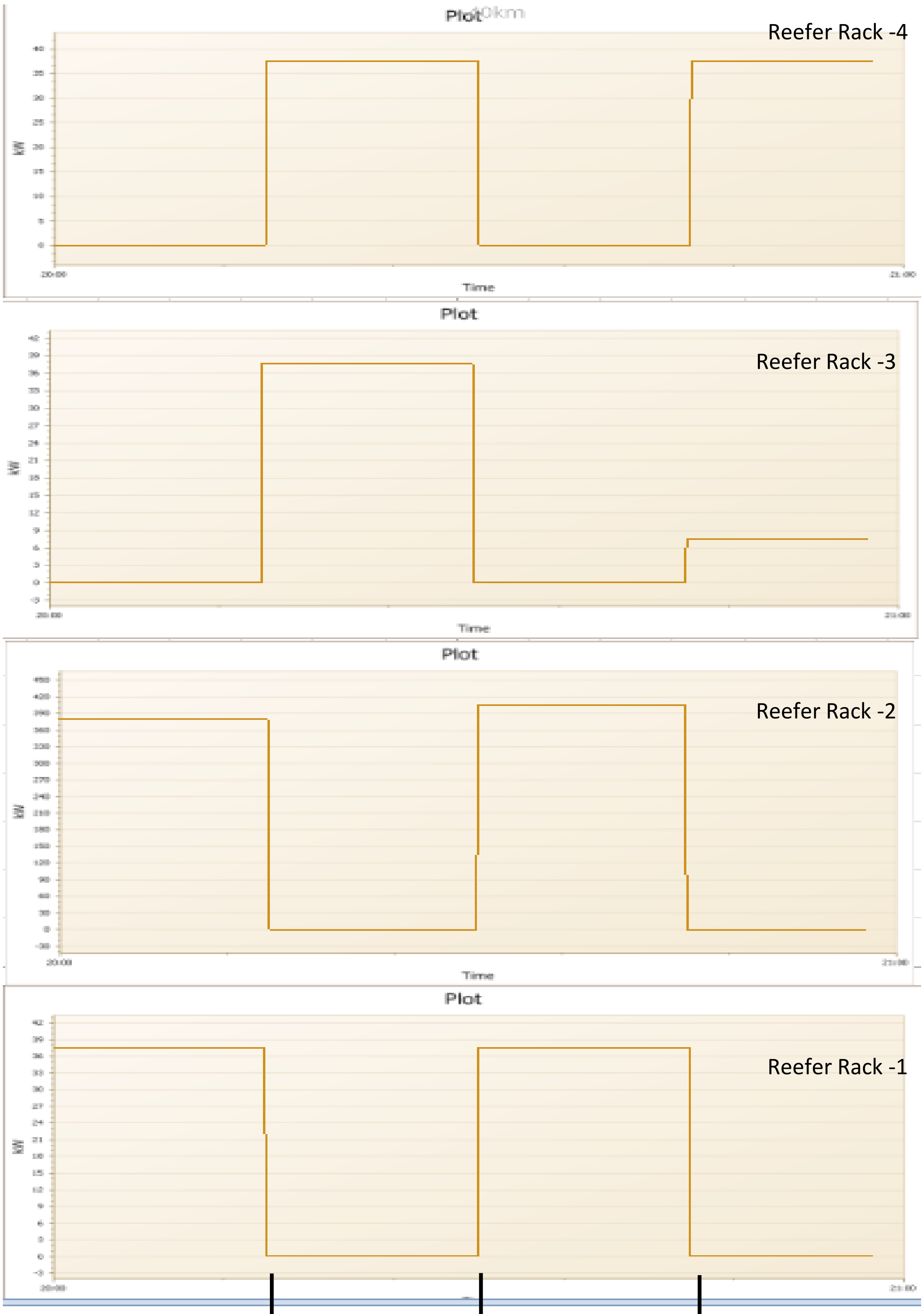

FIGURE 47. HOURLY SUPPLY OF POWER TO REEFER RACKS IN 15-MIN TIMESLOTS

A sample division of power supply is shown in FIGURE 47. The peak power at sample terminal is calculated every 15 minutes. This time interval of peak power calculation is determined by the contract between the terminal operator and the energy utility company. The time step for power calculations in this research is also 15 minutes. Hence, an hour of power supply is divided into these timeslots. In first 15 minutes timeslot, the power is supplied to the bottom two reefer racks while the power supply to the top two reefer racks is switched off. Hence, the reefers in bottom two racks operate in the on/off mode while the temperature of the reefers in the top two racks rises/fall. However, in the next 15 minutes, the power supply procedure is reversed and thereby the reefer operating procedure. Thus, the reefers in Rack - 1, Rack - 2 and Rack - 3, Rack - 4 operate in an alternating manner. This alternating operating cycle of reefers affects the peak power demand and the total energy consumption.

For the each 15 minutes cycle, the total power consumption is the sum of the power consumption of each operating reefer rack. Thus, in this case, for the initial quarter of an hour the total power consumption is sum of power consumption by Rack - 1 and Rack - 2. For the next 15 minutes, total power is equal to the sum of power consumption by Rack - 3 and Rack - 4. Thus, for each 15 minutes, total power consumption is the sum of the power consumption of two reefer racks instead of four. This has huge impact on the instantaneous power consumption by reefers. The impact of this intermitted power supply to reefer racks is discussed below.

Energy Consumption by reefers

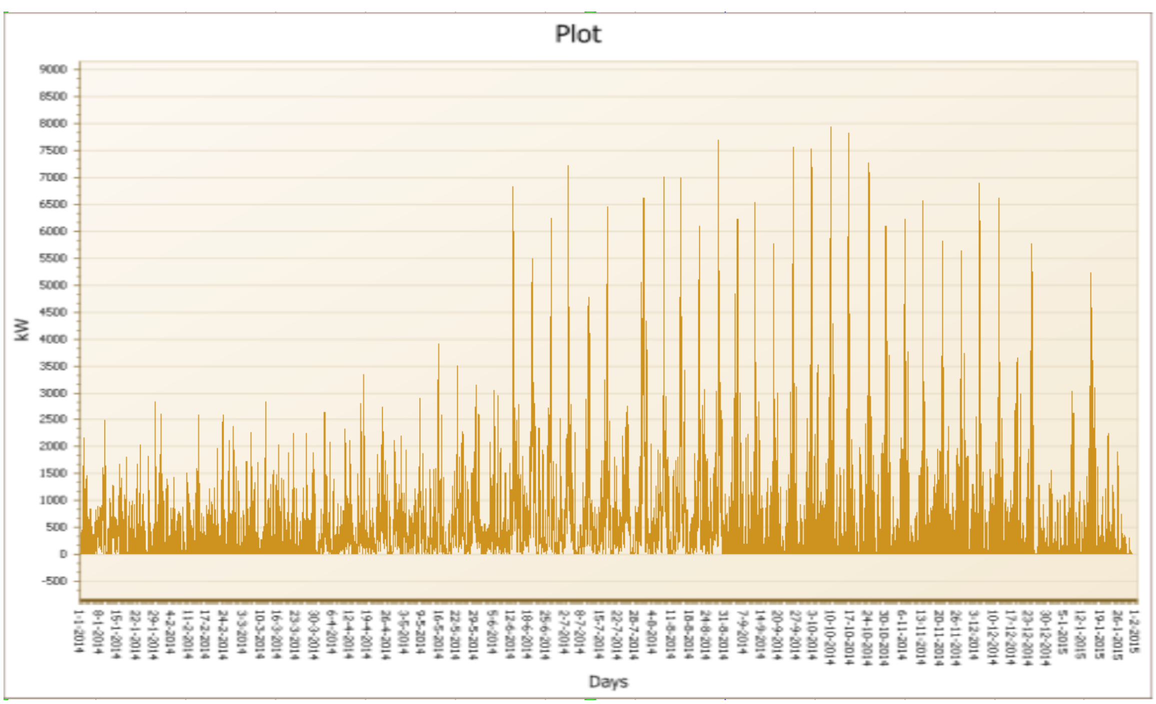

FIGURE 48. ENERGY CONSUMPTION BY REEFER AFTER IMPLEMENTATION OF POWER DISTRIBUTION SOLUTION (CASE - 1)

The FIGURE 48 shows energy consumption by reefers after implementing this case among the reefer racks. When compared to the base case, the power consumption for the entire duration has reduced drastically. Also, the peak power consumption has reduced below 8500 kW. This value is well below the allowed threshold limit. Hence, as seen, power distribution is effective is reducing the peak power demand of reefer containers. The peak power reduction of reefers has impact also on the monthly energy consumption of by reefers.

Monthly Energy Consumption

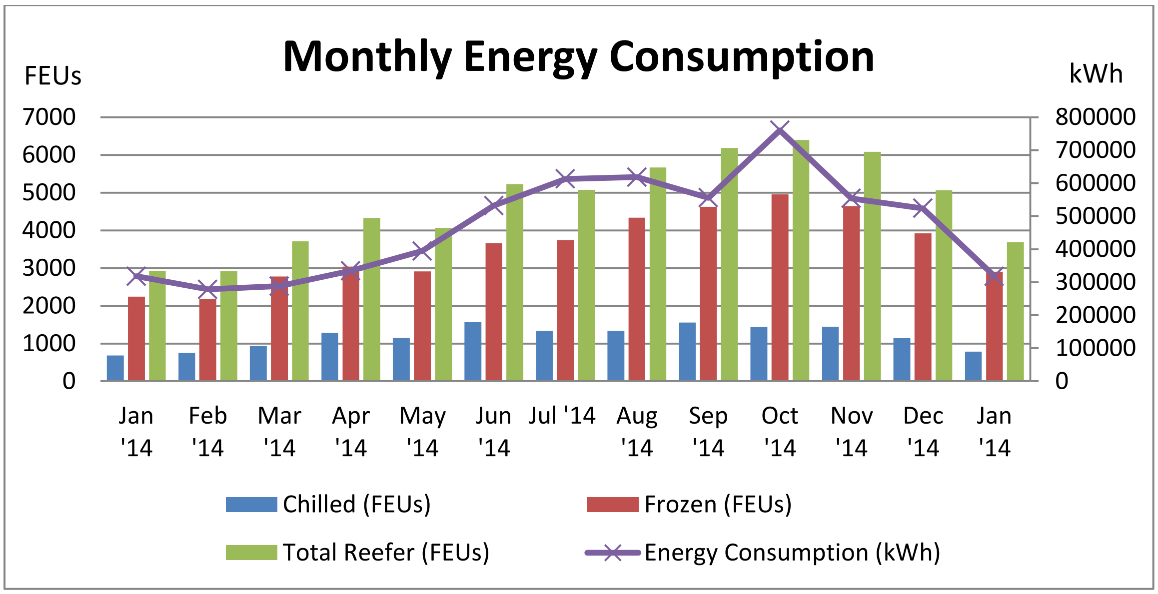

FIGURE 49. MONTHLY ENERGY CONSUMPTION AFTER IMPLEMENTATION OF POWER DISTRIBUTION SOLUTION (CASE -1)

The monthly energy consumption profile after implementing this case also undergoes changes. This profile is shown in FIGURE 49. As seen, the energy consumption still corresponds with the arrival pattern of reefers. However, its amount has decreased due to alternate power supply to reefer racks. The maximum monthly energy consumption in this case is half of the maximum monthly energy consumption from the base case. In conclusion, this solution has the combined effect of reducing the peak power and the total energy consumption. This has a profound effect on the energy costs.

Energy Costs

Output	Values
Peak Power Consumption	**8266 kW ± 201.5 kW**[9]
Average Power Consumption	544 kW ± 0.5 kW
Total Energy Consumption	6 Million kWh
Peak Energy Costs	0 €/year
Total Energy Costs	400000 - 500000 Euros
Annual Energy Cost Savings	**600000 - 700000 Euros**

TABLE 12. KEY OUTPUTS AFTER IMPLEMENTATION OF POWER DISTRIBUTION SOLUTION (CASE – 1)

The values of the key output after implementing this case are shown in TABLE 12. The peak power consumption of individual reefer racks is independent of each other. Thus, the total peak power consumption is not necessarily equal to the peak power consumption of individual racks. The peak power consumption is 8266 kW with half width of 201.5 kW and it is well below the allowed threshold. Due to distribution of power supply in timeslots, the total average power consumption has also reduced to 544 kW. The combined reduction of peak power demand and average power has also reduced the total energy consumption to 6 Million kWh. This is half of the total energy consumption in base case. Due to absence of peak power and reduction in total energy consumption, the total annual energy costs has also reduced to values between €400000 - €500000. Hence, it results in annual savings of between €600000 - €700000. However, it is important to study the impact of this power distribution on the reefer temperature. This is discussed in the following section.

Impact on Reefer Temperature

The cargo quality is the most important asset of a reefer. Its value is much more than the installation costs of a hundreds of reefer outlets. Hence, a study is carried out to study the impact of implementation of this solution of temperature of reefer. (ESL Power Systems, 2014)

As the power supply to reefer racks, in this case, is switched on/off, it is necessary to determine the number of hotspots reefers that arrive at the switched off time. This is because these reefers require immediate power supply to bring down the temperature to set point. If such a reefer arrives during an unpowered state, it results in additional temperature increase. This poses danger to the cargo inside reefer. In the simulation run, out of 61321 reefers, eight are

[9] For Details, Refer Appendix E

‘hot box’ reefers and four of them arrive when the power is switched off. Hence, additional provisions should be made for these kind of reefers. For the rest of the reefers, the temperature increase in switched off state is discussed below.

Temperature Increase	Number of Reefers (Frozen)
0 to 0.1	45488
0.1 to 0.2	361
0.2 to 0.3	61
0.3 to 0.4	9
0.4 to 0.5	3
0.5 to 0.6	1

TABLE 13. TEMPERATURE INCREASE FOR FROZEN REEFERS IN SWITCHED OFF STATE OF 15 MINUTES

In the remaining reefers, the one carrying frozen goods experience the maximum temperature rise. Most of these reefers have slight temperature increase as shown in TABLE 13. However, some reefers do undergo a high temperature increase. In this, the highest temperature rise is determined to be 0.53 ^{o}C for a single reefer with set point of -66 ^{o}C. This is marked with a red column as the chances of product damage in it are high. Other reefers (marked in green) undergo only a small temperature increase (below 0.5 ^{o}C) and thus the risk of product damage in them is less. The rapid temperature fluctuation within these reefers can damage the products inside. However, as the temperature sensitivity of frozen goods is high (± 2 ^{o}C), it is feasible to switch off power supply for 15 minutes.

Temperature Increase in Switched off State	Number of Chilled Reefers
-0.2 to -0.1	26
-0.1 to 0	4073
0 to 0.1	11294
0.1 to 0.2	5

TABLE 14. TEMPERATURE INCREASE FOR CHILLED REEFERS IN SWITCHED OFF STATE OF 15 MINUTES

The temperature increase of sensitive products (chilled) in switched off state is shown in TABLE 14. Like frozen products, majority of these reefers undergo a minimum temperature rise. Out of the total of 15391 chilled reefers, only five chilled reefers have temperature increase of more than 0.1 ^{o}C (marked with red column). The maximum value of temperature rise is 0.12 ^{o}C. On the other hand, the temperature of reefers with high set point decreases due to cold ambient conditions. From Table 14, 26 reefers have a temperature decrease of more than -0.1 ^{o}C (marked with red column) with the maximum value of -0.18 ^{o}C. Hence, from the table it is seen that switching off power for 15 minutes does not lead to a massive temperature increase in chilled products.

Case - 2: Intermitted Power Supply in 5 minutes timeslots

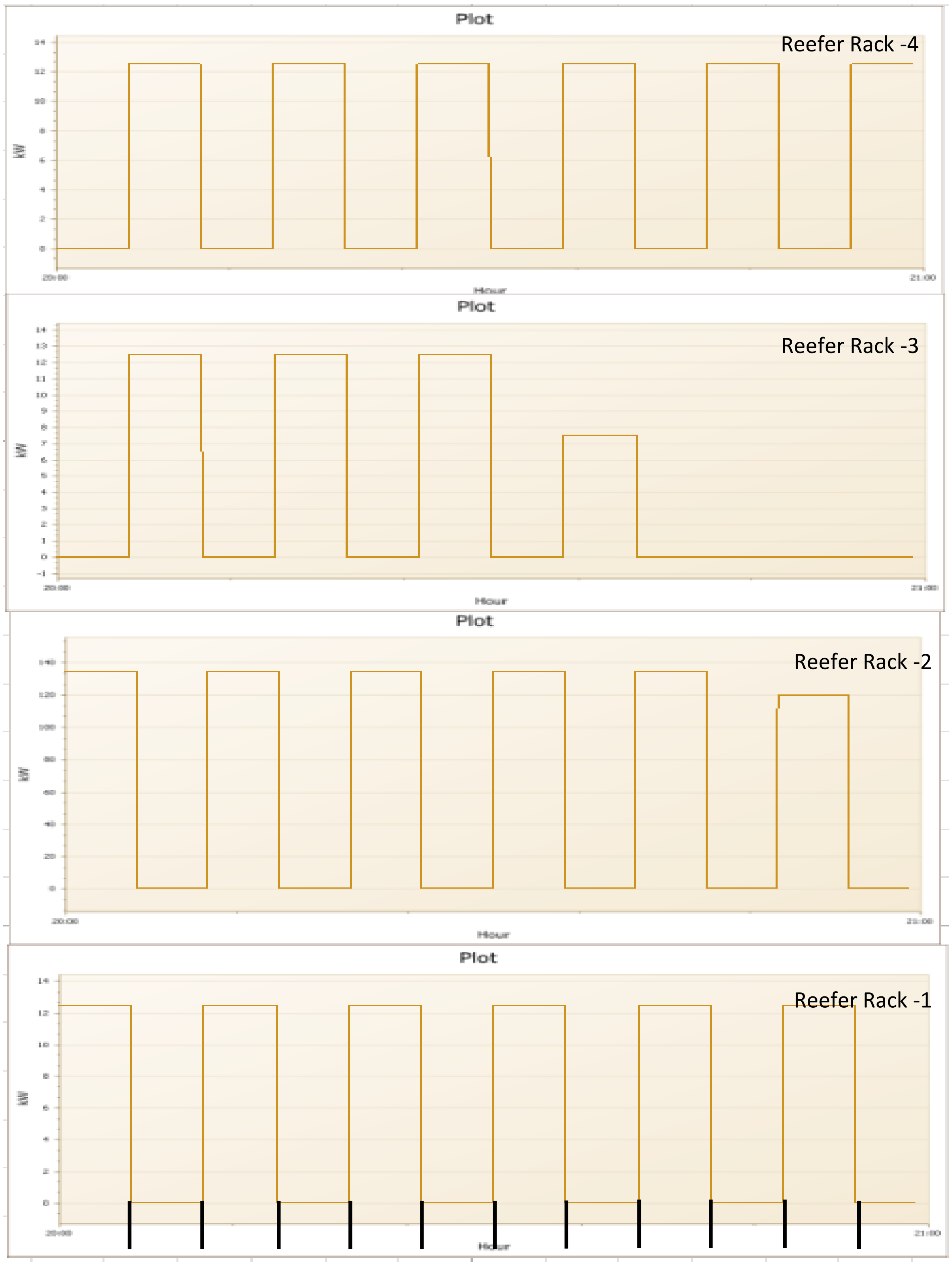

FIGURE 50. HOURLY SUPPLY OF POWER TO REEFER RACKS IN 5-MIN TIMESLOTS

A sample division of power supply for this case is shown in FIGURE 50. Like case - 1, the power is supplied in intermitted pulses. However, in this case, the timeslot is reduced to 5 minutes instead of 15 minutes. Thus, for each 5 minute timeslot, two out four reefer racks operate in normal mode while the other two are switched off. Besides this distinction in timeslot, modus operandi of case - 1 and case - 2 is exactly the same. However, peak power and average power consumption is greatly affected by this variation in timeslot.

Energy Consumption by reefers

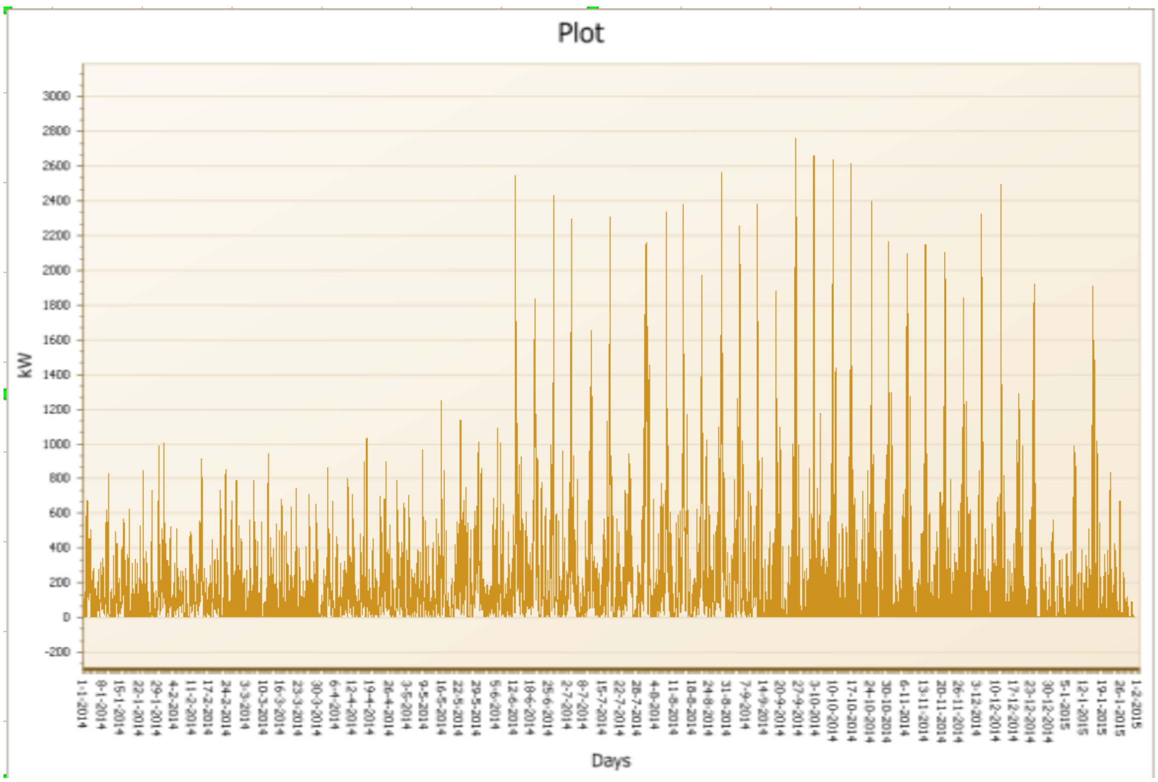

FIGURE 51. ENERGY CONSUMPTION BY REEFER AFTER IMPLEMENTATION OF POWER DISTRIBUTION SOLUTION (CASE - 2)

The FIGURE 51. shows energy consumption by reefers after implementing this case among the reefer racks. When compared to the base case, the power consumption for the entire duration has reduced drastically. Also, the peak power consumption has reduced below 3000kW. This value is well below the allowed threshold limit. Hence, as seen, power distribution is effective is reducing the peak power demand of reefer containers.

When compared to case - 1, this case reduces the peak power consumption even further. This is because, in this case, the hourly timeslot is divided into even smaller divisions (5 Minutes) when compared to case - 1 (15 Minutes). The smaller division leads to more rapid on/off of power supply of reefer which reduces the width of power pulse. This reduction of width prevents the simultaneous accumulation of power pulses which drastically reduces the peak power consumption. Thus, in general, the smaller the hourly division of time, lower the peak power consumption. This variation in timeslots also affects the monthly power consumption.

Monthly Energy Consumption

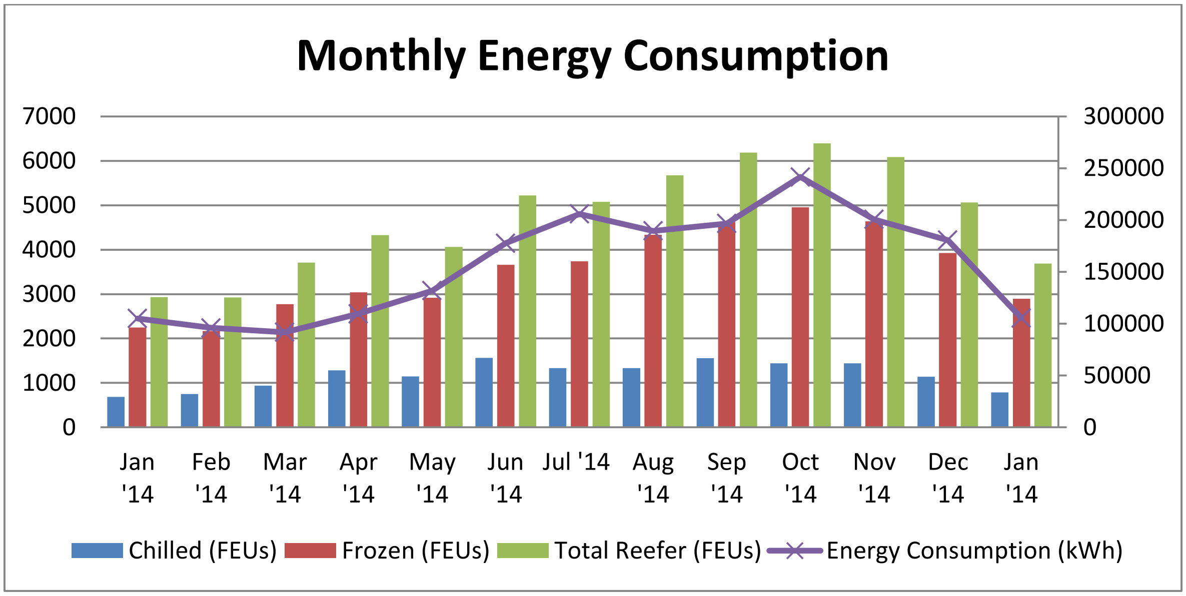

FIGURE 52. MONTHLY ENERGY CONSUMPTION AFTER IMPLEMENTATION OF POWER DISTRIBUTION SOLUTION (CASE - 2)

FIGURE 52 shows the monthly energy consumption profile after implementing this case. As seen, the energy consumption still corresponds with the arrival pattern of reefers. However, its amount has decreased even further when compared to case - 1. This is again due smaller division of timeslots leading to more rapid switching on/off of power supply to reefer. The maximum monthly energy consumption in this case is approximately 1/7rd and 1/3rd of the maximum monthly energy consumption from the base case and case - 1 respectively. In conclusion, this case, leads to even further reduction in the peak power demand and total energy consumption. Like previous case, this has a profound effect on the energy costs.

Energy Costs

Output	Value
Peak Power Consumption	**2763 kW ± 80.3 kW**[10]
Average Power Consumption	186 kW + 0.2 kW
Total Energy Consumption	2 Million kWh
Peak Energy Costs	0 €/year
Total Energy Costs	€100000 - €150000
Annual Energy Cost Savings	**€1 Million**

TABLE 15. KEY OUTPUTS AFTER IMPLEMENTATION OF POWER DISTRIBUTION SOLUTION (CASE – 2)

The values of the key output after implementing this case are shown in Table 15. In this case, this peak power consumption is 2763 kW with half width of 80.3 kW and it is well below the allowed threshold. This value is approximately 1/3rd of the peak power consumption in case - 1. Due to distribution of power supply in shorter timeslots, the total average power consumption has also reduced to 186 kW as compared to 544 kW in case - 1. This drastic reduction in peak power demand and average power consumption has also reduced the total energy consumption to 2 Million kWh. This is 1/6th of the total energy consumption in base case and 1/3rd of the total energy consumption in case - 1. Due to absence of peak power and drastic reduction in total energy consumption, the total annual energy costs has also reduced by a large amount. The total energy costs is between €100000 - €150000. Hence, this Case results in annual savings of up to €1 Million . Like in previous Case, it is important to study the impact of this Case on the reefer temperature. This is discussed in the following section.

Impact on Reefer Temperature

The impact of this case on reefer temperature with frozen and chilled cargo in this Case is shown in TABLE 16 and TABLE 17 respectively.

Temperature Increase	Number of Reefers (Frozen)
0 to 0.1	45899
0.1 to 0.2	24

TABLE 16. TEMPERATURE INCREASE FOR FROZEN REEFERS IN SWITCHED OFF STATE OF 5 MINUTES

[10] For Details, Refer Appendix E

As seen, all the frozen reefers undergo a minimum temperature increase. The maximum temperature increase is 0.18 ^{O}C. However, as the sensitivity of frozen goods in higher, none of the reefers face the danger of product damage.

Temperature Increase in Switched off State	Number of Reefers (Chilled)
-0.1 to 0	1765
0 to 0.1	13632

TABLE 17. TEMPERATURE INCREASE FOR CHILLED REEFERS IN SWITCHED OFF STATE OF 5 MINUTES

Like frozen reefers, majority of the chilled reefers have minuscule temperature increase. Likewise, none of these reefers risk any product damage.

As seen from above, case - 2 has more impact than case - 1 when compared to all the aspects of energy consumption of reefers. This is evident from the lower peak power consumption, lower average power consumption and lower total energy consumption. The higher reduction in these factors also leads to more energy saving in Case - 2 compared to Case – 1. Also, the reefers in Case - 2 undergo minimum temperature increase. Hence, it general, it can be concluded that shorter the division of time for the power supply of reefer, higher the reduction in key factors and also, lesser the likelihood of product damage in reefers.

Implementation of the Solution

This above solution is easy to implement as it requires a switch with an internal timer in it. The timer can be set to any time interval such as 3 minutes, 5 minutes and 15 minutes. Its ease of implementation has been confirmed by ABB.

Conclusion

As discussed in the above paragraphs, distributing the power in timeslots among the reefer racks greatly reduces the peak power demand. It also decreases the average power demand and thereby total annual energy consumption. This leads to massive saving in energy costs. Thus, the power distribution among reefer racks can be implemented in an operational environment to support container terminals to save costs. However, precaution has to be taken about the temperature fluctuations of reefers. For frozen cargo, the temperature rise is more in switched off mode while for chilled cargo temperature rise/fall is less. This is compensated by their sensitivity to temperature fluctuations. Hence, an appropriate time slot of power distribution is essential for maintaining the quality of goods. In general, shorter the timeslot smaller the risk of product damage in reefers. Finally, after implementing this solution, terminals can annually up to a Million Euro in energy costs.

4.2. Solution - 2: Spreading of Power pulses followed by limitation on total power consumption

As discussed in the working of the reefer, its temperature increases/decreases till it has reached its upper limit/lower limit. After this, the cooling power is applied to bring the temperature back to its set point. This working is illustrated in FIGURE 53. In this example, the set point temperature is 10 °C with the upper and lower allowed temperature as 12 °C and 8 °C respectively. The time period of this sample model is 240 hours. In this time period, the cooling power pulse occurs three times. Though it happens for a short time duration, number of times it is happens (three) is high. The result is more pronounced for a reefer with low allowed temperature bandwidth. Thus, there is a need to spread these cooling power pulses over the time period. This is achieved by utilizing the entire bandwidth of allowed temperature.

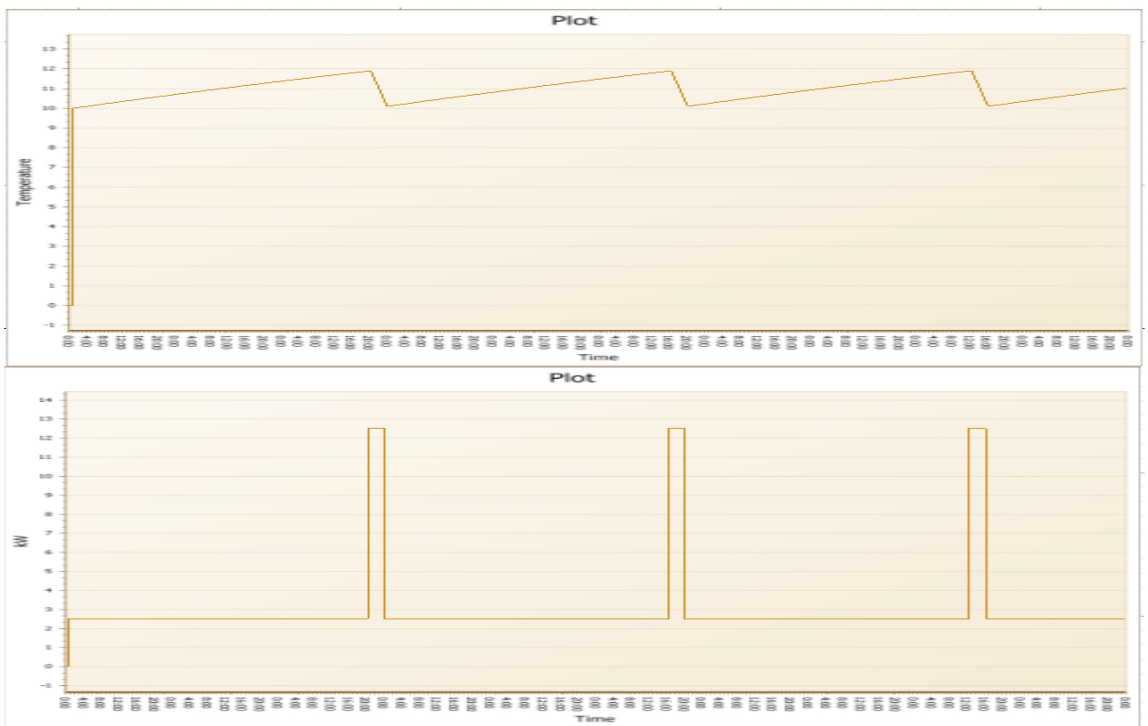

FIGURE 53. POWER PULSE IN A REEFER WITH TEMPERATURE FLUCTUATION FROM UPPER LIMIT TO SET POINT

In the same example, the reefer is now made to utilize its entire bandwidth of allowed temperature as shown in FIGURE 54. Thus, after reaching it upper temperature limit of 12 °C, the cooling power is applied till the lower allowed temperature is reached (8 °C). In such as case, though the cooling power is applied for a longer duration, the number of its pulses has reduced from three to two in the same time period. For a system of reefers operating simultaneously, this operation affects the probability of overlapping of cooling power. The result is more impactful for reefers with small allowed temperature bandwidth. Thus, by changing the behavior of power pulses, the simultaneously overlapping of cooling power can be modified.

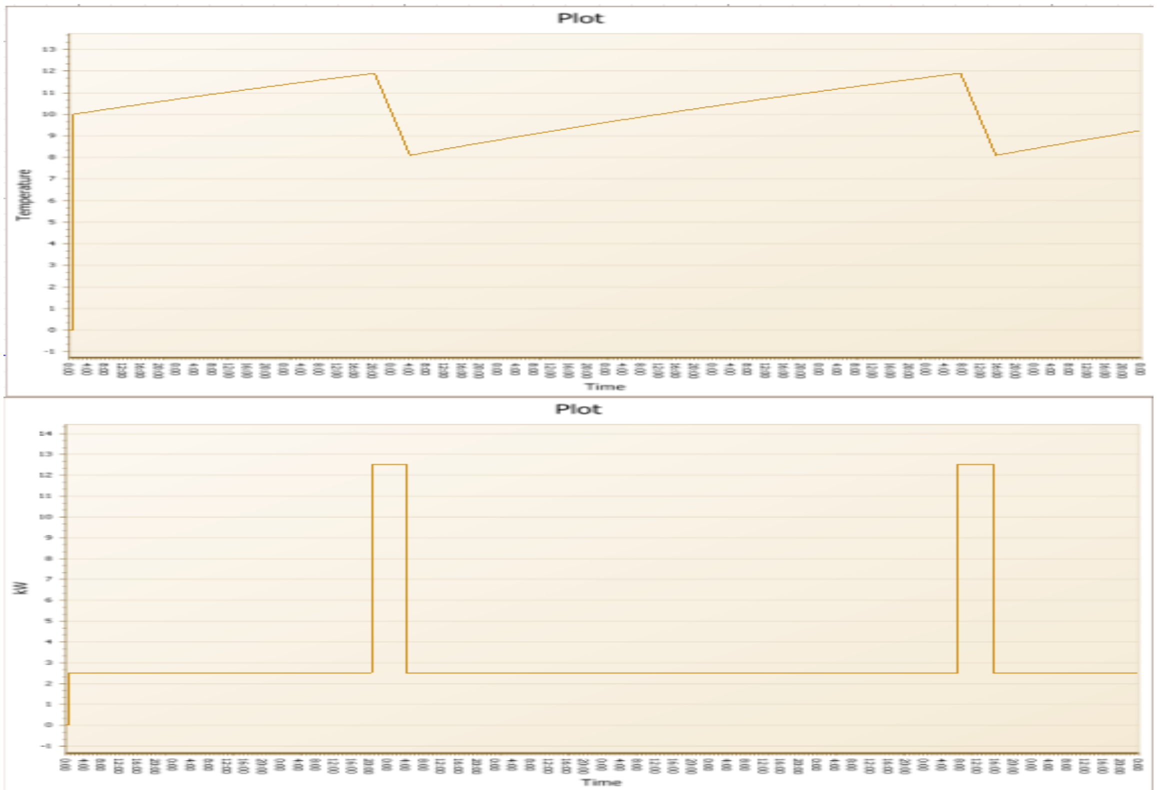

FIGURE 54. POWER PULSE IN A REEFER WITH TEMPERATURE FLUCTUATION FROM UPPER LIMIT TO LOWER LIMIT

These changes are implemented in the base case energy model. However, it is observed that the peak power demand does not decrease below the threshold value. Hence, additional restriction has to be imposed to order to reduce the peak demand.

The additional restriction involves continuous check on the total power consumption whether it has crossed the allowed limit value. If this limit value is crossed, a reduced power is supplied to reefers for their cooling operations. Thus, a restriction is put on supply of cooling power if the limit value is crossed. The algorithm for this power limitation is shown in FIGURE 55.

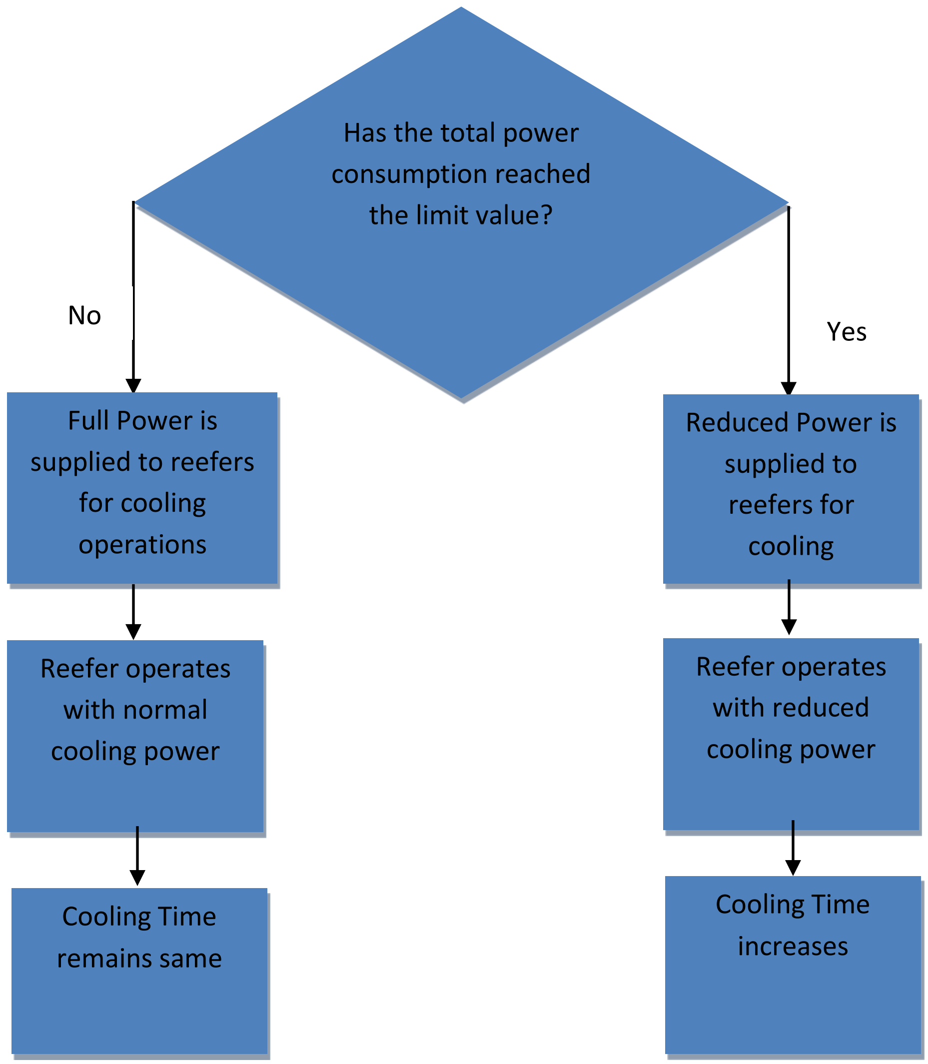

FIGURE 55. ALGORITHM FOR LIMITATION ON TOTAL POWER CONSUMPTION

The combined operation of utilization of full temperature bandwidth and limitation on total power consumption is then implemented into the energy consumption model. Its impact on the energy consumption of reefer is discussed below.

Energy Consumption by reefers

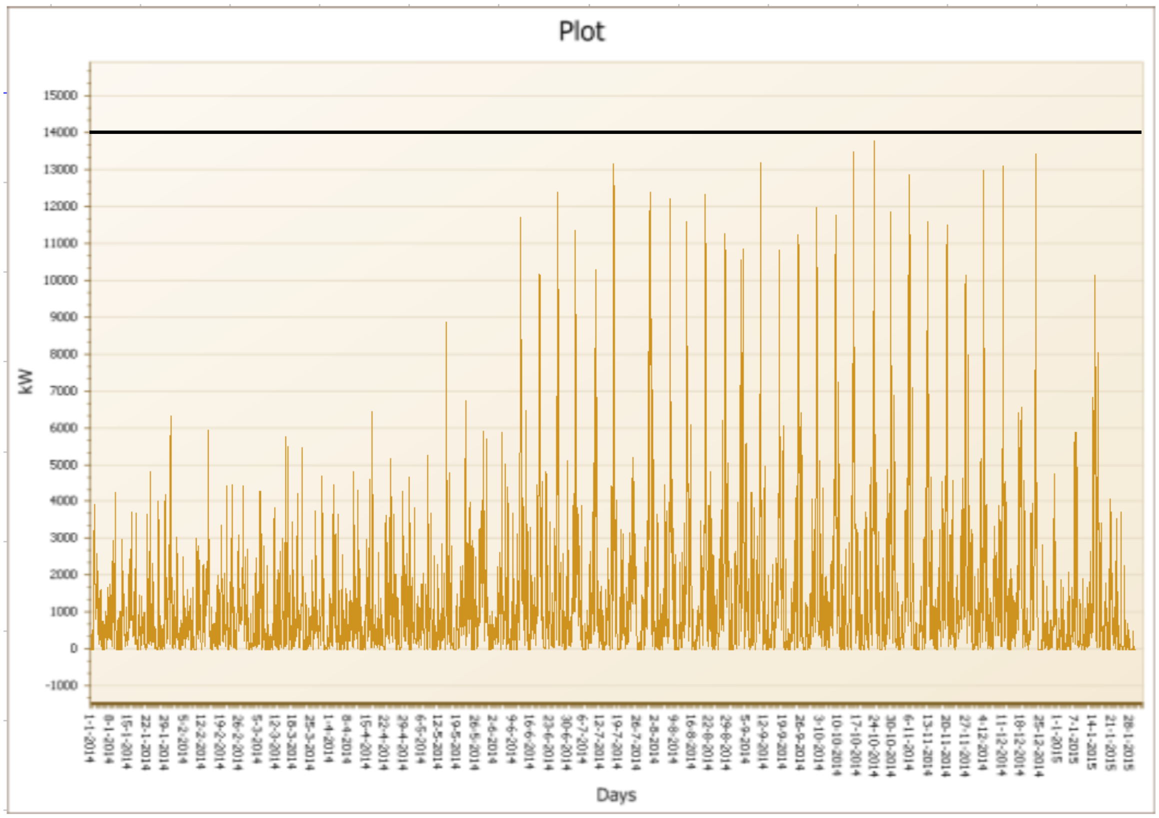

FIGURE 56. ENERGY CONSUMPTION AFTER IMPLEMENTATION OF FULL TEMPERATURE BANDWIDTH AND POWER LIMITATION SOLUTION

As seen in FIGURE 56, the combined operation of the utilization of full temperature bandwidth and limitation on total power consumption reduces the peak power demand below the allowed threshold of 14000 kW. This is because, based on above algorithm, once the power limit of 10000 kW is crossed, all the incoming reefers operate at reduced cooling power. An average of 500 reefers out of 61321 operate in this manner. However, as soon as the peak power is below 10000 kW, all the reefers operate with full cooling power by utilizing their complete temperature bandwidth. Thus, the combined effect of the operations reduces the peak power below the threshold value. This operation also affects the monthly energy consumption by reefers.

Monthly energy consumption

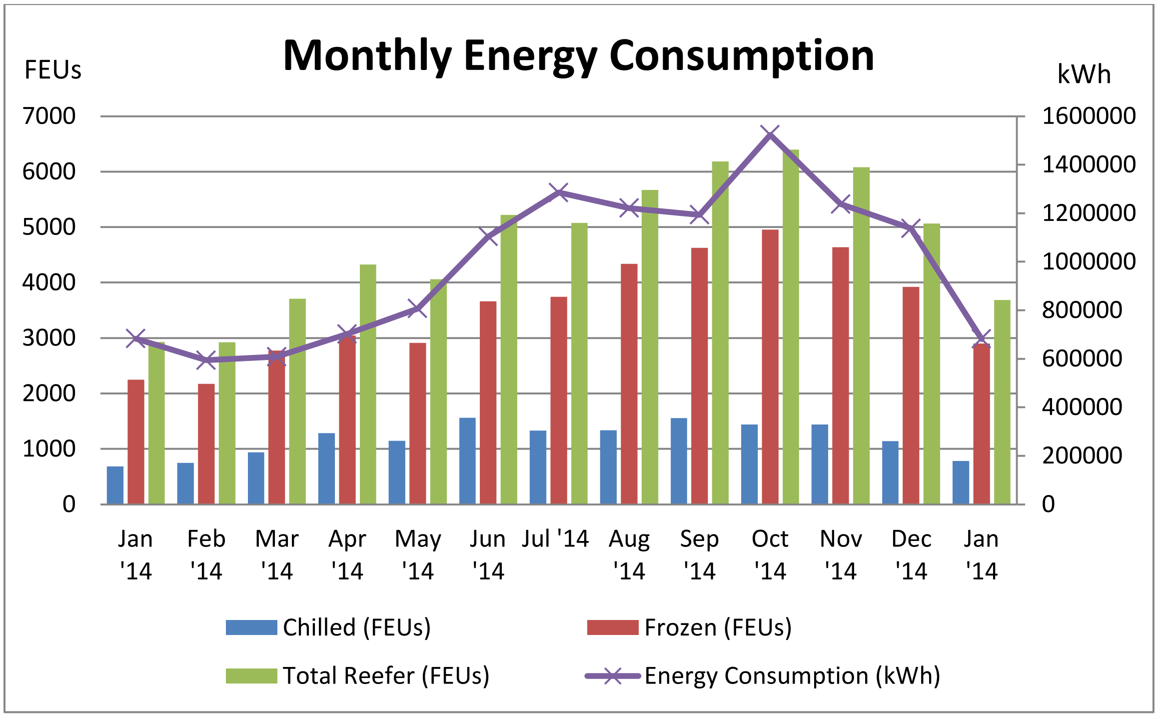

FIGURE 57. MONTHLY ENERGY CONSUMPTION AFTER IMPLEMENTATION OF FULL TEMPERATURE BANDWIDTH AND POWER LIMITATION SOLUTION

The monthly energy consumption also witnesses a change after implementing this solution as shown in FIGURE 57. Maximum amount of energy consumption takes place in the month of October. However, the peak from this month is over the other months. Through this spreading of power over the time period, the peak power demand is reduced. And this reduction in peak power leads to overall saving in energy costs.

Energy Costs

Output	Value
Peak Power Consumption	**13760 kW ± 18.5 kW**[11]
Average Power Consumption	1340 kW ± 0.3 kW
Total Energy Consumption	12,7 Million kWh
Peak Energy Costs	0 €/year
Total Energy Costs	€850000 - €900000
Energy Cost Savings	**€200000 - €250000**

TABLE 18. KEY OUTPUTS AFTER IMPLEMENTATION OF FULL TEMPERATURE BANDWIDTH AND POWER LIMITATION SOLUTION

The key results after implementation of this solution are shown in TABLE 18. The peak power demand has reduced to 13760 kW and its half width is 18.5 kW. Hence, this solution achieves the objective of power reduction below the threshold value. However, the average peak power consumption has increased to 1340 KW. This is due the flattening of peak power demand. Hence, this solution reduces the peak power demand by spreading it over the time period. This increases the average power demand leading to higher amount of total energy consumption when compared to the base case. However, this increased energy consumption does not lead to high energy costs due to elimination of peak power. The annual energy costs for operating reefer in this case is between €850000 - €900000. Thus, this solution saves up to €250000 in energy costs for terminals. Like Solution - 1, it is important to determine the impact of current solution on the reefer temperature.

Impact on Reefer Temperature

As in this case, the power to a reefer is never switched off, the reefer temperature cannot rise beyond the allowed bandwidth. The only possibility is a delayed time for cooling operations. Also, the hot box reefers, are first brought within the temperature limit before any limitation is imposed on cooling power. Hence, the reefer temperature condition is perfectly maintained in this solution.

Implementation of the Solution

The above solution is also easy to implement as a capacity constraint limit has to be agreed between the energy utility company and the terminal. Previous data of energy consumption

[11] For Details, Refer Appendix E

combined with future forecast of reefers can be helpful in determining the optimum limit. After setting the limit, the amount of power to be supplied can be effectively calculated. Also, the terminal facilities can use generators (Peak Sharing), in case of emergency additional power. Thus, this solution can be easily implemented in combination with Peak Sharing.

Conclusion

As discussed in the above paragraph, the combined effect of utilization full temperature bandwidth and limitation on total power consumption results in reduction of peak power demand. However, this decrease in peak power is countered by increase in average power consumption and thus the total energy consumption. Despite this increase, the absence of peak power greatly reduces the annual energy costs. Also, the temperature of the reefer is kept intact during the entire operation. Hence, in conclusion, the implementation of this solution leads to savings of up to €200000 - €250000 in energy costs.

4.3. Analysis of Solutions

The results presented in the two section 4.1 and section 4.2 conclude that it is possible to reduce the peak demand and save energy costs. However, it is important to take an integrated approach when analyzing these solutions. The solutions are analyzed based on the following criteria:

Peak Power Reduction

The aim of an container terminal is reduce the peak power consumption by reefers. This is because reduction in peak power leads to large savings in energy costs. Both the solutions are able to achieve this primary objective. In this, the Solution - 1 drastically reduces the peak power consumption while Solution - 2 reduces it below the threshold limit. Hence, in this criteria, Solution - 1 is more effective than Solution - 2. However, if the quantity of peak reduction is insignificant, then both the solutions are equally effective.

Total Energy Consumption

In Solution - 1, the power supply to two of the four reefer racks alternates for 15 minutes in Case - 1 and 5 minutes in Case - 2. Hence, total energy consumption is drastically less when compared to Solution - 2. For Solution - 2, the peak power demand is spread over the period of time. Hence, the total energy consumption does not decrease by a large amount. Thus, in this criteria too, Solution - 1 is more effective than the Solution - 2.

Annual Energy Savings

Annual energy costs is the combination of peak power demand and total energy consumption. Both the solutions are effective in reducing the peak power demand. However, as discussed, Solution - 1 leads to lower total energy consumption compared to Solution - 2. This results in higher annual saving in energy costs for Solution - 1 (up to €1 Million) when compared to

Solution - 2 (€200000 - €250000). Thus, in this case too, Solution - 1 is more effective than Solution - 2.

Maintenance of Quality of Product

The temperature of reefer is an indicator of the quality of product inside. Both the solutions have varying impact on reefer temperature. In case - 1 of first solution, the reefer is left in a switched off state for a period of 15 minutes. This leads to temperature change is a reefer. As seen previously, the maximum temperature rise for chilled and frozen cargo in this period is 0.53 ^{o}C and 0.12 ^{o}C respectively. This can adversely affect the quality of product inside. Also, in some unfortunate circumstances, a hot box reefer may arrive during the switched off state of power supply. In the current simulation run, four such hot box reefers arrive during the switched off state. The probability of product damage for these reefers is extremely high. In Case - 2 of the same solution, the reefer does not receive power supply for a maximum time of 5 minutes. Hence, the temperature increase in lower when compared to Case - 1. This reduces the risk to products inside the reefers. Hence, an appropriate timeslot of power is necessary to minimize the damage to products. Nevertheless, both the cases in the solution pose a potential risk to product quality.

In case of Solution - 2, the reefer is never in switched off state. Thus, the temperature does not increase/decrease beyond the upper/lower limit. It only fluctuates between the upper limit and the lower limit. Thus, the temperature of reefer is always maintained within the bandwidth. This assures the quality of products inside the reefers.

The above analysis of both the solutions show that while Solution - 1 is highly effective in reduction of peak power demand, total energy consumption and annual energy savings, it poses a risk for reefer temperature and hence the products. Solution - 2, on the other hand, reduces the peak power demand and also maintains the reefer temperature within the bandwidth. Hence, in order to extract maximum benefits a combination of the two solutions is suggested.

4.3 Combined Operations

It is possible to combine both the solution in an effective way . Their combination can lead to higher saving in energy costs without damaging the products inside reefers. The following factors should be taken into consideration while implementing the combination of Solution - 1 and Solution - 2.

Geographical Location of the Terminal

As discussed previously, ambient temperature and sun intensity affect the temperature increase of reefers. Higher the sun intensity and the ambient temperature, faster is the temperature rise of a reefer. In terms of implementation, Solution - 2 is effective irrespective of the geographical location of the terminal. However, Solution - 1, the temperature rise of reefer is faster when exposed to extreme conditions. In worst case scenario[12], the temperature rise can be as high as 1.5 °C and 0.8 °C for frozen and chilled cargo respectively. This is highly damaging for temperature sensitive products such as Bananas. Hence, though Solution - 1 is highly effective, it is a risk in extreme ambient conditions.

***Period of the Day*:**

The reefer temperature rises at a faster rate during day time as it is exposed to maximum sun intensity and high ambient temperature. Hence, Solution - 1 during day time can lead high temperature fluctuations which is detrimental to the products. Hence, like previous case, Solution - 1 is a risk during this period of the day.

The previous paragraphs analyzed the solutions based on different criteria and showed the factors to take into consideration for combined operation of both the solutions. The following section determines the implication of both the solutions on different actors

4.4. Implication of Results

Reefer in Switched off State

The biggest hindrance in the implementation of Solution - 1 is to convince the terminal operators to switch off the power supply for the determined timeslots. Currently, due to high uncertainty in product damage, the terminal operators are skeptical to follow this norm. Also, they want to avoid the risk additional cost of insurance claim due to product damage. The lack of remote temperature monitoring system is also one of the reason for this reluctance. However, Reefer Monitoring and Control System technology has made it possible to remotely monitor the changes in reefer temperature. Hence, the hurdles in implementation of Solution - 1 can be more effectively tackled if the provision of remote temperature monitoring of reefers is available.

Change in Working Algorithm of Reefer

The utilization of entire temperature bandwidth and reduction of cooling capacity for power limitation requires changes in the working algorithm of reefer. This involves building an refrigeration system with variable power drive. Fortunately, most of the reefer manufacturing companies are working along this same line. Hence, after more enhanced research a breakthrough can be expected in refrigeration system of reefer.

Determination of Appropriate Power Limit

In this case, the major actors are the power utility companies and the terminal operators. Based on the current peak power demand, these two actors can effectively collaborate to set the optimum value of power limit.

[12] Maximum Ambient temperature and Sun Intensity, Poor thermal insulation, Very low cargo mass.

4.5. Conclusion

The two rules of operations are suggested to reduce the peak power demand by reefer operating on terminals. These two rules of operations are power distribution among reefer racks in 15 minute and 5 minutes timeslots and the combination of utilization of complete temperature bandwidth and limitation on total power consumption.

The Solution - 1 is highly effective in reducing the peak power demand by reefers. It also reduces total energy consumption and thereby results in saving of up to €1 Million energy costs. However, there is risk of temperature increase among reefer especially in extreme condition such as high ambient temperature and extreme sun intensity.

The Solution - 2 is less impactful but more robust than Solution - 1. It also reduces peak power demand but leads to an increase in average power consumption and thereby the total energy consumption. However, due to the absence of peak power, there is an annual saving of a quarter million Euros in energy costs. Hence, in order to bring out the best out of the two solutions, a combined operation can be implemented.

The important factors to be taken into consideration for the combination of solutions are the geographical location of the terminal and the period of the day. In general, Solution - 1 is a potential risk at terminal with high average ambient temperature and during the day time.

In this way, two Solutions are recommended for peak shaving the electricity demand by reefers at container terminals (sub-question 7). Both the solutions have its own advantage and disadvantage. Solution - 1 is more impactful than Solution – 2 but it also presents a risk for product damage. Hence, a combined operation is recommended. The detailed recommendations is provided in Chapter 5.

5. Conclusions and Recommendations

In this research, the working of reefer is discussed in chapter 2, which leads to the development of the energy consumption model, the simulation model and finally the problem analysis in chapter 3. The solutions for solving the problem described and discussed in chapter 4. In this chapter, the research is concluded in paragraph 5.1, presenting the most remarkable findings. Based on these findings, recommendations and directions for future research are given in sections 5.2 and 5.3 respectively.

5.1. Conclusions

The research has shown that it is possible to smoothen the peak demand of a container terminal by implementing two solutions. The points to focus in these solutions are

- Peak power reduction
- Total energy consumption
- Annual Energy savings
- Maintenance of Quality of Products

The results for these two solutions are discussed below.

Solution 1 - Power Sharing among reefer racks

- Case - 1: Intermitted Power Supply in 15 minutes timeslots

By distributing power in timeslots of 15 minutes to two of the reefer racks and repeating this procedure alternatingly, the peak power demand by reefers reduces from 14831 kW (base case) to 8266 kW. Due to reduction in peak demand, no additional energy costs are incurred.

Due to alternating power supply to reefer racks, the average power demand also decrease from 1275 kW (base case) to 544 kW. This reduces the total energy consumption from 12,1 Million kWh (base case) to 6 Million kWh. Thus, total energy consumption is reduced to half of the base case. The absence of peak power and reduction in total energy consumption affects the total energy costs.

The total energy cost reduces from €1,09 Million (base case) to approximately €400000 - €500000. Thus, by implementation of this solution, a terminal can annually save between €600000 - €700000 in energy costs. However, despite this energy saving, there is one major risk associated this case.

As the reefer stays without power supply for 15 minutes, it temperature increases during this time period. This increase depends on several factors such as reefer characteristics, ambient conditions and cargo type. In the current simulation, the maximum temperature of frozen and chilled reefer increased by 0.5 ^{o}C and 0.12 ^{o}C respectively in the timespan of 15 minutes. In worst case, this may be higher. The temperature of a chilled reefer with high set point decreases. The maximum decrease is 0.18 ^{o}C for the same time span.

- Case - 2: Intermitted Power Supply in 5 minutes timeslots

By distributing power in timeslots of 5 minutes to two of the reefer racks and repeating this procedure alternatingly, the peak power demand by reefers reduces from 14831 kW (base case) to 2763 kW. This reduction is higher when compared to case - 1. Likewise, as the peak power demand is below the threshold value, no additional energy costs are incurred.

The average power demand also decrease from 1275 kW (base case) to 186 kW. This reduces the total energy consumption from 12,1 Million kWh (base case) to 2 Million kWh. These reduction are again greater when compared to case - 1. These massive reduction total energy consumption and the absence of peak leads to reduction in the total energy costs.

The total energy cost reduces from €1,09 Million (base case) to approximately €100000 - €150000. Thus, by implementation of this solution, a terminal can annually save up to €1 Million in energy costs.

The maximum temperature increase in the Case is 0.18 ^{o}C for a frozen reefer. All the other reefers, have minimum temperature increase/decrease. Hence, there is less risk of product damage in case - 2 when compared to case - 1.

In conclusion, despite energy savings in this solution, precautions have to be taken about the temperature increase and thereby the quality of products in reefers . In general, shorter the division of timeslots, lower the risk of product damage in reefers. Hence, it important to choose an appropriate timeslot to have minimum temperature increase/decrease in reefers and thereby avoid damage to products.

Solution 2 - Spreading of Power pulses followed by limitation on total power consumption

By the combination of utilization of complete temperature bandwidth and thereby followed by limitation on total power consumption, the peak power demand reduces from 14831 kW to 13760 kW. Here, too, the absence of peak power results in saving of energy costs.

The reduction in peak power is achieved by spreading the power demand over the time period. Hence, the average power demand increases to 1340 kW from 1275 kW. This also increases the total energy consumption from 12,1 Million kWh to 12,7 Million kWh. Thus, there is a slight increase in the total energy consumption from the base case. However, the absence of peak power reduces the total energy costs.

The total energy costs reduces from €1,09 Million to approximately €850000 - €900000 . Thus, by implementation of this solution, a terminal can annually save between €200000 to €250000 in energy costs. Besides this energy savings, there is no negative impact on reefer temperature after implementing this solution.

A summary of the base case and the two Solutions is given in TABLE 19.

	Peak Power (kW)	Average Power Consumption (kW)	Total Energy Consumption (kWh)	Energy Savings (kWh)	Energy Costs (€)	Energy cost Savings (€)	Impact of Reefer Temperature	Risks
Base Case	14831	1275	12,1 Million	NA	1,09 Million	NA	NA	NA
Solution – 1 (Intermitted Power Supply in 15 minutes timeslots)	8266	544	6 Million	6,1 Million	400000 - 500000	600000 - 700000	Maximum Temperature Rise: Frozen Cargo: 0.5 ºC Chilled Cargo: 0.12 ºC Maximum Temperature Decrease Chilled Cargo : -0.18 ºC	In extreme ambient conditions, high risk of product damage.
Solution – 1 (Intermitted Power Supply in 5 minutes timeslots)	2763	186	2 Million	10 Million	100000 - 150000	1 Million	Maximum Temperature Rise: Frozen Cargo : 0.18 ºC Chilled Cargo : Negligible Temperature Increase/Decrease	Less risk to product damage when compared to case - 1
Solution - 2	13760	1340	12,7 Million	-600000	850000 - 900000	200000 - 250000	No negative impact on reefer temperature	No significant risk to products

TABLE 19. SUMMARY OF RESULTS FOR BASE CASE AND THE TWO SOLUTIONS

5.2. Recommendations

Though the main aim of terminal operator is to reduce peak power consumption by reefers, it cannot afford to negatively impact product quality inside reefer. This can lead to additional insurance costs and more importantly affect the reputation of the terminal. Hence, in order to achieve the aim of peak power reduction without negatively affecting the reefer temperature, the following recommendations are suggested:

Recommendations for ABB

- Smart Energy Management System

In order to have maxing savings in energy without damaging the product quality inside reefers, it is important to utilize the best of the two solutions. While the Solution - 2 is applicable 24/7 for 365 days, some restriction do apply for Solution - 1. It is recommended to use this solution at terminals where average ambient temperature is not very high or not very low. Also, it is recommended to use this solution during night time as rate of temperature rise during this time is low.

- Pilot Project

The current results and the solutions are based on simulation model which is built after making some assumptions. Hence, in order to obtain realistic results, a pilot project is recommended at a terminal. Thereby, real results can be obtained and the practicability of the solution be tested.

- Utilization of additional resources at terminal

Due to advancement in technology, the terminals have become highly automated and use enhanced software such as Reefer Monitoring and Control System to ensure the maintenance of reefer temperature. Terminal operating System (TOS) is also used by many terminals to improve their productivity. Hence, it is recommended to use the above mentioned solutions in tandem with the available resources at the terminal.

Recommendations for Terminals

- Proper regulations on the usage of reefers

From the sensitivity analysis, it is evident that key variables affecting the temperature changes in reefers are mass and thermal conductivity. Hence, it is recommended to have regulations to check the cargo mass in reefer and the quality of reefers operating on terminals[13].

- Proper Schedule Management

It involves connecting the reefers at appropriate time according to their temperature deviations. The one hour timeline available between the arrival of reefer in reefer racks and the moment they are plugged in can be utilized to the fullest extent. If possible, it is recommended to delay

[13] Age below 8 years, no door openings, no ventilation problems, no cracks or gaps.

the connection of reefers with the least temperature deviation by 45 minutes or more. Thus, a priority can be set among the plug-in time of reefers

- Innovative Roof Technologies

The primary aim of shading roofs is to minimize the impact of sun intensity on reefers (Richard Marks, 2012). Additionally, photovoltaic panels can be installed on roofs to provide regenerative energy to reefers. Its practical implementation in the Hakata Port in Japan has led to significant energy savings (Froese & Toter, 2014). However, the challenge is not the hinder the operation of handling equipment. Thus, proper implementation of innovative roof technologies can lead to significant energy savings at terminals.

Recommendations for Scientists

- Enhanced research on the refrigeration system of reefer

The refrigeration system is the most critical component of a reefer. Hence, its malfunctioning can lead to high power consumption for a reefer. Scientific community can focus making this system more efficient leading to lower power consumption by reefer.

5.3. Directions for future research

Based on the research and its recommendations, the following directions for future research can be identified.

- Enhanced research is required to study to impact of these two solutions on reefers products considering additional factors such as fluctuations in humidity level, variations in levels of essential gases like ethylene, oxygen

- Research towards the carbon footprint of reefers operating on terminals, the environmental impacts of operating reefers at terminals and how to minimize these impacts, if any. This can provide further incentives to bring in regulations for proper reefer management at terminals

- Deep analysis of the relation of global reefer trade and the energy consumption at terminals across the globe. This can provide deeper understanding of the seasonality of reefer and energy consumption at terminals

- Energy consumption of reefers across its entire supply chain from producer to consumer can help provide integrated solutions to reduce the overall energy consumption by reefers.

6. Reflection

The reflection in this chapter presents several of my personal findings on several aspects of the research. First the methodology is discussed, followed by the data and validation, and finally the results of experiments.

- **Methodology**

For simulating the energy consumption of large number of reefers at a container terminal, a discrete-event simulation is applied. For of an individual reefer, several techniques such as energy balance, heat transfer models, finite element and CFD are available. Several simulation environments such as MATLAB, SIMULINK, DYMOLA enable the use of these techniques. All these models are for extensive research on individual reefer. Hence, they are not useful for the intended purpose of this research. From a systems perspective, agent based and continuous modeling do not capture the event-based character of reefers. Thus, only discrete event simulation facilitates the simulation of containers that are transported and can be seen as active objects running through a model. Hence, I am satisfied about the use of Simio as software for constructing the simulation. It was essential to develop processes simulating the current working a single reefer. So, in the first instance, I constructed the simulation model of a single reefer. It took several iterations to develop this simulation. This model was replicate for the reefer data provided by ABB for a sample terminal in Port of Rotterdam. However, this required changes as each individual reefer had its own characteristic. For this, a data sheet was created and linked to the Simio software. The property of Simio to extract data by linking it to external file was the fastest way to run the model and obtain the desired results. Also, in order to be able to get all needed statistics out of the model, additional statistics were added to the model. From Simio, a highly realistic terminal operations simulation could have been created. However, as the aim of the research was the reduction of peak power consumption at terminal, the focus was kept on the process of energy consumption of reefers than on the design of terminal operations.

- **Data and validation**

A real comprehensive data of a terminal was needed to develop the simulation model. This is because the simulation model would then generate the energy consumption profile of that particular terminal over a period of time. Therefore, the data collection was very dependent on the willingness of a terminal to collaborate. ABB was extremely helpful in this case as it was able to provide realistic data of reefer logistics for a sample terminal. However, some assumption were made to cope with the unavailable data such as terminal operations, reefer characteristic and energy cost calculations. Because previous research did not focus on the energy consumption by reefers at terminals, I needed to develop the conceptual model for this. After the integration of conceptual model, data analysis and some assumptions, the simulation model for energy consumption was built. Expert validation of the model was done by ABB and by the manager of ECT. Besides this, previous research from experts in this field also helped in validation. It would be exciting to see the implementation of model and its corresponding solutions at an actual terminal.

- **Results of Model**

The main research question was to find solutions that contribute towards reduction of the peak power demand. After analyzing the causes of peaks, two solution were proposed. They can be view from two perspectives. The 1st solution - Power distribution among reefer racks results in annual savings of up €1 Million in energy costs for terminals. However, this solution is high risk for reefer temperature if proper precautions are not taken. The 2nd solution - Spreading of Power pulses followed by limitation on total power consumption eliminates the power peaks by reefers but leads to increase in total energy. It also presents no risk for reefer temperature and is thus more reliable. Additionally, I have provided how to combine these solutions for the best use of the terminal. Finally, I have listed other potential solutions which can reduce energy consumption by reefers at terminals.

As final reflection, I sincerely hope this research has provided insights into reefers operations at terminals despite some assumptions and limitations in the model, and it will be practically implemented to reduce peak power demand to save millions of Euros in energy costs.

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Appendix A: Seasonality of Fruits in South Africa

DECIDUOUS FRUIT	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Apricots		✓	✓	✓	✓							
Peaches	✓	✓	✓	✓	✓	✓						
Nectarines	✓	✓	✓	✓	✓	✓						
Plums		✓	✓	✓	✓	✓	✓					
Table Grapes	✓	✓	✓	✓	✓	✓	✓	✓				
Pears				✓	✓	✓	✓	✓	✓	✓	✓	
Apples				✓	✓	✓	✓	✓	✓	✓	✓	
Kiwi									✓	✓	✓	
Cherries			✓	✓								
CITRUS FRUIT	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Easy Peelers & Mandarins	✓					✓	✓	✓	✓	✓	✓	✓
Lemons						✓	✓	✓	✓	✓	✓	
Oranges	✓	✓					✓	✓	✓	✓	✓	✓
Grapefruit							✓	✓	✓	✓	✓	✓
SUB-TROPICAL FRUIT	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Avocados					✓	✓	✓	✓	✓	✓	✓	✓
Litchi's		✓	✓	✓	✓	✓	✓					
Mangoes		✓	✓	✓	✓	✓						
Pineapples	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Passion Fruit					✓	✓	✓	✓	✓	✓	✓	
EXOTIC FRUIT	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Raspberries		✓	✓	✓	✓	✓						
Blueberries		✓	✓	✓	✓	✓						
Melons		✓	✓	✓	✓	✓						
Strawberries	✓	✓	✓									
Figs			✓	✓	✓	✓	✓	✓				
Pomegranates					✓	✓	✓	✓	✓			

Appendix B. Findings from Interviews

Interview with Mr. Peter Schoonen, Consultant Logistics Development at Port of Rotterdam

Date - 20/5/2015

- A substantial amount of containers is stacked in the opposite direction. So the module to connect is not accessible for the person who has to connect the reefer as it is at the wrong side of the stacks. In this case a reefer has to go completely back into the stacking procedure and will be placed on an AGV (or in the area before the stacking lane [not sure about this]) again.
- The average plug-in time when a container comes from a ship is 30 minutes. The contract says it has to be done as soon as possible, which is open for interpretation. If it is not done in about 1 hour it is an excess. Connecting the containers happens when a containers is placed in the stacks and Delta Reefer Care gets an order to connect this container. The stacking priority depends on where a container has to leave the terminal (for barge, by train or by truck).
- Some shipping lines don't want to connect the reefer containers on the terminal when the dwell times are really short (mostly import containers). This happens more often the last period. ECT do not want this out of the risk to be responsible when cargo is damaged and companies start to claim.
- 5-10 % of the reefers needs small or large repair jobs on a terminal, which is not always done directly when the containers are in the stacks.
- The terminal has no access to all the available information on a level of a single reefer before the ships arrive so they cannot take this into account in their stowage plan and the way they stack the containers. Only real sensitive containers with medicines, blood plasma etc. are arriving with extra information and will get an extra priority and sometimes extra handling instructions.
- Energy management software for reefer containers is done on the level of a container by the module/computer on the container. For frozen containers they are sometimes almost completely turned off for 1 hour or more.
- 2 seasonal peaks are regular, one in April-May and other in September-October
- Integrating energy management systems requires big investments in a market that is quite uncertain at the moment for ECT.
- During peak season, reefer operations consume 30% of total terminal energy.
- Roof cover is difficult at ECT due to operations by cranes.
- During peak season, a terminal may harbor reefer intended for other terminal leading to additional energy consumption

Interview with Mr. Ronal Kolijn, Delta Reefer Care, ECT Terminal

Date - 20/5/2014

- Delta Reefer Care charges ECT a certain amount of Euros related to the number of reefers. Repair jobs etc. are charged at the shipping lines.
- Maximum temperature deviation witness is 10 ^{o}C

- Responsible for all reefer activities as temperature checks, plug-in en plug-out jobs, technical inspections, maintenance, repairs and so on
- Keep the disconnection time as short as possible, Delta Reefer Care has to connect to containers within 1 hour after the container is in the stacks. This is arranged in a service level agreement with ECT. The shipping line is the organization that checks if these arrangements are really implemented by the terminal and Delta Reefer Care.
- Biggest temperature differences on the terminal are related to export containers.
- Employees of Delta Reefer Care receive a connection job or a temperature check on their handheld. This is related to the stacking protocol.
- The bandwidth for the cargo temperature is around 1.5 to 2 degrees Celsius around the set temperature.
- Hard to say if the shipping lines are transparent about the conditions of the reefers.
- The data recorders show exactly when a container is turned on and off.
- Reefer temperature checked 3 times a day
- A reefer is never plugged out during its dwell time
- There is different contract for handling reefer contaienrs

Both, Mr Schoonen and Kolijn, agree that shipping industry must corporate more. This make the supply chain more transparent.

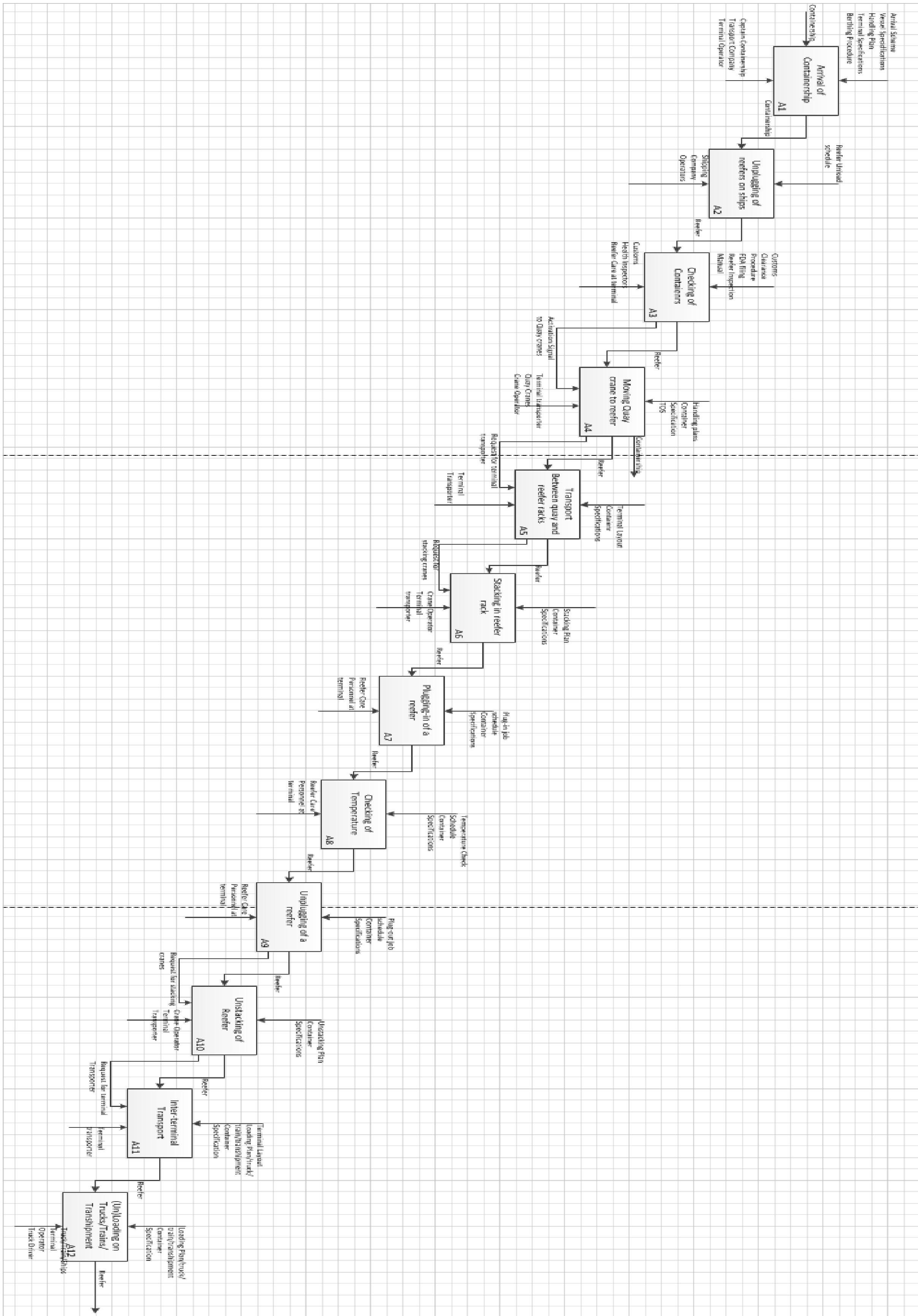
Current there is no energy management system for reefer management at ECT

Interview with Patrick Surmount, Technical, Program Manager Product Management Global Marine and Rail at Ingersoll Rand

Date – 11/6/2015

- Innovation in hardware has reached the maximum limit unless major breakthrough takes place in material science eg. Carbon nanotubes
- Majority of research in energy management of reefer deal with variable drive motor which intelligently adjusts the cooling power

Appendix C. IDEF0 Diagram

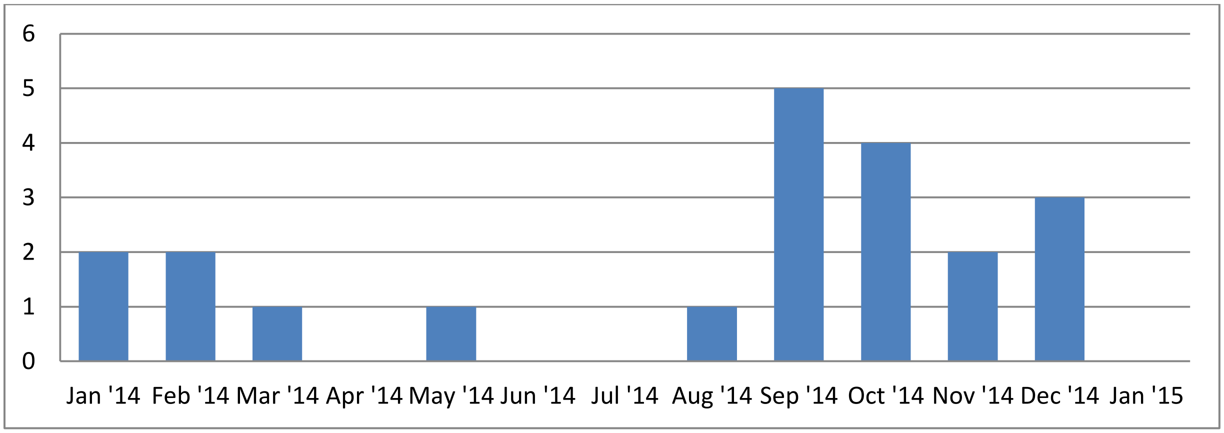

Arrival of Containership
A1
Unplugging of reefers on ships
A2
Checking of Containers
A3
Moving Quay crane to reefer
A4
Transport Between quay and reefer racks
A5
Stacking in reefer rack
A6
Plugging-in of a reefer
A7
Checking of Temperature
A8
Unplugging of a reefer
A9
Unstacking of Reefer
A10
Inter-terminal Transport
A11
(Un)Loading on Trucks/Trains/ Transhipment
A12

Appendix D. Monthly Arrival Pattern of Reefers with Different Set Points

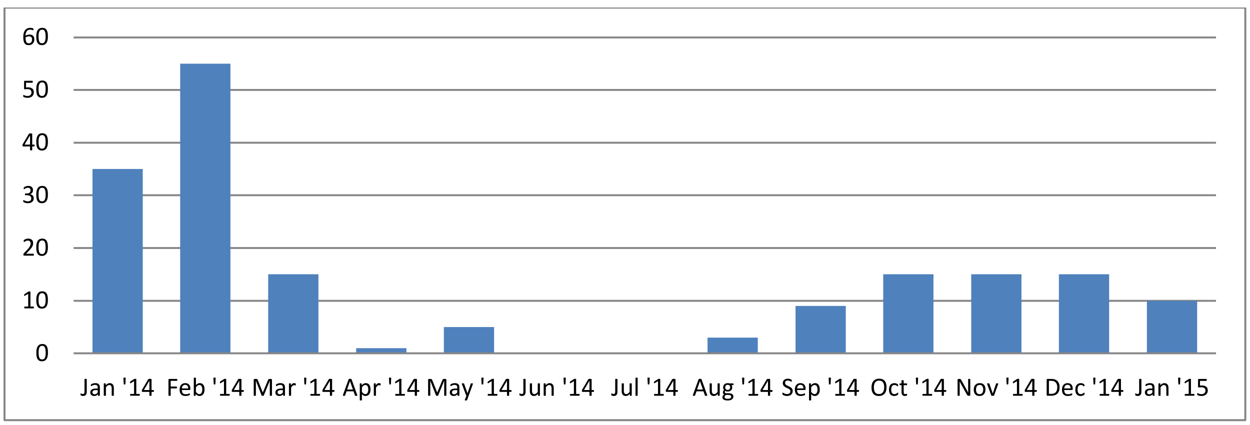
Count of 8150419	Column Labels			
Row Labels	**chilled**	**frozen**	**(blank)**	**Grand Total**
1	**1470**	**5145**		**6615**
2014	685	2246		2931
2015	785	2899		3684
2	**750**	**2171**		**2921**
3	**938**	**2773**		**3711**
4	**1285**	**3042**		**4327**
5	**1146**	**2914**		**4060**
6	**1563**	**3660**		**5223**
7	**1333**	**3741**		**5074**
8	**1334**	**4336**		**5670**
9	**1558**	**4624**		**6182**
10	**1440**	**4955**		**6395**
11	**1442**	**4638**		**6080**
12	**1139**	**3924**		**5063**
(blank)				
Grand Total	**15398**	**45923**		**61321**

(Blue - Frozen, Red – Chilled, Unit - FEUs)

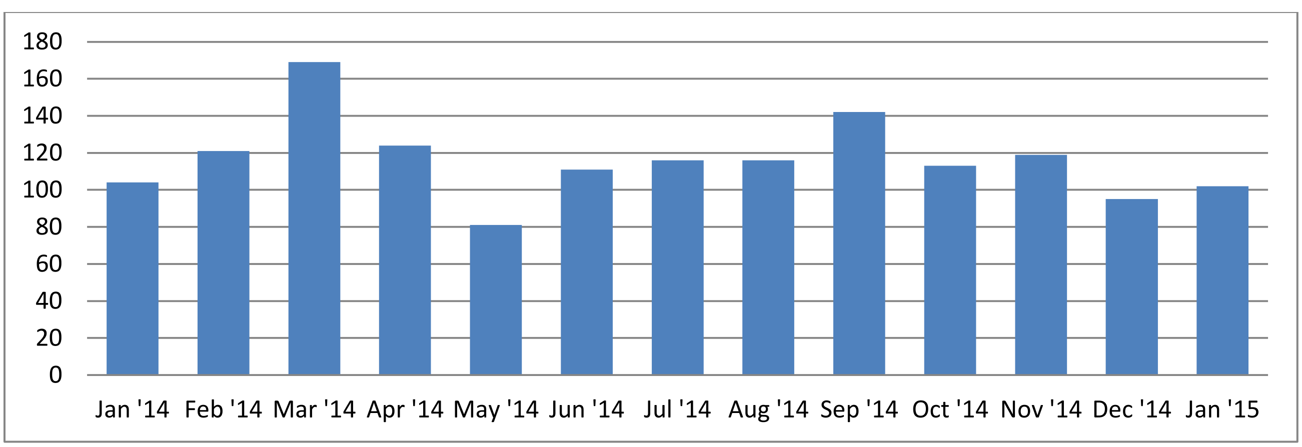
1. **Set Point - 60 °C - Total Count 61**



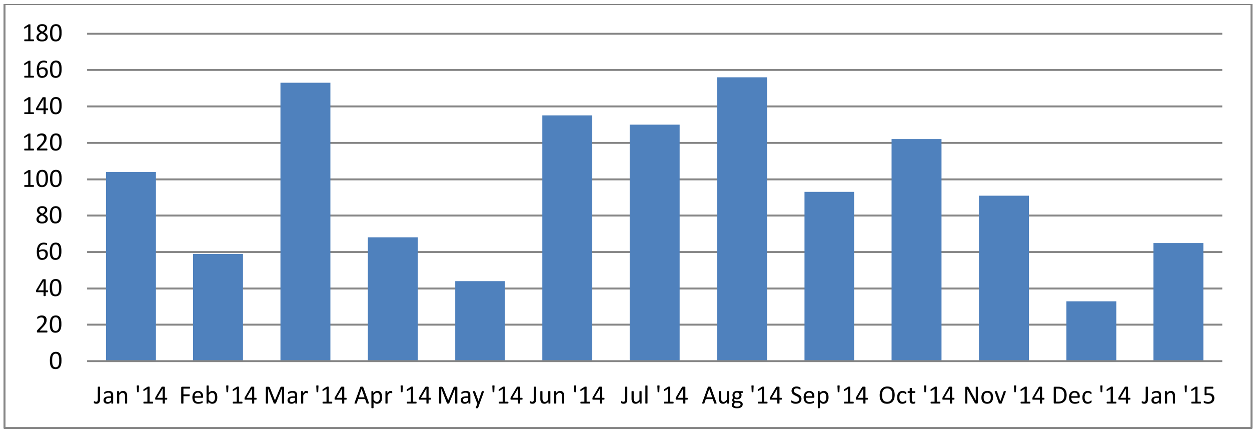
2. **Set Point - 26 °C - Total Count 172**



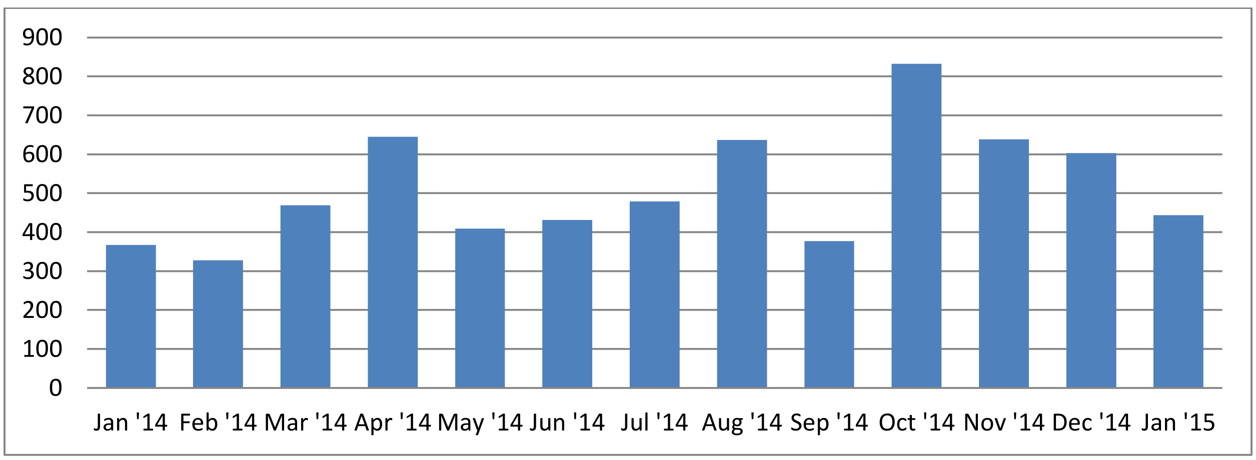
3. **Set Point -25 °C - Total Count 1513**



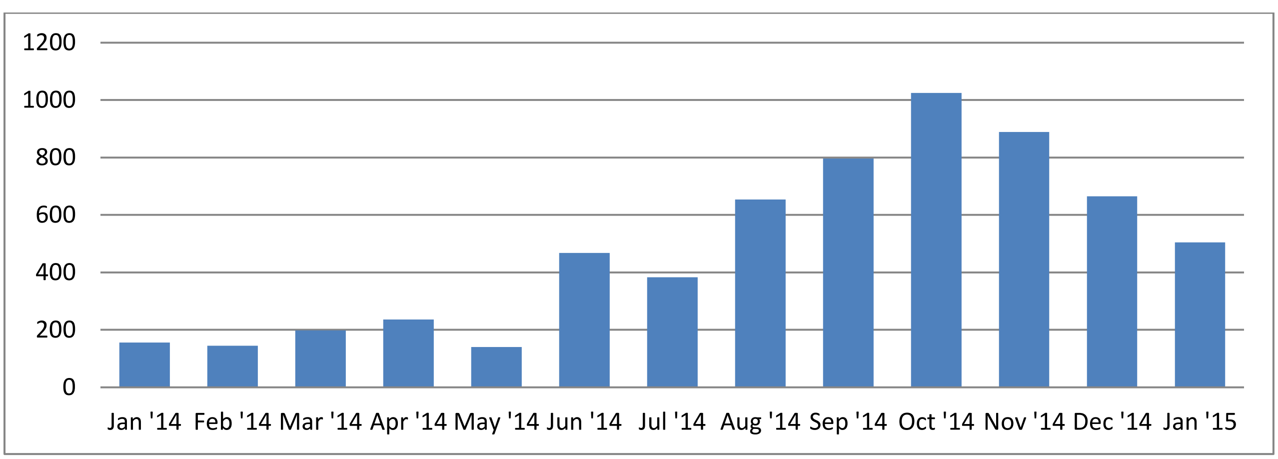
4. **Set Point -24 °C - Total Count 1253**



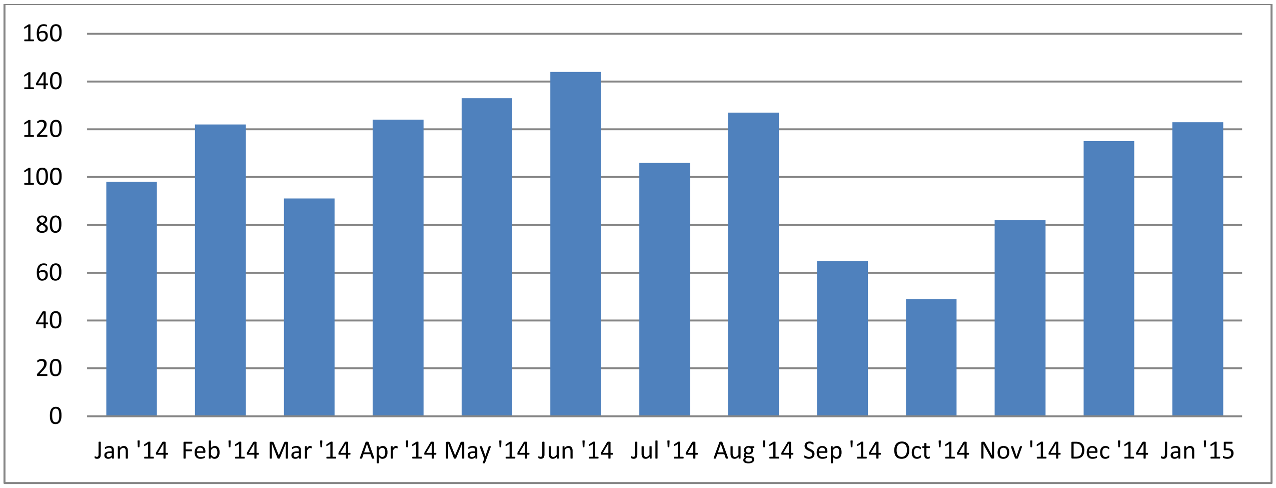
5. **Set Point -23 °C - Total Count 6659**



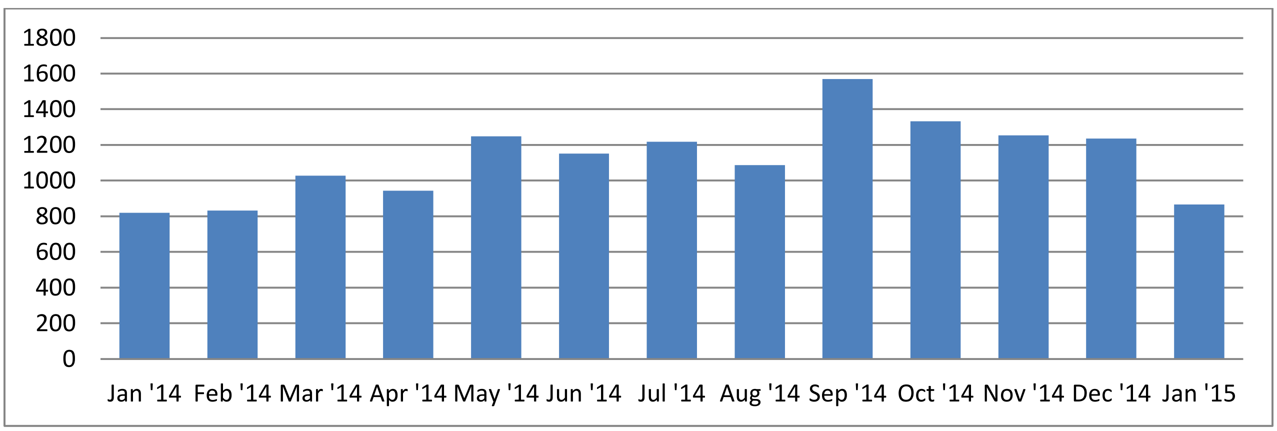
6. **Set Point -22 °C - Total Count 6260**



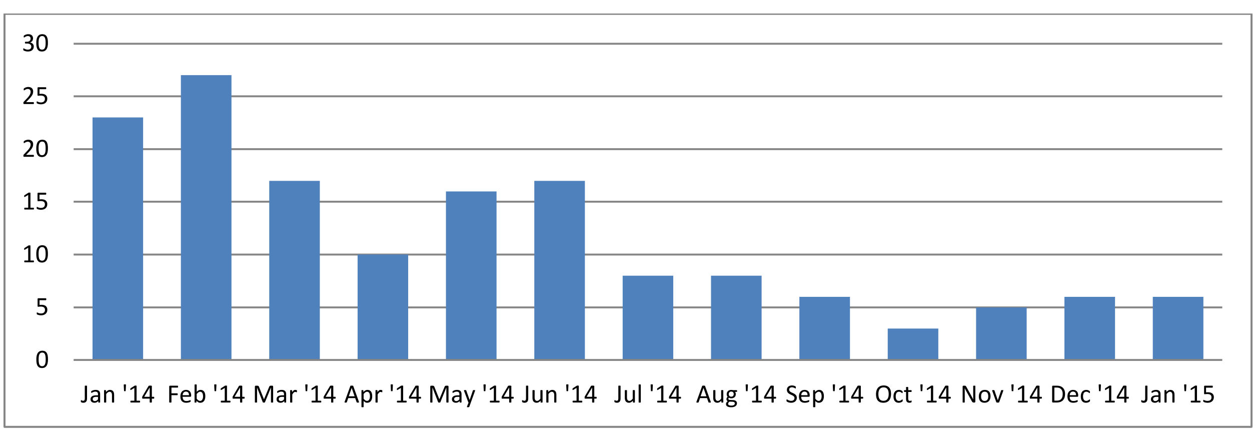
7. **Set Point -21 °C - Total Count 1379**



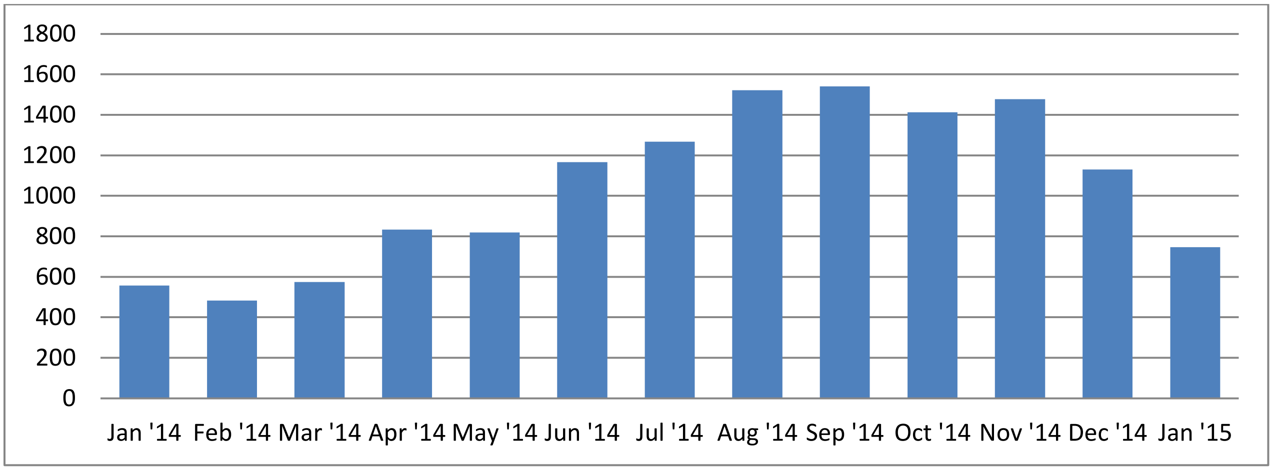
8. **Set Point -20 °C - Total Count 14586**



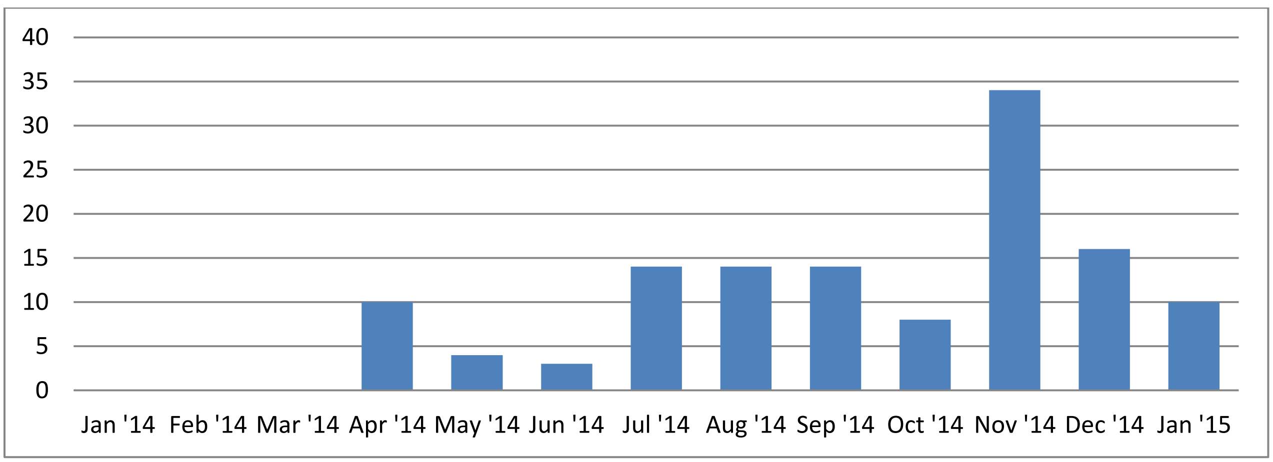
9. **Set Point -19 °C - Total Count 152**



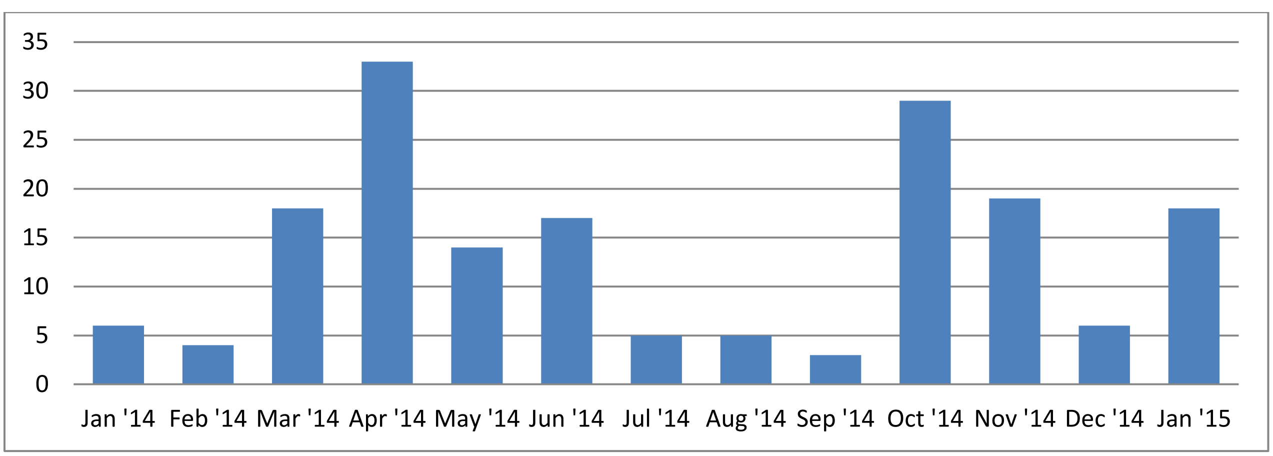
10. **Set Point -18 °C - Total Count 13527**



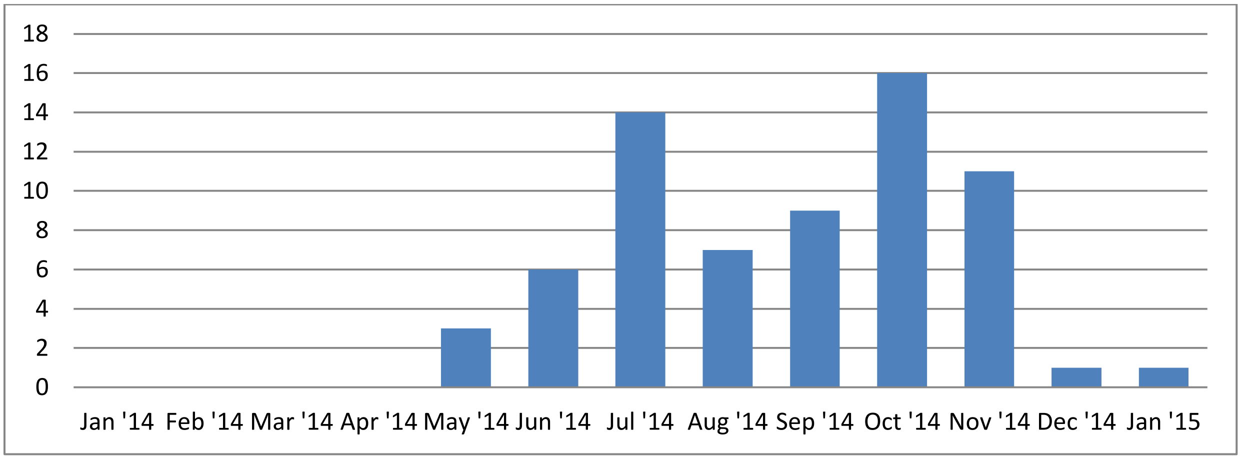
11. **Set Point -16 °C - Total Count 127**



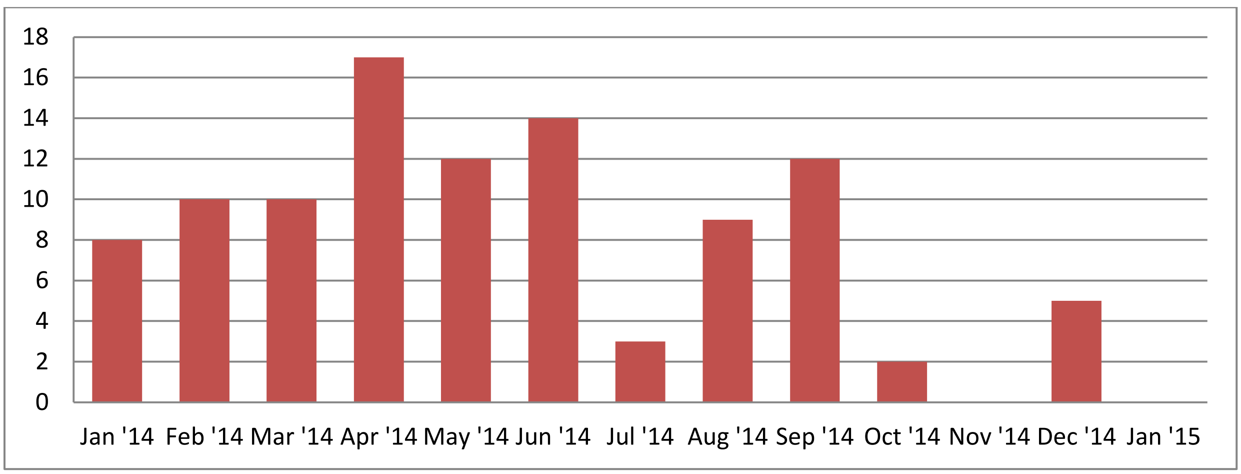
12. **Set Point -15 °C - Total Count 177**



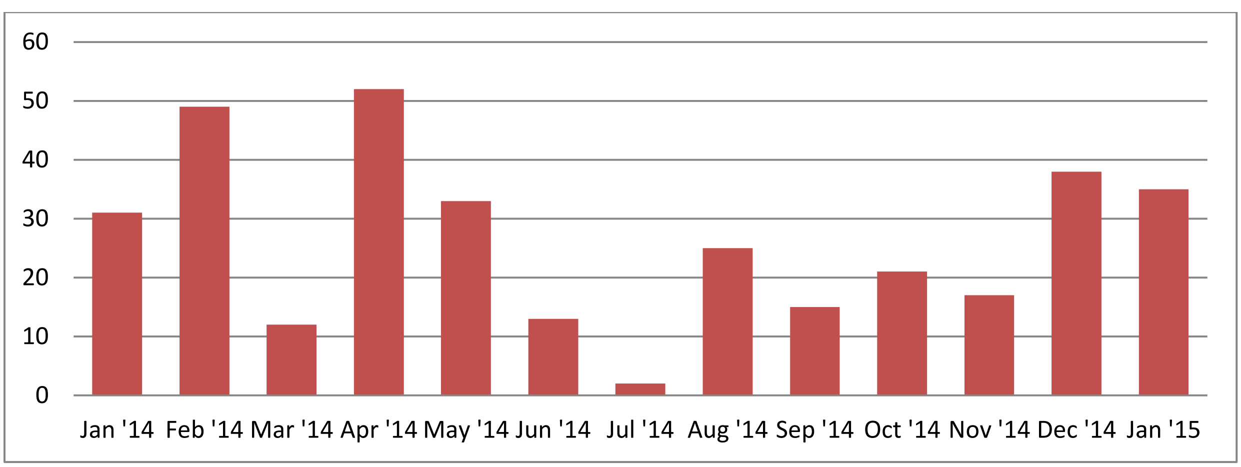
13. Set Point -13 °C - Total Count 68



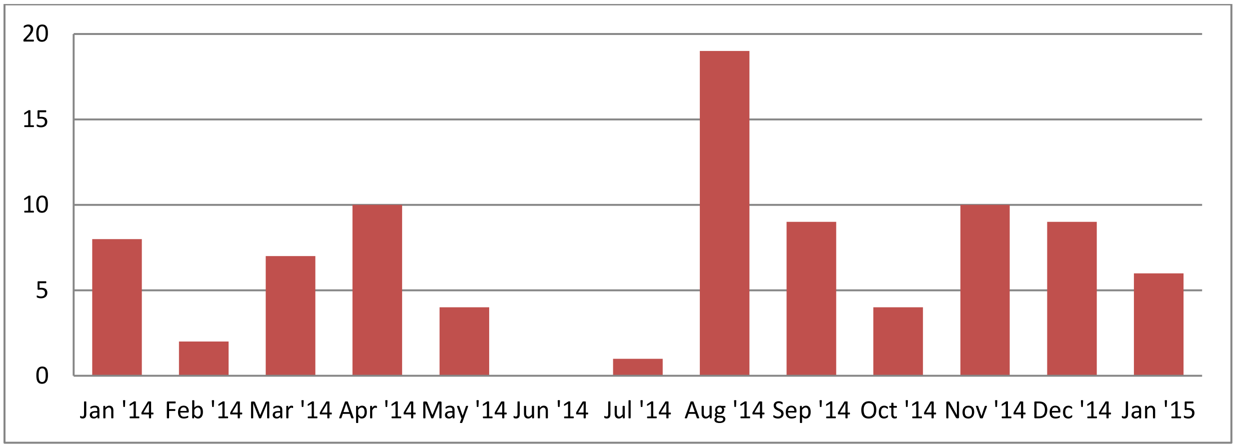
14. Set Point -5 °C - Total Count 102



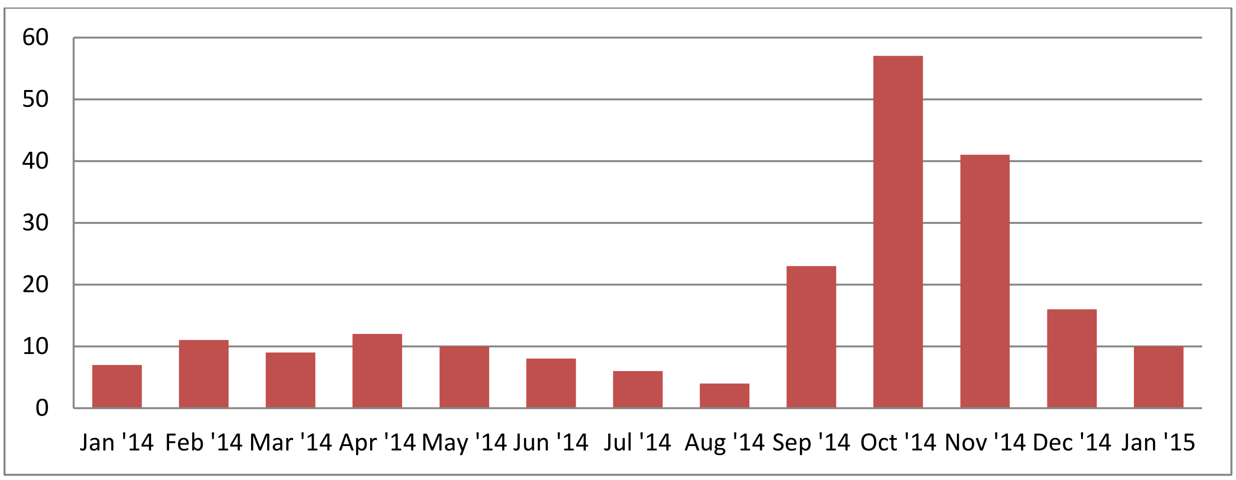
15. Set Point -3 °C - Total Count 343



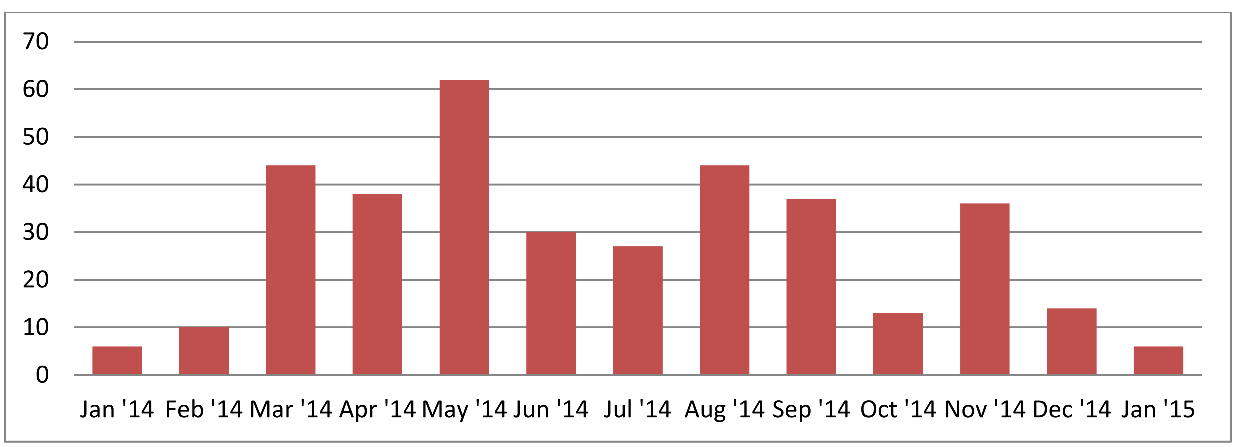
16. **Set Point -2.9 °C - Total Count 89**



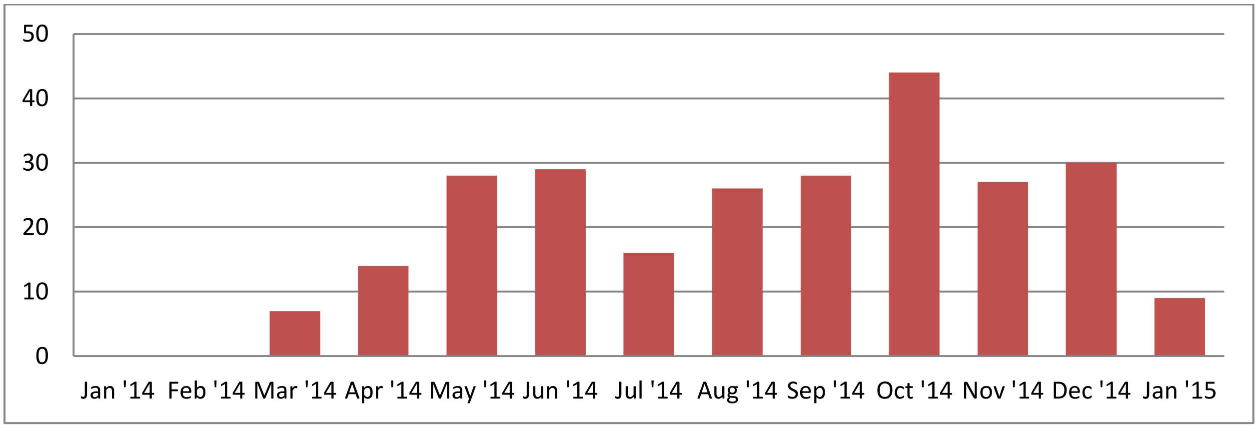
17. **Set Point -2 °C – Total Count 214**



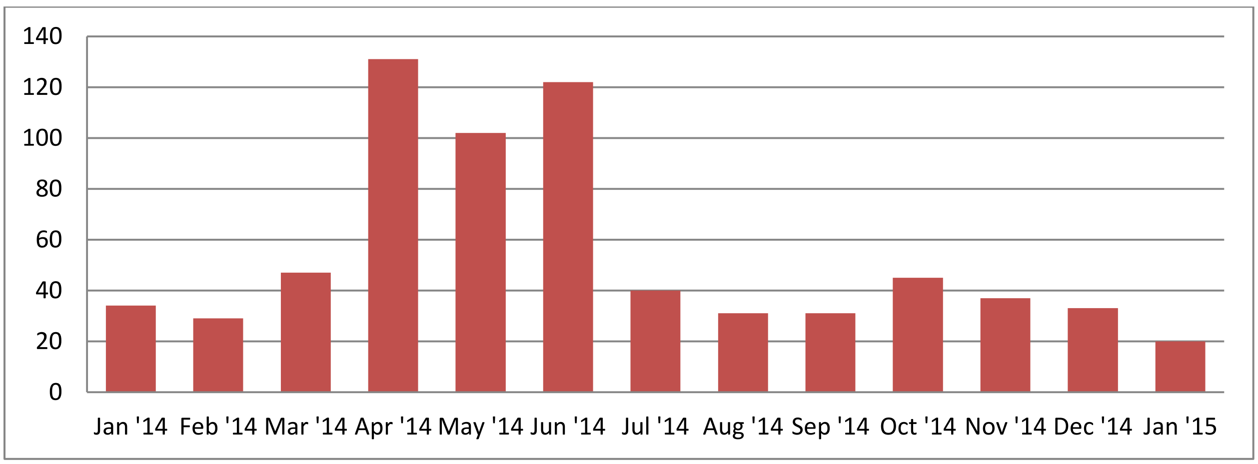
18. **Set Point -1.5 °C - Total Count 367**



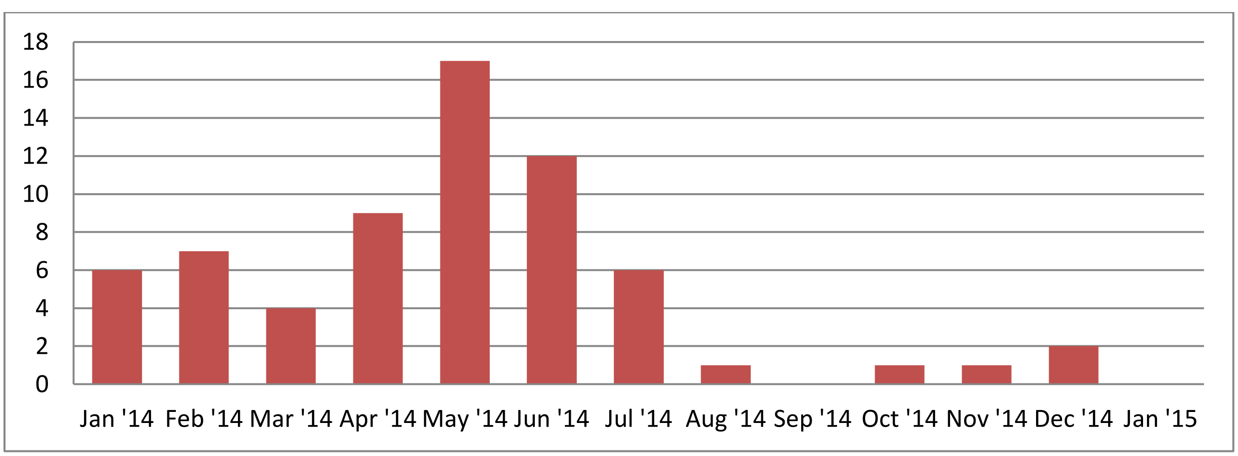
19. **Set Point -1.4 °C - Total Count 258**



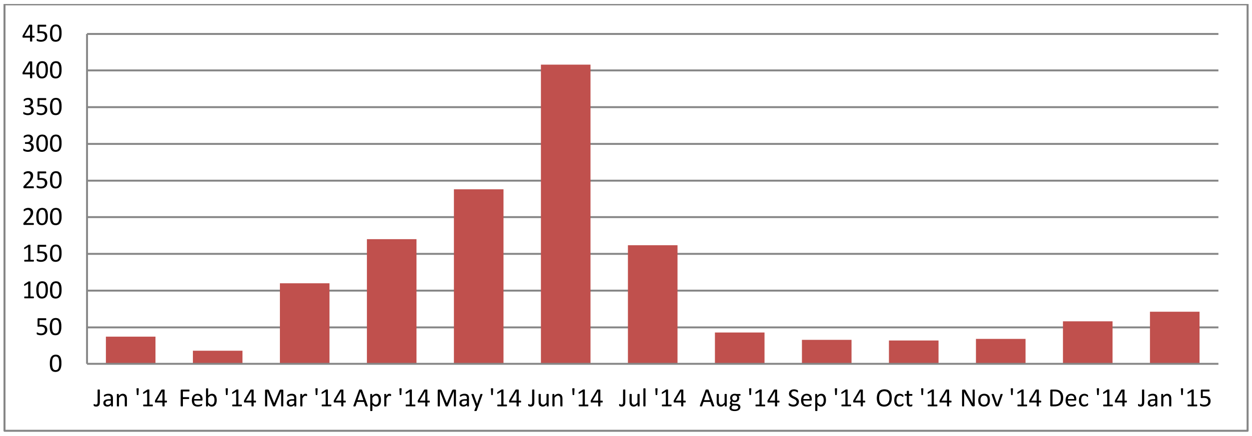
20. **Set Point -1 °C - Total Count 702**



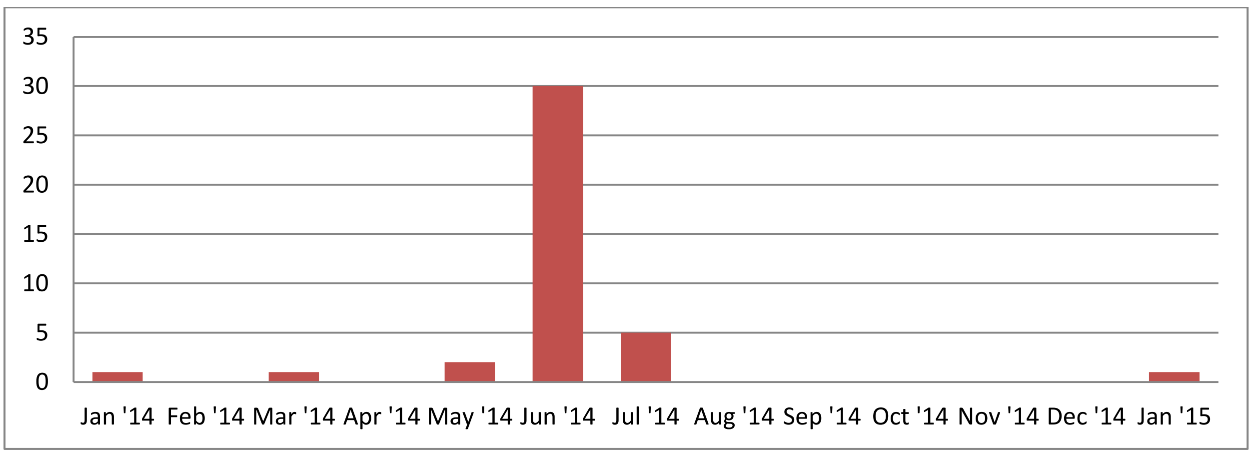
21. **Set Point -0.5 °C - Total Count 66**



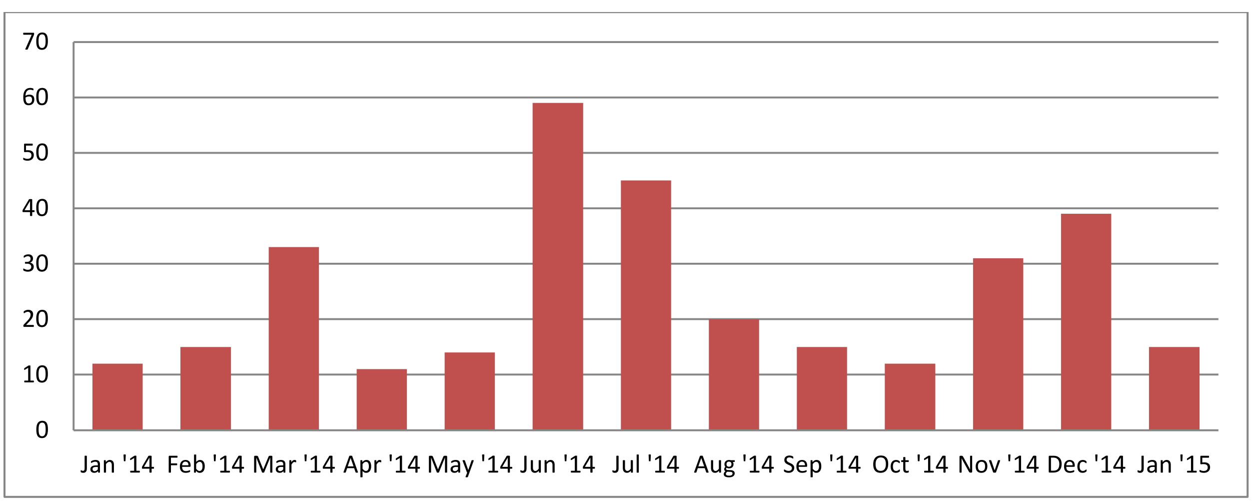
22. Set Point 0 °C - Total Count 1414



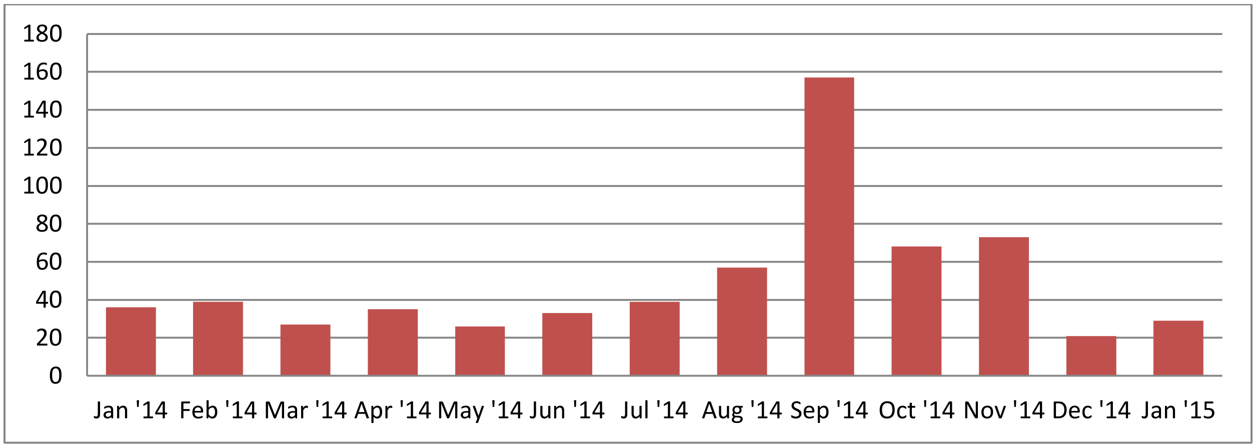
23. Set Point 0.5 °C - Total Count 40



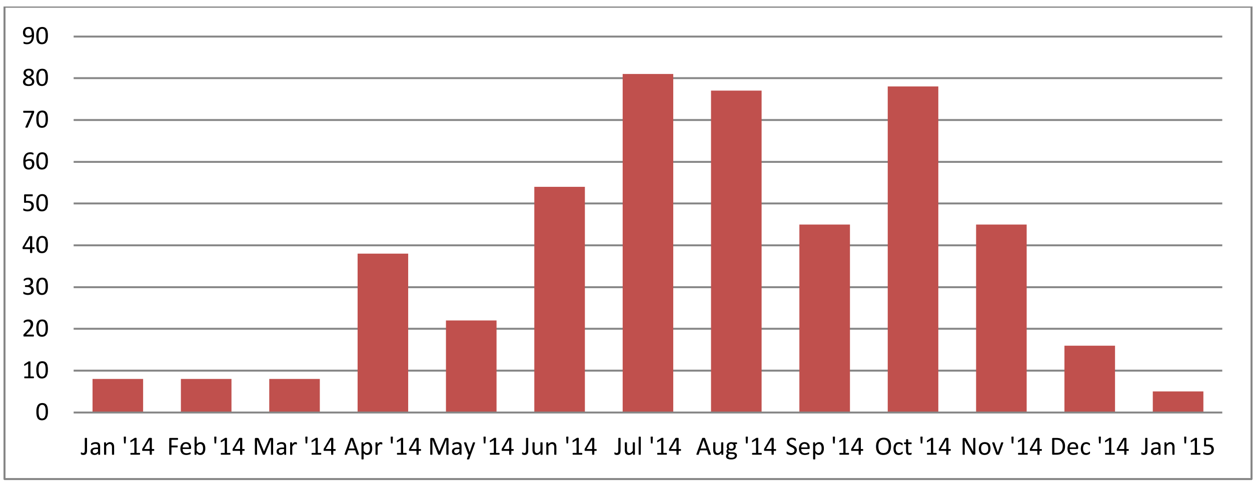
24. Set Point 1 °C - Total Count 321



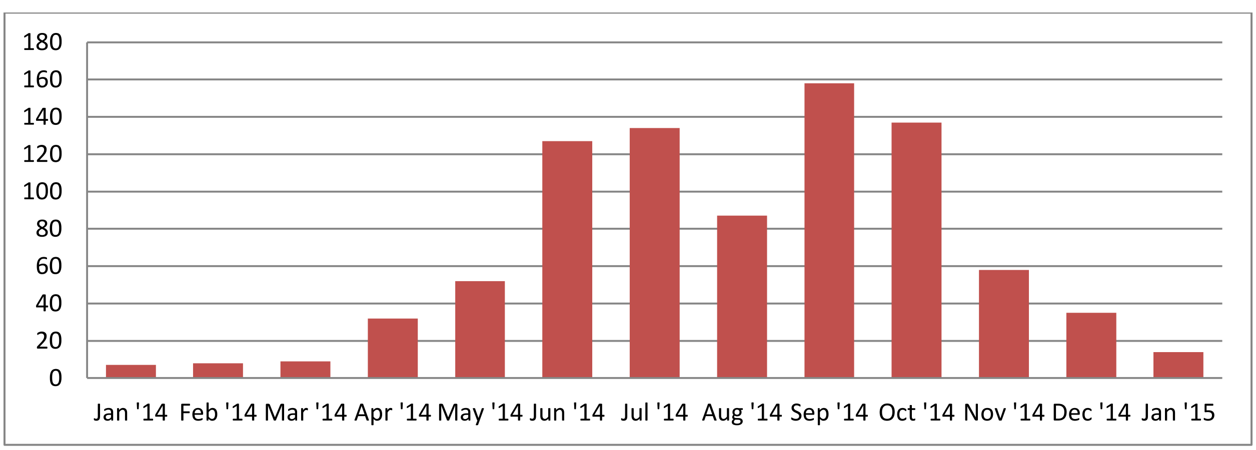
25. Set Point 2 °C - Total Count 640



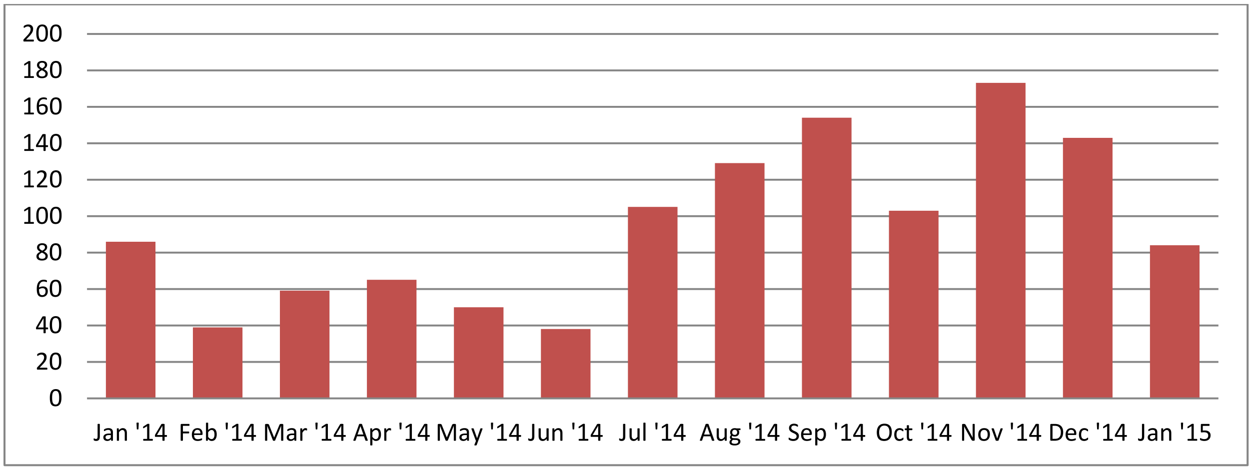
26. Set Point 3 °C - Total Count 485



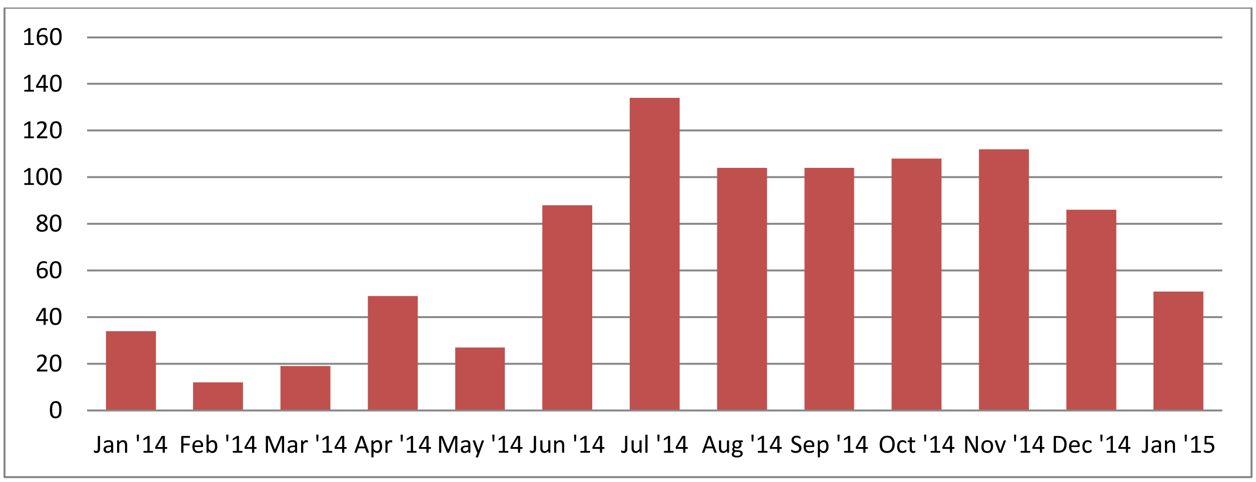
27. Set Point 4 °C - Total Count 858



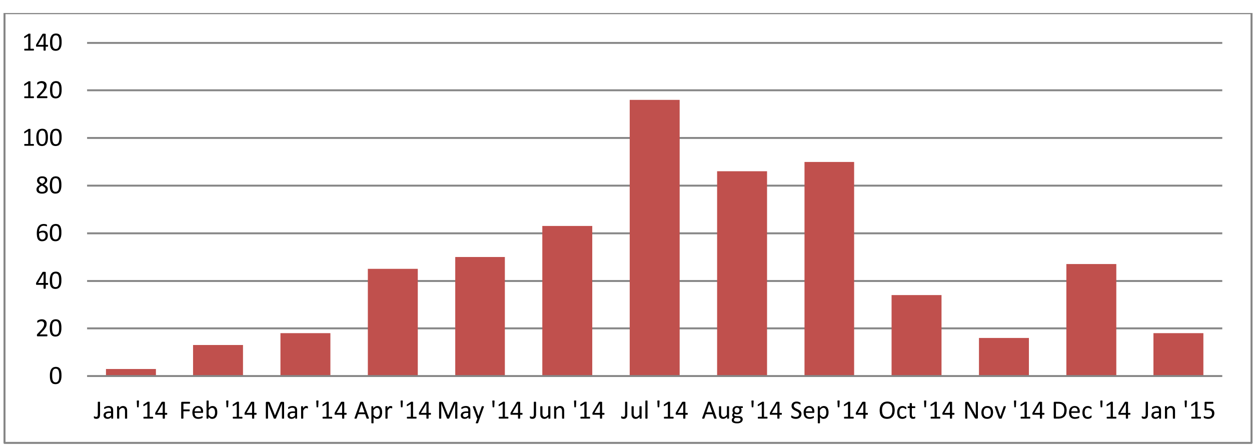
28. Set Point 5 °C - Total Count 1228



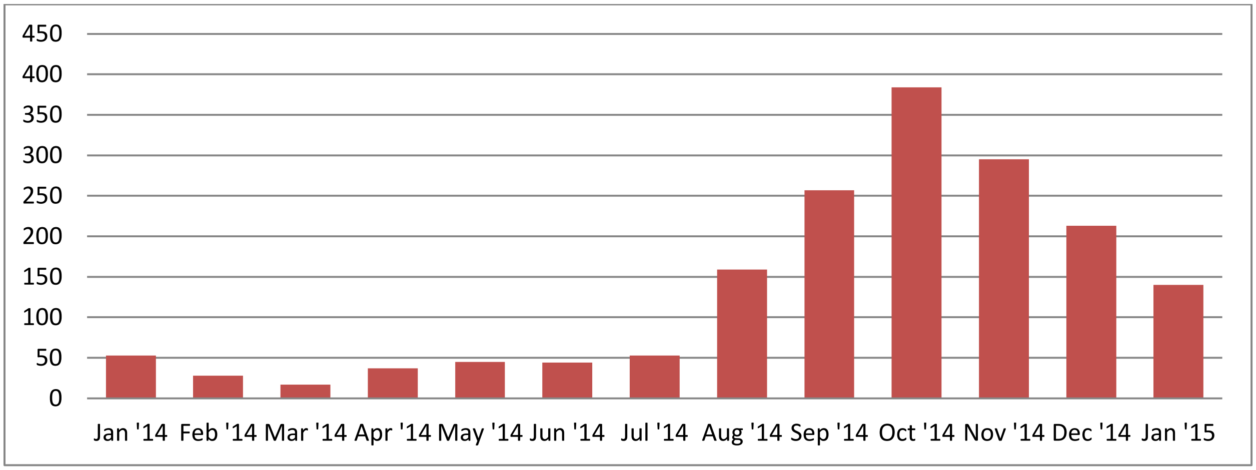
29. Set Point 6 °C - Total Count 928



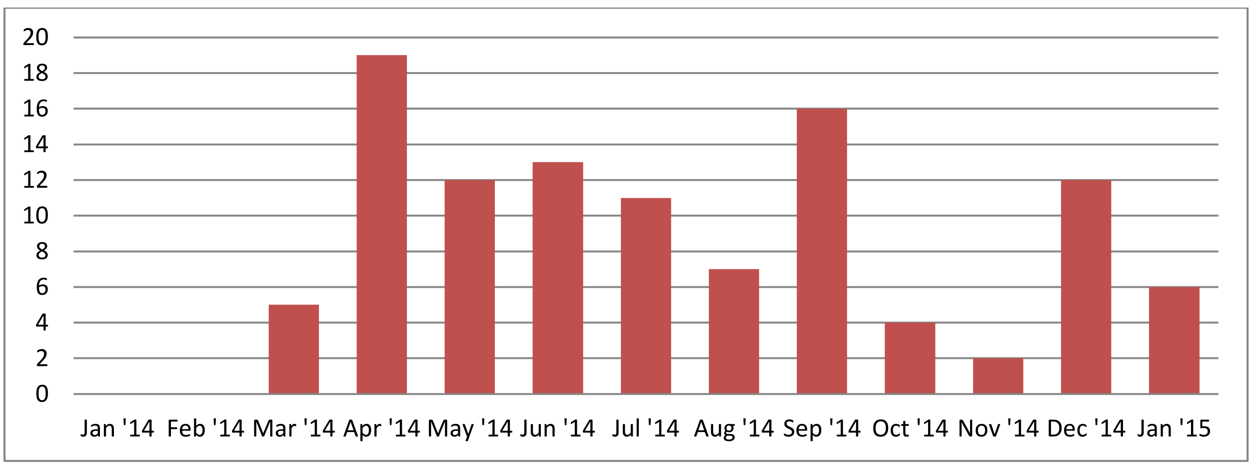
30. Set Point 7 °C - Total Count 599



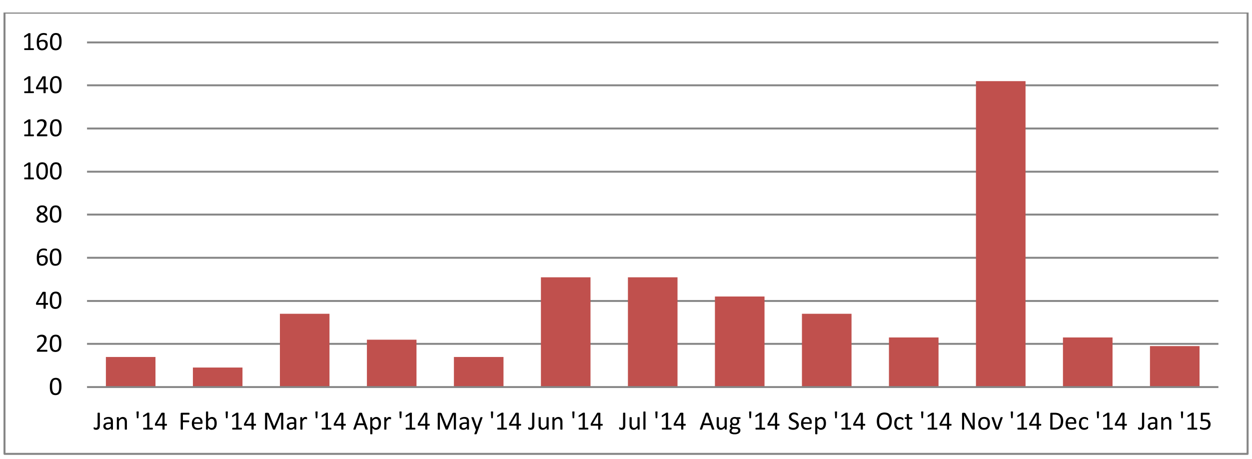
31. Set Point 8 °C - Total Count 1725



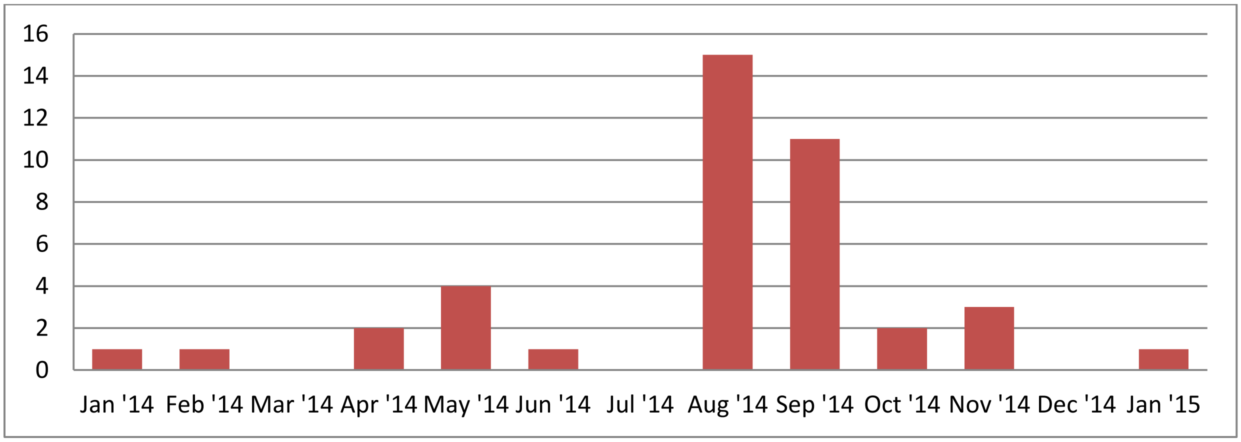
32. Set Point 9 °C - Total Count 107



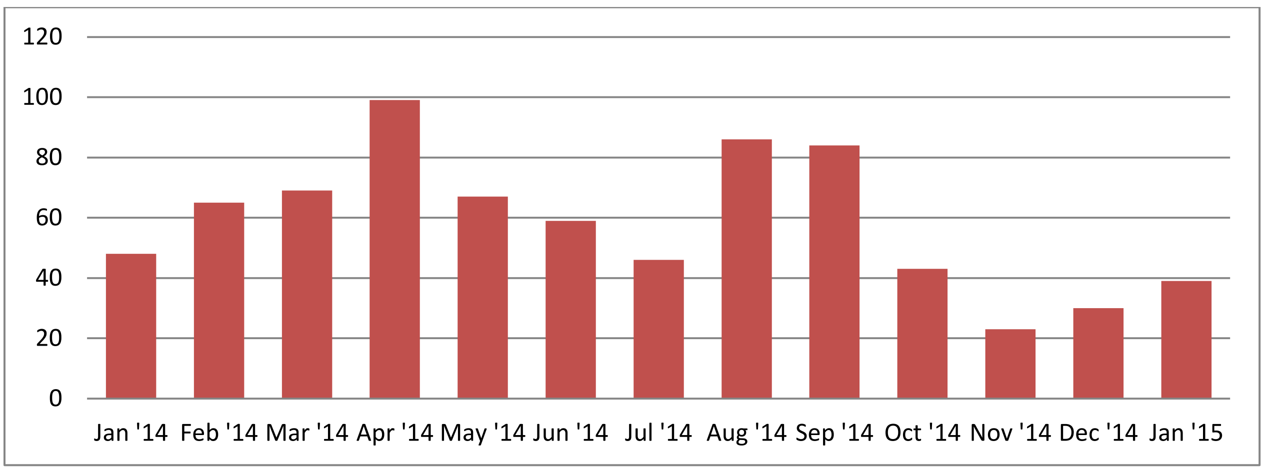
33. Set Point 10 °C - Total Count 478



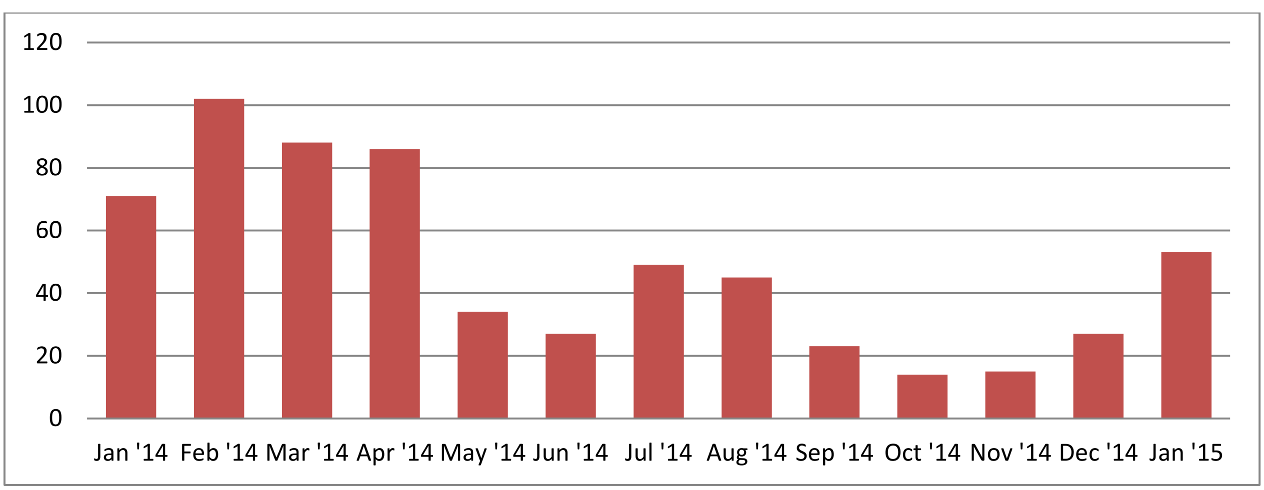
34. Set Point 11 °C - Total Count 41



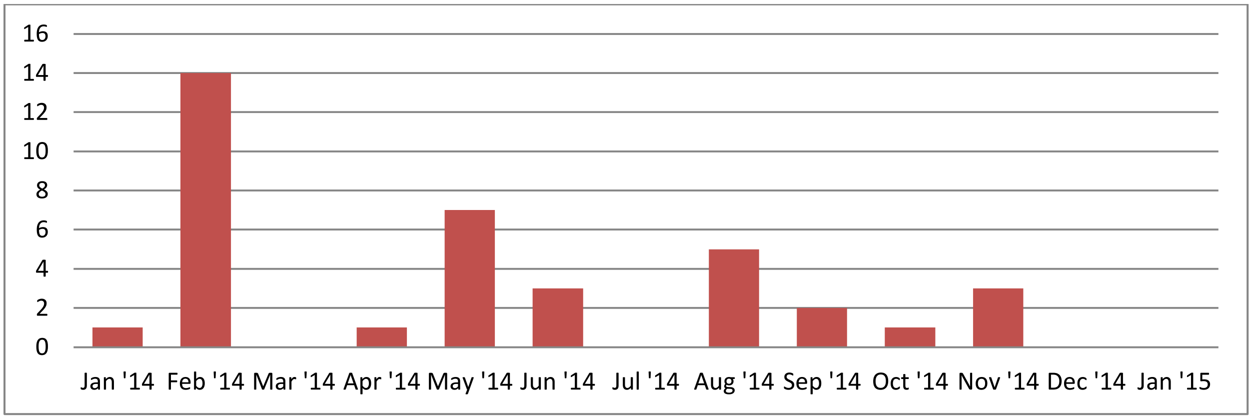
35. Set Point 12 °C - Total Count 758



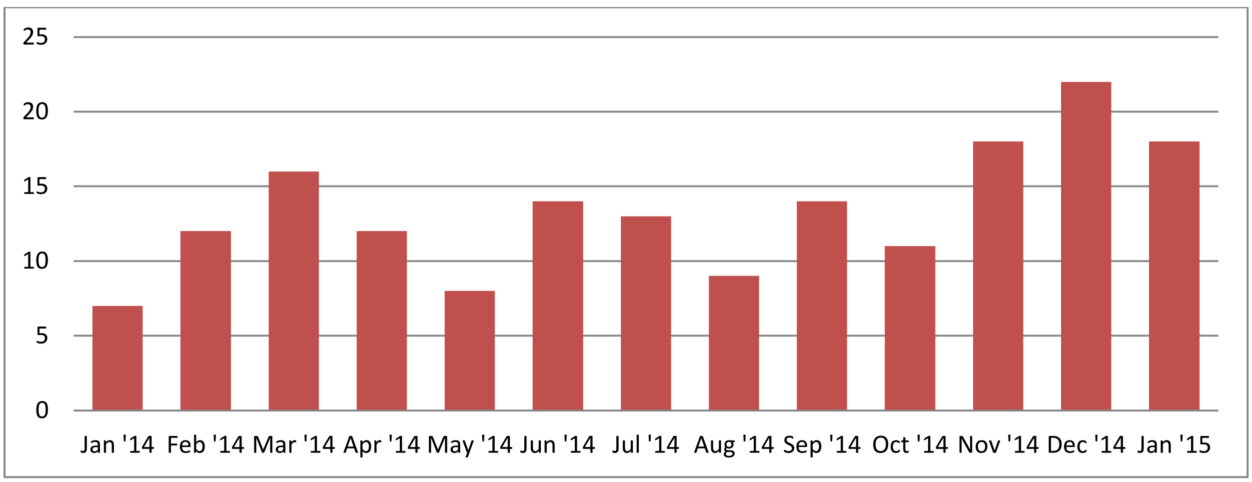
36. Set Point 13 °C - Total Count 634



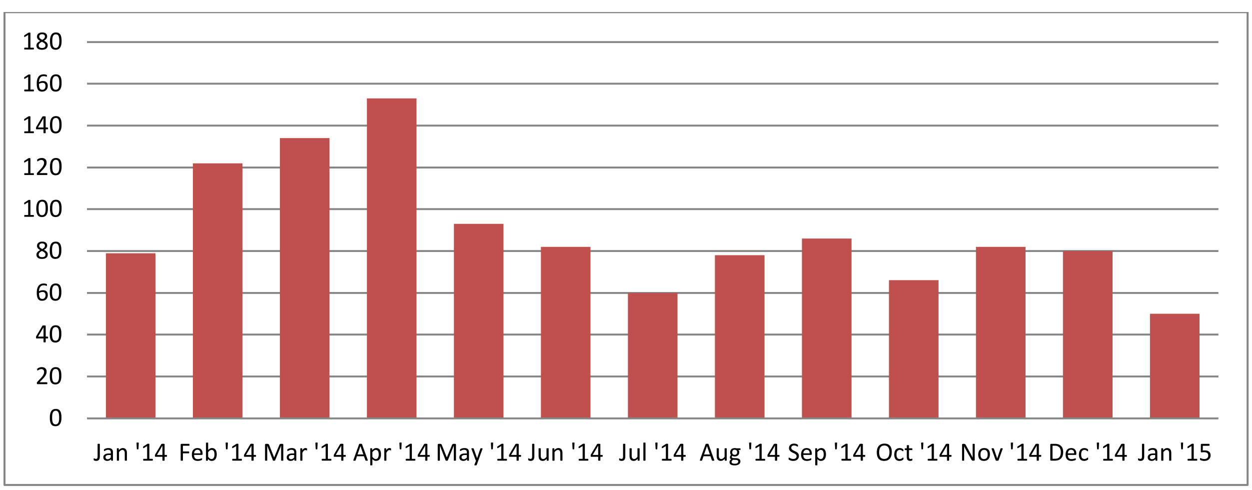
37. Set Point 13.5 °C - Total Count 37



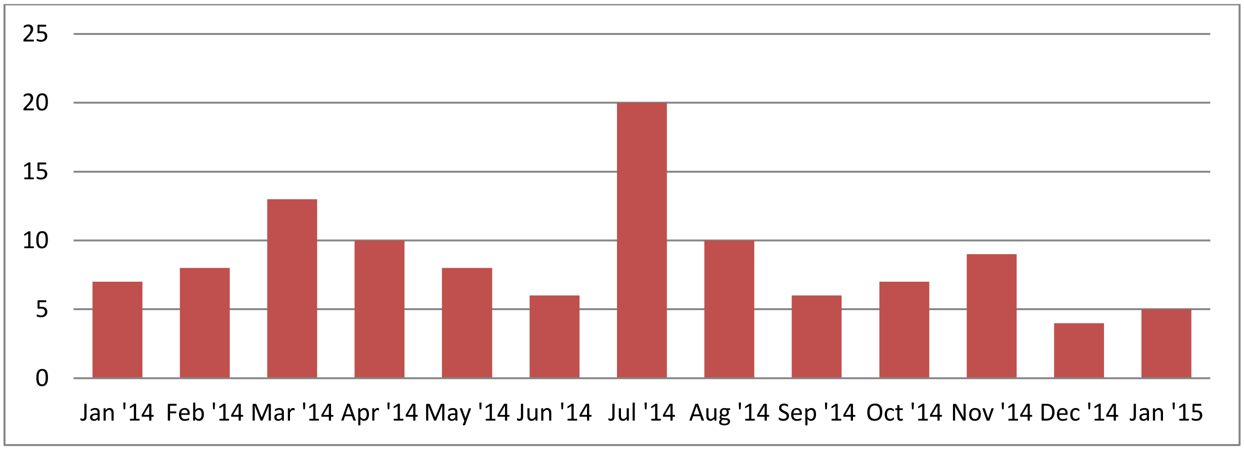
38. Set Point 14 °C - Total Count



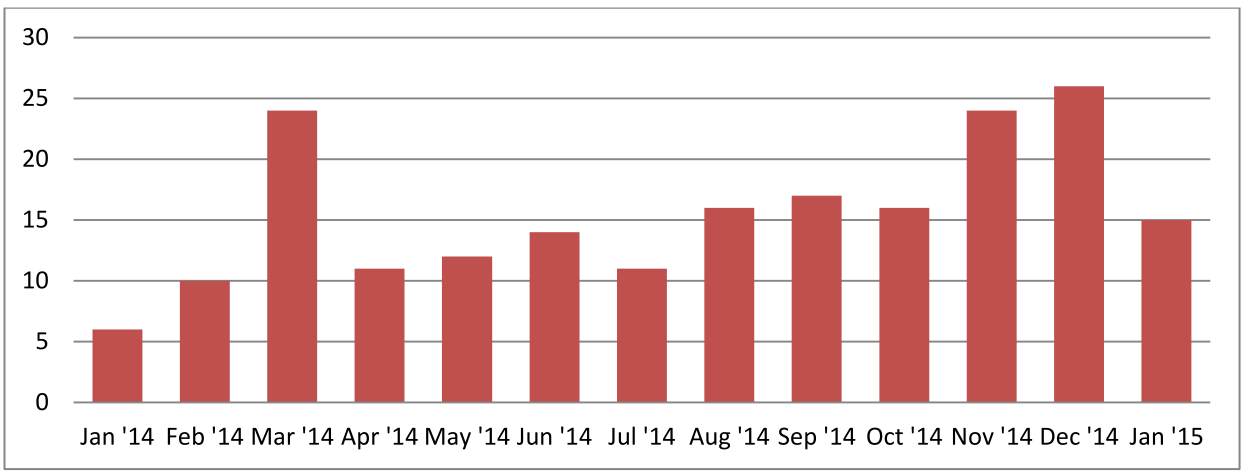
39. Point 15 °C - Total Count 1165



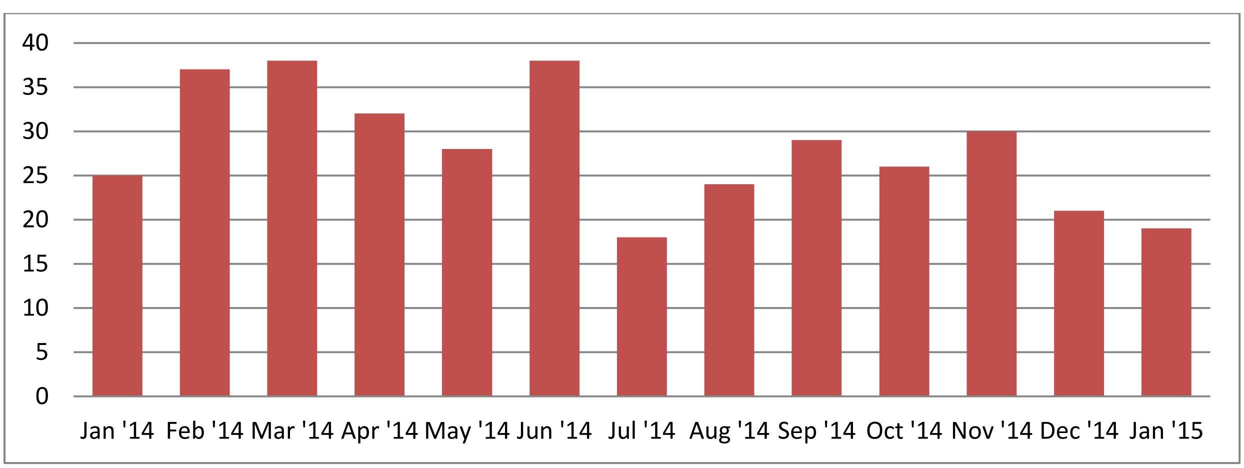
40. Set Point 16 °C - Total Count 113



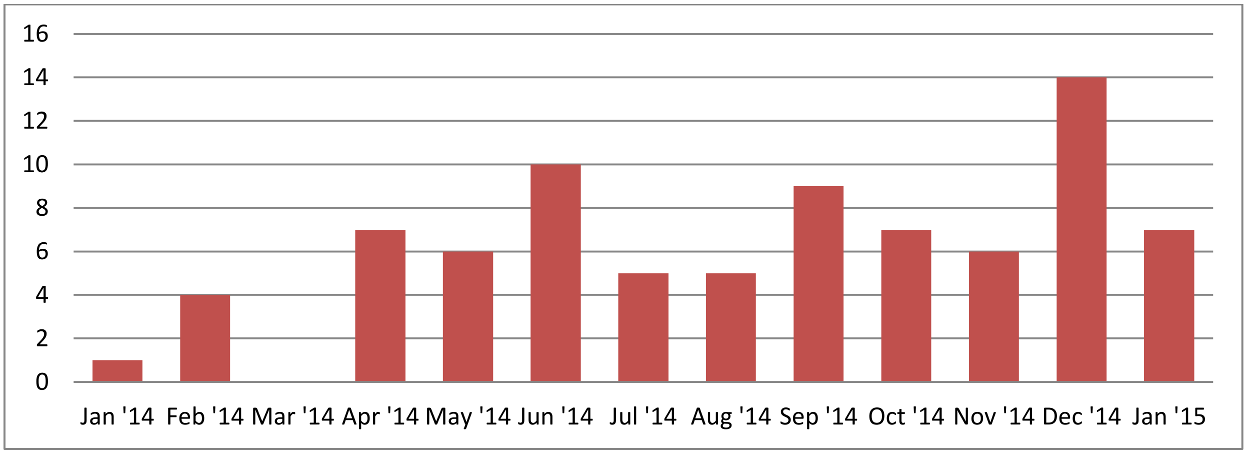
41. Set Point 17 °C - Total Count 202



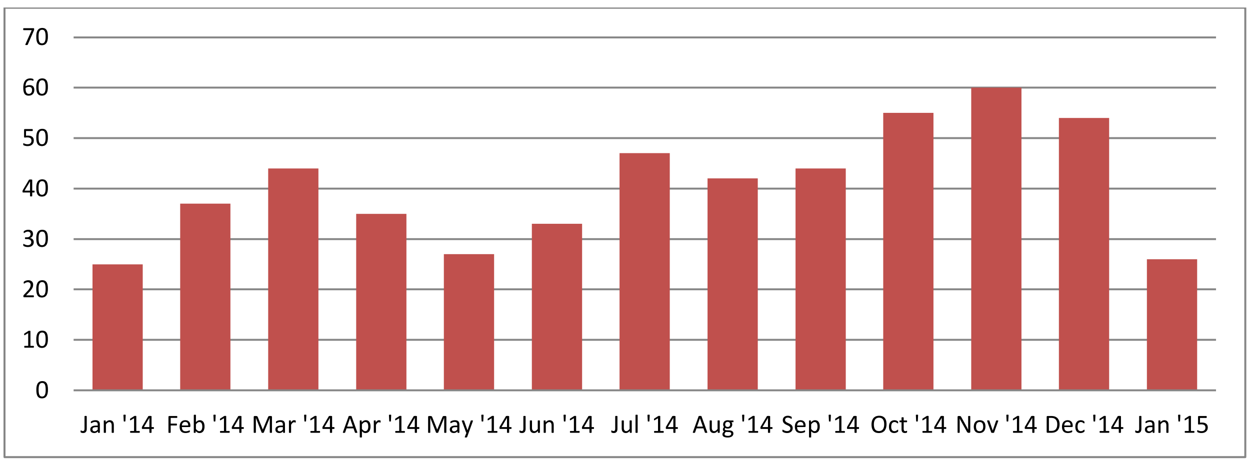
42. Set Point 18 °C - Total Count 365



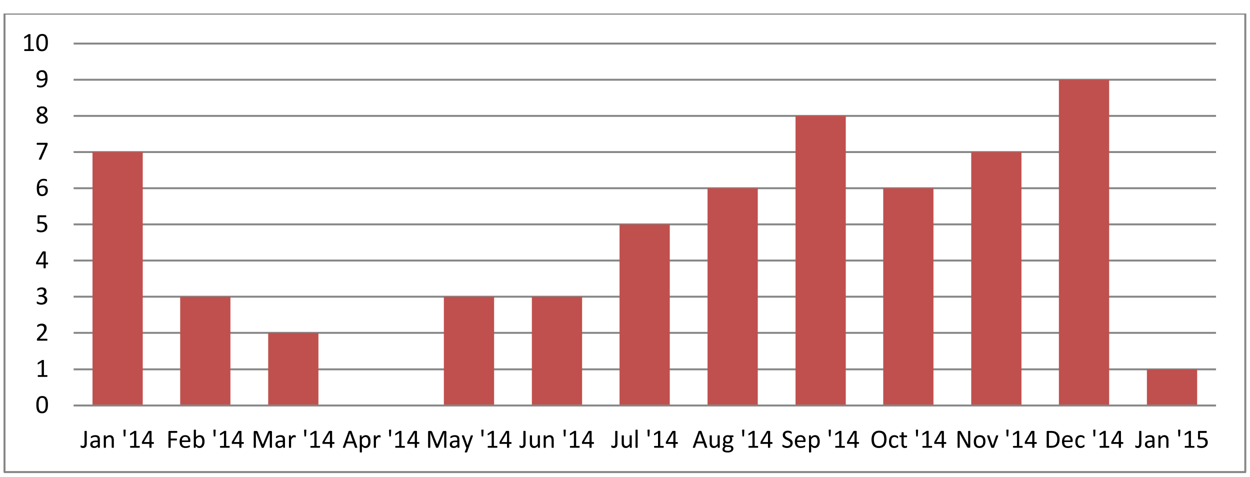
43. Set Point 19 °C - Total Count 81



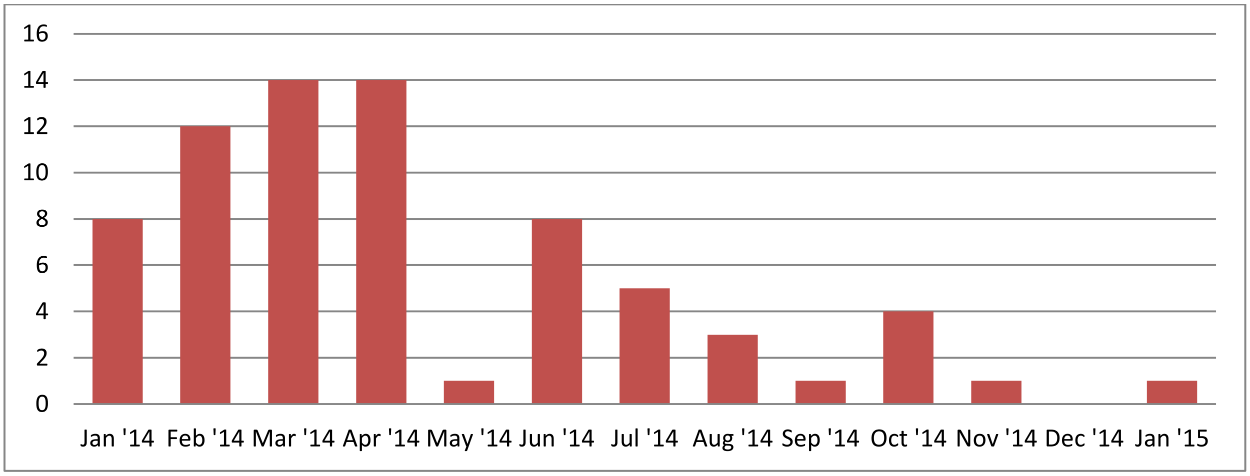
44. Set Point 20 °C - Total Count 529



45. Set Point 22 °C - Total Count 60

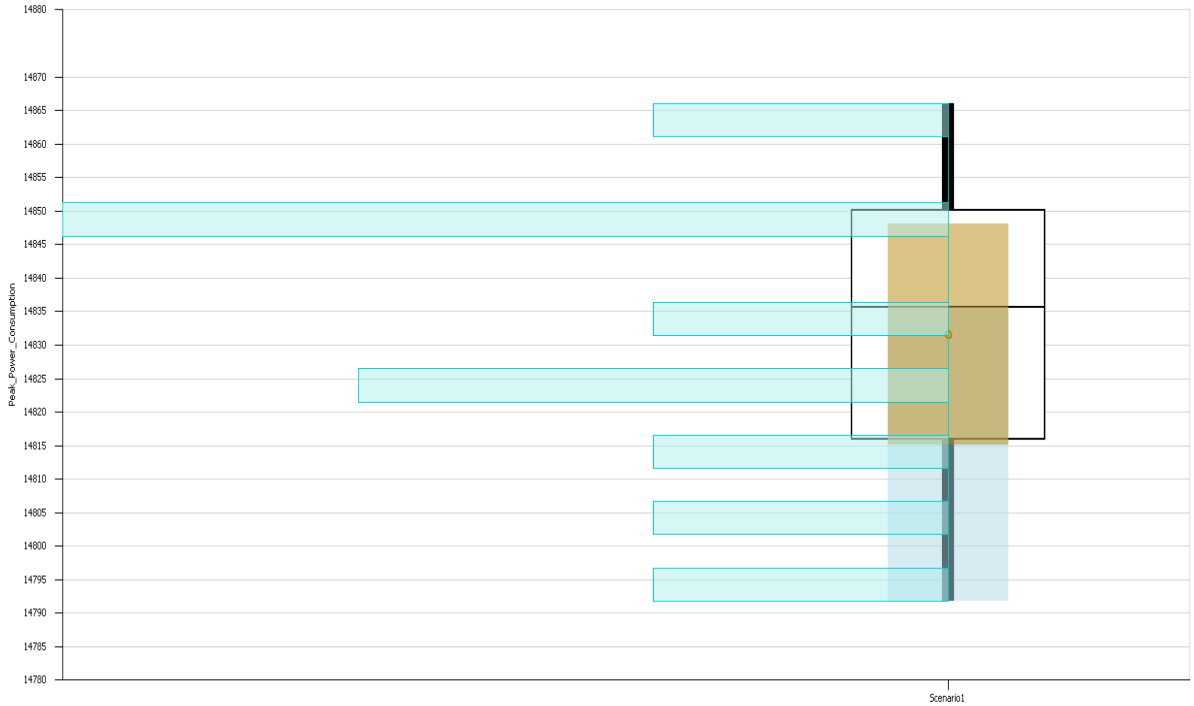


46. Set Point 25 °C - Total Count 72

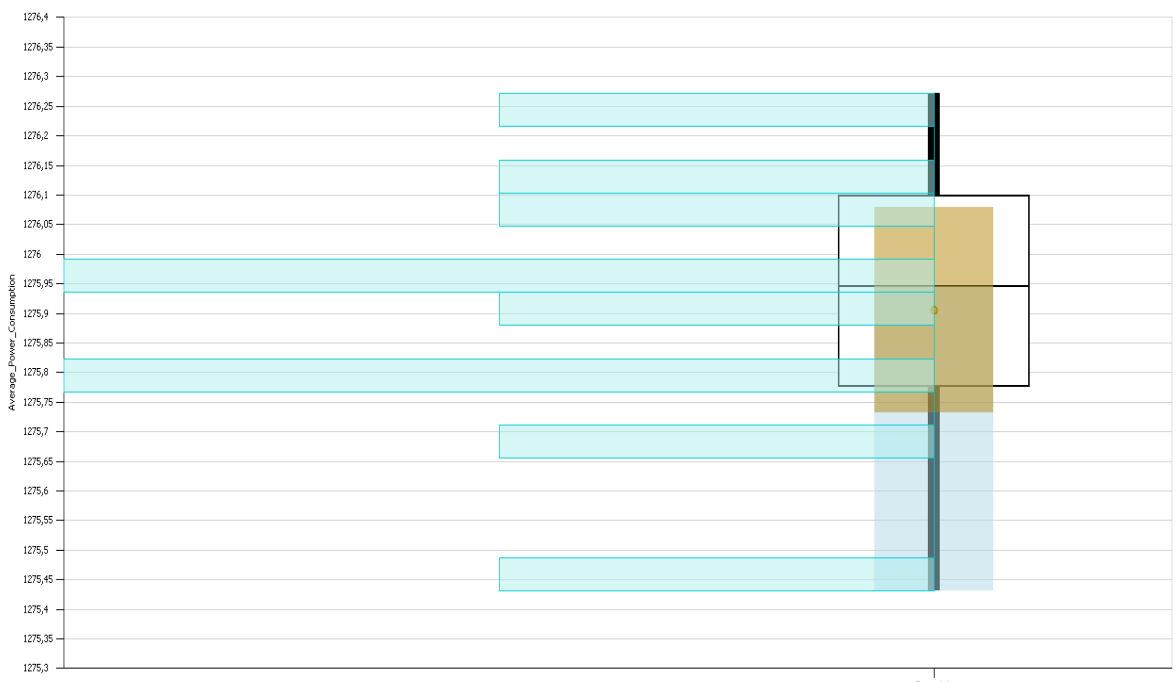


Appendix E. Deviation of Peak Power and Average Power Consumption

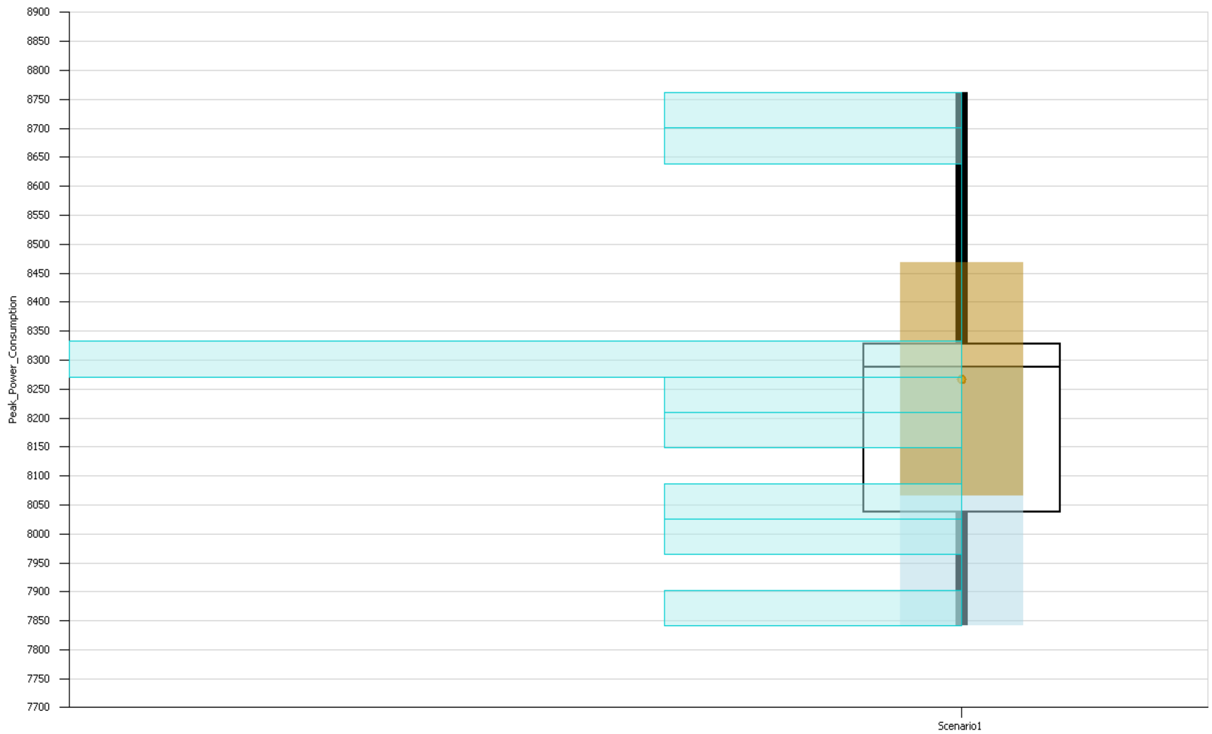
Base Case: Peak Power Consumption



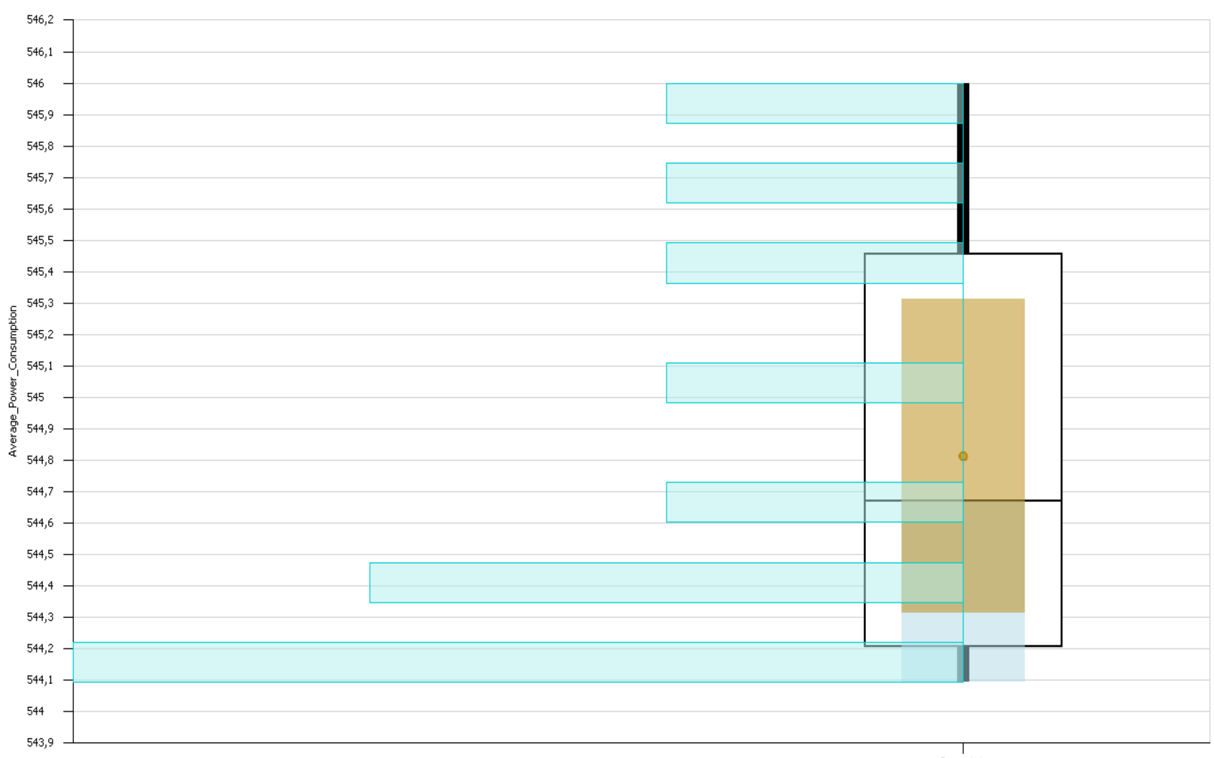
Base Case: Average Power Consumption



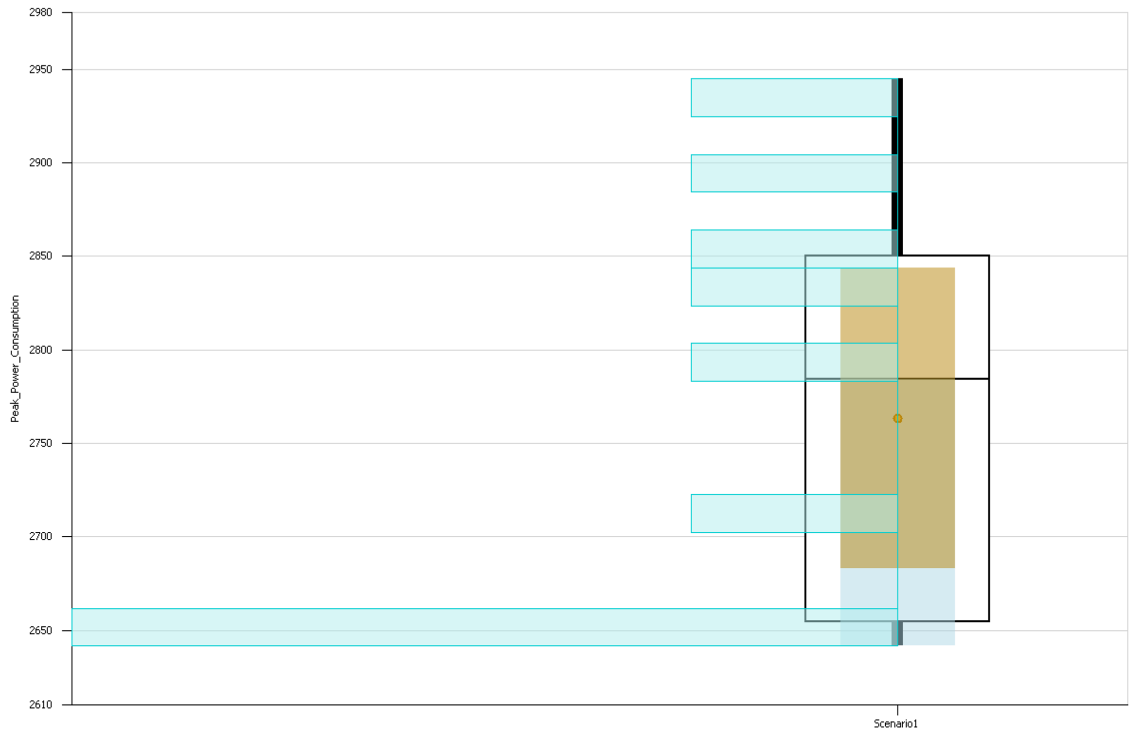
Solution - 1: Peak Power Consumption (Intermitted Power Supply for 15 Minutes)



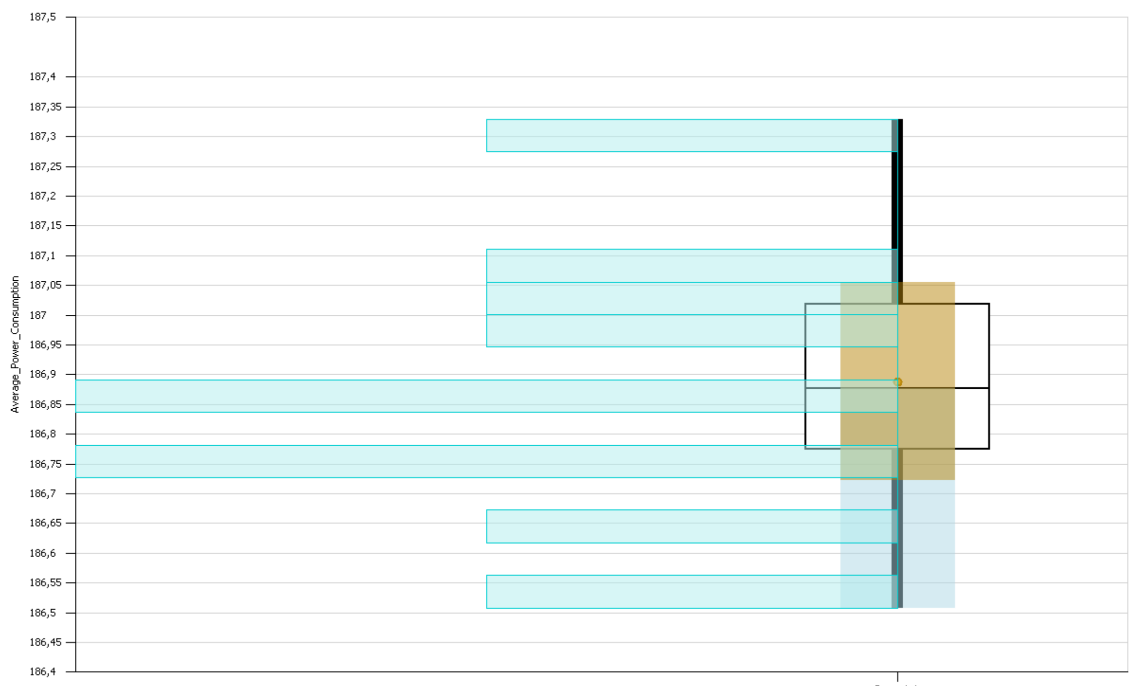
Solution - 1: Average Power Consumption (Intermitted Power Supply for 15 Minutes)



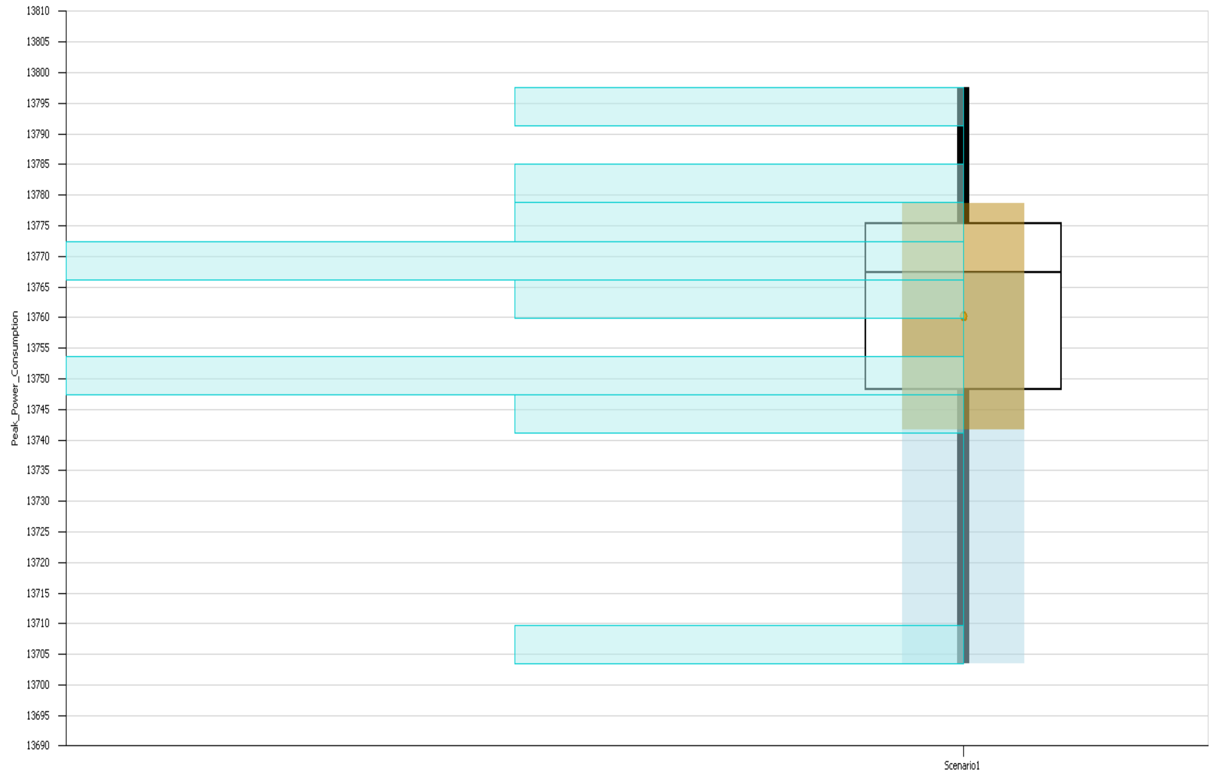
Solution - 1: Peak Power Consumption (Intermitted Power Supply for 5 Minutes)



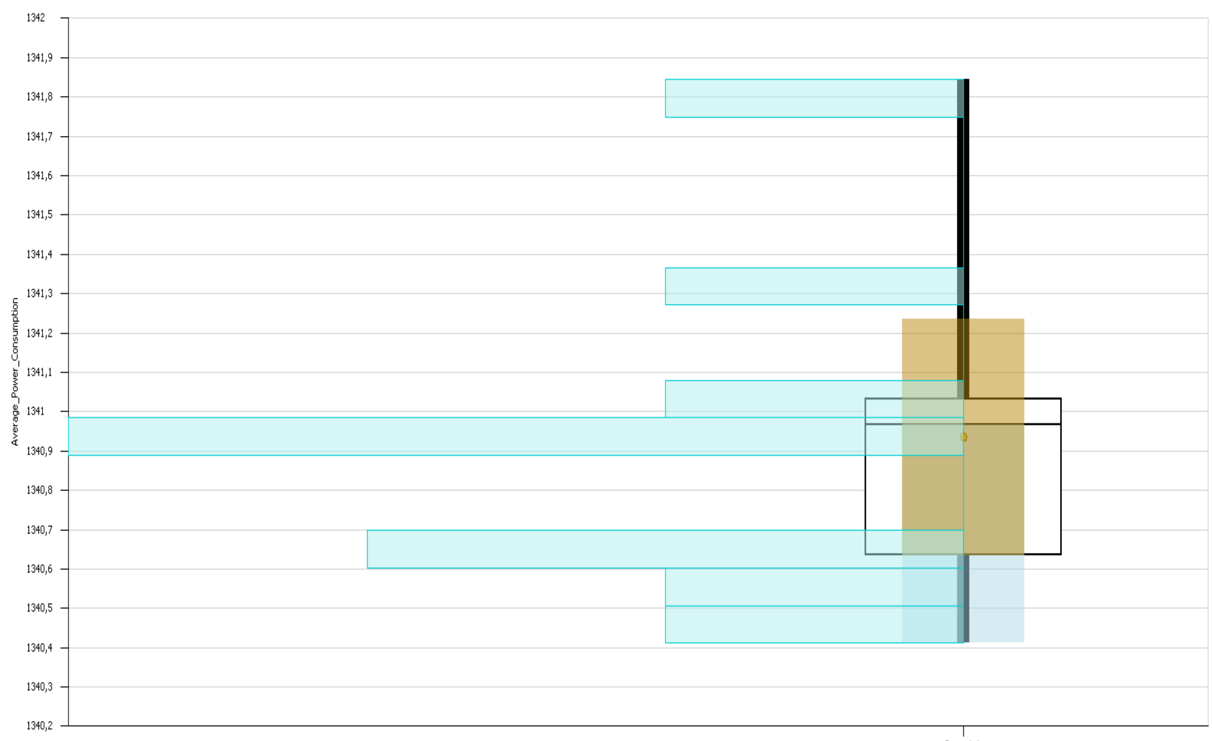
Solution - 1: Average Power Consumption (Intermitted Power Supply for 5 Minutes)



Solution - 2: Peak Power Consumption



Solution - 2: Average Power Consumption



Appendix F. Daily Energy Consumption

Daily Energy Consumption									
	Base Case			*Solution -1 (15 – Minutes)*			*Solution - 2*		
Date	Day	Night	*Monthly Energy Consumption (kWh)*	Day	Night	*Monthly Energy Consumption (kWh)*	Day	Night	*Monthly Energy Consumption (kWh)*
1-01-14	1049	2446		999	1910		794	2390	
2-01-14	24893	20154		9035	8400		28046	22313	
3-01-14	19554	12651		9025	4767		20100	14570	
4-01-14	5761	15771		2903	7911		5974	15864	
5-01-14	4510	2722		2582	1759		4738	2914	
6-01-14	4507	7829		2280	2868		4560	7729	
7-01-14	5479	11100		2883	5920		5239	10665	
8-01-14	12469	7179		6351	2824		13576	8931	
9-01-14	17055	13788		8526	6139		16710	12288	
10-01-14	23801	1455		11045	1073		24856	2214	
11-01-14	4522	1777		1961	876		3983	1952	
12-01-14	5893	5849		4094	2601		4100	6229	
13-01-14	15332	10371		8570	5931		17282	9713	
14-01-14	6498	4029		3453	1850		5543	3952	
15-01-14	12362	18178		6105	7479		11832	19200	
16-01-14	18937	11072		10220	6143		22373	11953	
17-01-14	7530	11947		4097	6189		8209	12610	
18-01-14	16875	230		8004	50		18564	276	
19-01-14	7662	4450		5307	2666		8843	4874	
20-01-14	7765	6456		4944	3296		7954	6961	
21-01-14	8312	1482		5703	832		6637	1800	
22-01-14	17702	7416		10449	3236		18439	8203	
23-01-14	20530	11931		8654	5495		21732	15793	
24-01-14	8627	10614		4826	6663		11900	12950	
25-01-14	3754	857		1533	447		4063	1020	
26-01-14	349	14773		92	7347		172	14399	
27-01-14	5030	2504		1834	2112		4681	2439	
28-01-14	3922	8966		2067	4743		4573	8815	
29-01-14	23911	11519		12912	6447		27870	11997	
30-01-14	12301	19308		4765	8648		11532	19137	
31-01-14	37507	15580	638803	18520	7369	317730	45926	18225	683177
1-02-14	6135	5557		3885	3555		5134	6133	
2-02-14	10636	12135		5188	7375		12185	13553	
3-02-14	3948	1817		2102	1165		3038	2087	

4-02-14	8313	7563		5537	3251		6255	5900	
5-02-14	12586	6928		6261	4073		14110	5167	
6-02-14	9400	8279		5299	4313		9919	10127	
7-02-14	8816	6632		4187	4168		9778	8289	
8-02-14	4052	4724		1670	1922		3443	5481	
9-02-14	777	8984		365	3559		882	7330	
10-02-14	16383	12518		8056	6995		18131	17189	
11-02-14	10975	4153		5092	2809		10413	5438	
12-02-14	6773	6778		2825	3726		6581	10762	
13-02-14	12021	19611		6022	8139		10976	21815	
14-02-14	32661	18476		16442	9525		33555	25439	
15-02-14	3824	3911		1248	1399		3433	4338	
16-02-14	3169	3889		1183	1697		2654	4591	
17-02-14	6080	3952		3336	1768		6008	3557	
18-02-14	11025	5709		4865	2897		11743	5873	
19-02-14	15622	8784		8495	4287		26395	11564	
20-02-14	10827	6365		4776	3500		10217	6990	
21-02-14	18082	7070		7783	2733		17908	8489	
22-02-14	2715	10404		1272	6412		2115	9049	
23-02-14	29635	13310		14708	5472		23611	14264	
24-02-14	6687	1610		3777	607		7156	1750	
25-02-14	7694	25558		1995	13014		8618	22191	
26-02-14	9353	9178		6252	5255		12890	10394	
27-02-14	22771	24903		10494	11925		22064	26173	
28-02-14	16287	5649	561694	6516	2884	278056	14122	6717	593984
1-03-14	16428	3475		8146	1444		16679	3274	
2-03-14	3292	1168		1071	395		3094	1713	
3-03-14	7245	3025		4395	2010		8031	3077	
4-03-14	10895	6503		6677	2914		12108	7374	
5-03-14	6289	16082		3632	5828		8976	17515	
6-03-14	24804	8250		14251	5407		25926	9527	
7-03-14	15763	4883		8406	2436		15248	5205	
8-03-14	1588	7376		1356	4802		1400	6758	
9-03-14	135	2742		75	1797		150	2675	
10-03-14	2494	3448		727	1186		2518	3097	
11-03-14	17824	15558		8271	11621		22709	16505	
12-03-14	8879	7130		5172	2811		11036	7607	
13-03-14	14180	4884		8342	2805		12814	5685	
14-03-14	17550	8408		8584	4200		16411	9454	
15-03-14	8253	5938		4041	2935		7541	11469	
16-03-14	24667	10147		13066	4286		25417	15047	

17-03-14	8064	2705		2848	1730		10370	2786	
18-03-14	12384	5400		6396	2633		13703	6744	
19-03-14	7204	12773		3718	6304		7387	12239	
20-03-14	15868	4425		7995	2519		22429	4122	
21-03-14	9416	26644		3527	12792		8717	27260	
22-03-14	11556	817		5875	222		12379	552	
23-03-14	8155	2432		4339	1410		7656	2968	
24-03-14	5691	4301		3114	2137		5591	5586	
25-03-14	8046	7237		3488	4334		7049	8330	
26-03-14	8029	20331		3071	8870		7966	18523	
27-03-14	12811	5984		5231	4150		14554	6800	
28-03-14	8974	5894		5421	3348		8710	5718	
29-03-14	27456	22356		13203	11538		29109	24956	
30-03-14	3509	712		1700	450		3910	750	
31-03-14	3395	2645	564517	1472	995	287919	2985	2787	608676
1-04-14	9101	3967		5044	2719		9694	4035	
2-04-14	9523	23505		5311	12059		9495	24397	
3-04-14	18135	9599		8710	4635		19586	11070	
4-04-14	5669	10995		3111	6179		4882	12050	
5-04-14	1037	10346		794	6870		1381	8903	
6-04-14	9365	1711		4750	762		9371	2047	
7-04-14	5988	5977		2196	3683		6212	6701	
8-04-14	6363	10952		3011	5701		6101	9104	
9-04-14	9410	9229		5562	4773		8632	10032	
10-04-14	27237	14703		13459	7027		29932	19067	
11-04-14	10148	11352		3520	3729		11556	9714	
12-04-14	17251	7515		10183	3436		19385	10077	
13-04-14	3637	2841		1317	1555		4200	3317	
14-04-14	3351	3729		1732	1732		3400	3542	
15-04-14	17612	6649		9026	3841		18913	7330	
16-04-14	25632	6065		13941	3314		32268	8366	
17-04-14	43947	10487		22090	5694		44800	11341	
18-04-14	8857	4855		4237	2626		8339	4656	
19-04-14	3854	9259		1642	4232		3541	9293	
20-04-14	3477	8247		1380	5238		3312	7336	
21-04-14	4240	783		2262	579		3724	770	
22-04-14	22499	14146		9467	6642		20267	13775	
23-04-14	15923	14806		7630	8604		17202	14314	
24-04-14	28682	17765		16277	10423		35257	17581	
25-04-14	12809	9886		6565	4131		17263	12868	
26-04-14	5584	4052		4164	2714		8637	3906	

27-04-14	5692	450		3344	75		6949	557	
28-04-14	3761	29370		2238	12034		4279	27965	
29-04-14	19083	9746		10105	4819		21014	9476	
30-04-14	14341	12306	657501	8203	3321	334418	14827	13984	701993
1-05-14	19231	5073		8073	2495		18505	9017	
2-05-14	10931	6933		5329	3731		11754	5395	
3-05-14	18544	3319		9154	2508		17694	3235	
4-05-14	6566	10421		4584	4597		6002	10286	
5-05-14	8246	6475		4919	2708		8114	5991	
6-05-14	12028	11092		5663	6475		12230	12075	
7-05-14	7354	9183		3457	6731		6808	10148	
8-05-14	32044	11932		14778	6004		29922	15188	
9-05-14	13837	9145		6329	3617		14928	11484	
10-05-14	5628	6577		1971	3411		5033	8458	
11-05-14	1930	2231		987	675		1535	2253	
12-05-14	12961	4401		7217	2124		10644	5883	
13-05-14	9977	8879		4251	4063		8792	9734	
14-05-14	13687	2822		6446	1460		12241	3680	
15-05-14	46014	12427		24802	6228		52555	14212	
16-05-14	21176	5244		8797	2246		26073	5219	
17-05-14	9404	1659		4404	857		9768	1562	
18-05-14	925	412		777	142		1122	370	
19-05-14	7727	2657		4240	1505		9157	4072	
20-05-14	8446	12729		4431	7319		7211	13360	
21-05-14	15488	9908		8134	4900		14947	9947	
22-05-14	33355	16946		18391	10265		30432	19532	
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24-05-14	23659	16730		13470	8688		23610	19428	
25-05-14	10944	637		6598	445		12944	595	
26-05-14	16677	6373		7578	5140		16537	7684	
27-05-14	5272	16153		2546	8961		4412	18902	
28-05-14	24585	29063		11129	15661		26179	31334	
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2-06-14	5806	5801		2488	2189		4962	5185	
3-06-14	7161	17759		4271	9584		6840	13209	
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5-06-14	30805	6091		16186	3310		28728	6034	
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7-06-14	9763	18083		4442	12906		11233	21268	
8-06-14	4503	5155		2987	3246		1598	4318	
9-06-14	10188	4293		4774	2522		11597	7918	
10-06-14	7031	3071		3146	1819		6810	3705	
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12-06-14	81295	45266		35065	19683		82702	53291	
13-06-14	31026	14449		14789	5889		32738	16075	
14-06-14	31564	15175		16166	8887		34410	16732	
15-06-14	5433	5589		2813	2556		7328	4309	
16-06-14	14056	12739		6015	8618		17644	15633	
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Cost	559470,6	258633,4		278445,1	130326		577026,3	278375,5	
Energy Cost		818104			408771			855401	
Peak Cost		272160			0			0	
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