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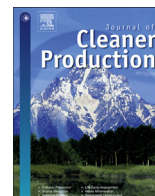
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Cooling down: A simulation approach to reduce energy peaks of reefers at terminals

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ABSTRACT

The increase in population, high standards 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 (reefers) play an important role, due to their ability to maintain the quality of product throughout the journey. However, the transportation and operation of reefers requires a constant supply of power throughout the supply chain. This results in a significant energy consumption by reefers. When large numbers of reefers are involved, this results in high amount of energy consumption at terminals as well. From a terminal perspective, the monthly throughput of reefers shows a lot of variation due to the seasonality of food products. As a result, 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 utility companies apply extra charges for the highest observed peak demand, it is beneficial for terminals to keep this demand as low as possible to reduce energy costs. There is no prior research on peak energy consumption caused by reefers at a terminal. To investigate the opportunities for container terminals to reduce their peak demand, an energy consumption simulation model is developed. With the model two energy reduction strategies are tested to analyze their impact on peak demand: intermittent distribution of power among reefer racks and restriction of peak power consumption among operating reefers. Both strategies show significant opportunities for cost reductions.

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1. Introduction and motivation

Transport plays a crucial role in modern society. A well-functioning maritime transportation system facilitates the process of globalization and ongoing economic growth. Much of the world's welfare today has been supported by or at least facilitated by sea-ports and their related activities: ports are the locations where trade, logistics, and production converge. This growth is especially reflected in the increase in container transport over the last decades, and this can be considered a reflection of the economic dynamics whereby ports have become a motor for economic progress

(Hou and Geerlings, 2016).

Looking at the process of containerization one can observe a number of important developments. There is an increasing demand for 'conditioned transport' with a temperature that varies between −60C and +14C degrees, where the refrigerated containers are called 'reefers'. The United Nations Conference on Trade and Development (UNCTAD, 2015) reports 1.5% as the refrigerated cargo share of the total dry cargo for the years 2000–2015, with an annual growth rate of 45%. The proportion of reefer market share in total conditioned shipping transport increased from 47% in 1990 to 75% in 2014; and it is expected that in the coming 5–10 years global growth will be around 8% per year (Rodrigue and Notteboom, 2014). This is partly due to the fact that fresh logistics chains are based more and more on the export of fruit and vegetables from Africa and Middle and South America (see Fig. 1).

The entrepreneurs in these countries have a clear focus on the

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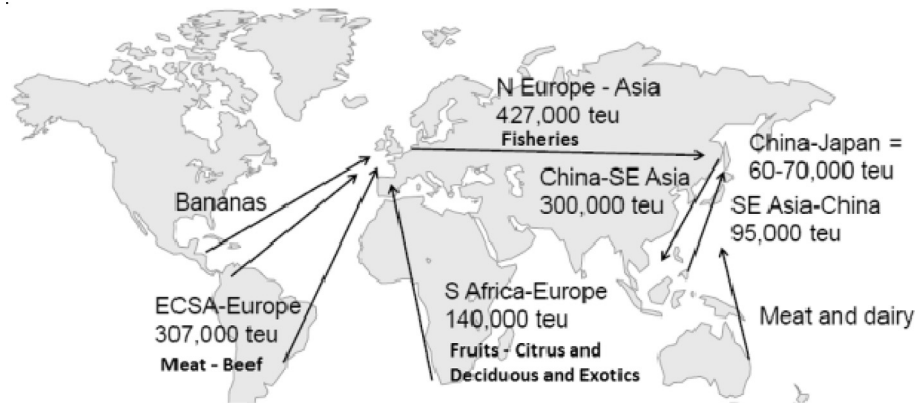


Fig. 1. Global trade of reefer fleets (Rodrigue and Notteboom, 2014).

European market in general and its unique infrastructure (auctions system, the unique configuration of actors in the ‘fresh sector’, the logistics system, and so forth). Reefers contain different categories of products, each of which requires a pre-determined cargo storing temperature, humidity level, and air exchange rate (Hamburg Sud, 2010). Also, each of them has a different sensitivity to temperature fluctuations. Rodrigue and Notteboom (2014) have classified products based on their temperature class, including perishable goods such as food, flowers, fruit, and vegetables, but also medicines (including plasma) and musical instruments (see Table 1). New conservation developments in conditioned transportation (as observed for instance in the flower industry) makes a modal shift possible from fast air transport towards slower but cheaper deep-sea transport.

The growth in conditioned transport across the globe has led to a tremendous increase in the size of the reefer fleet. This fleet increased from 294,000 TEUs in 1990 to 1,215,000 TEUs in 2005, signifying a growth of 313% over this period, mainly caused by a shift from traditional reefer vessels to container vessels. By January 2012, this figure had reached 2.1 million TEUs. This rapid growth in container vessels increased the reefers’ market share in the total container fleet from 7% in 2012 to 11% in 2012 (World Shipping Council, 2011). The seasonality of food products further affects the movement of these fleets. The different temperature requirements of many of these products lead to variation in reefers’ power requirements. As the transported products are also highly sensitive to temperature variations, there is a small bandwidth time to switch them on or off. The nature of the cargo, e.g. chilled/deep frozen or pre-cooled/not pre-cooled, the insulation/age of the reefer, and the ambient temperature are other factors that strongly influence energy consumption; and energy consumption at port terminals has increased accordingly. In general, reefers are responsible for about 30–35% of the energy consumption at terminals (Green Cranes, 2013; Geerlings and Van Duin, 2011).

At these terminals, electricity is a primary source of energy used for reefer operations. This electricity is provided by an energy

utility company. The seasonality of reefers means that the energy demand at terminals is very volatile. This volatility in reefers’ energy demand pattern leads to a peak power demand as shown in Fig. 2. 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 level than the average supply level. Peak power fluctuations, which may occur in daily, monthly, seasonal, and yearly cycles, lead to excessive energy costs due to additional peak charges applied by utility companies. Despite these peak power and excessive energy costs, port terminals rarely have energy efficiency measures and strategies in place (Wilmsmeier and Zott, 2014). Neither is there any incentive to change, because the reefer container handling charges usually cover the energy costs comprehensively.

The growth in reefers’ energy demands has led to diversification at terminals. Efficient reefer handling provides a unique selling point and a competitive advantage. However, the reefer cooling process also leads to increased electricity costs due to the volatility in reefers’ power demands. The stringent norms on product quality faced by terminal operators further add to the complexity of efficient reefer energy management. Thus, efforts are needed to reduce the energy costs by lowering reefers’ peak power consumption while ensuring the stringent temperature requirement of the products being transported. Although a lot of research is available on energy consumption of individual reefers, this paper integrates knowledge on individual energy consumption of reefers, simulation modelling and peak shaving to identify improved methods to reduce energy consumption on container terminals. Insights in the (peak) energy consumption for an entire terminal caused by the individual reefers at a terminal was never investigated.

This leads to the following research objective: *to investigate the possibilities for peak shaving the electricity demand at reefer stacks by applying new rules of reefer operation, while monitoring their impact on reefer temperature.*

To answer this question, a dedicated discrete-event simulation model has been developed to represent the volatility in the energy

Table 1

Temperature classification of products and their respective temperature sensitivity (Rodrigue and Notteboom, 2014).

Product	Temperature range (°C)	Temperature 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, paintings	18–21	Low

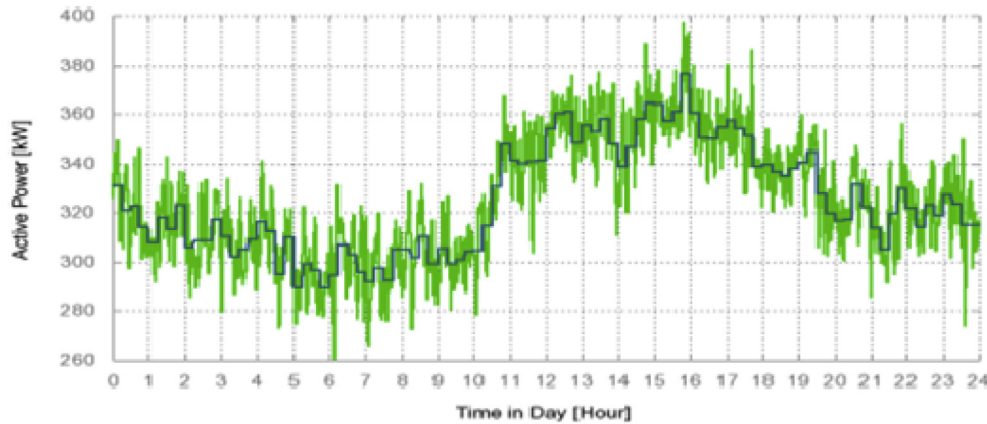


Fig. 2. Volatility in reefers' energy demands at terminals (Tao et al., 2014).

demand of individual reefers at a terminal. To build a bottom-up model of container terminal operations and performances, it is important that the outcomes are valid for all terminal operations. To develop such a model, a systematic and well-structured approach was used to determine the energy consumption of a container terminal as a whole and of the sub-processes. The approach consists of six consecutive steps that together provide a detailed insight into the energy consumption of each of the sub-processes at a container terminal. The six-step approach is congruent with Sargent's modelling paradigm (Sargent, 2013) (see Fig. 3).

Informed by Sargent's (2013) research methodology, this paper is structured in five sections. Section 1 provided information on the research topic, followed by the problem definition and research objective. Section 2 provides a literature review on current energy saving models, followed by specification of the knowledge gaps. In Section 3, following the description of reefer operations, the conceptual model for reefers' energy consumption is developed. This model is implemented and simulated for a reefer system to

generate the energy profile. Finally, the results are obtained from the simulation model and the problem is analysed. In Section 4, peak shaving opportunities are discussed, followed by their analysis and implications. Conclusions and recommendations are given in Section 5.

2. A literature review of methods for reefer energy control

A reefer unit consists of hardware components such as thermal insulation, gratings, and a software component used to control refrigeration. Consequently, two developments relevant to improving the energy efficiency of reefer units are: hardware improvements and software solutions.

Zsembinszki et al. (2014) carried out a numerical model evaluation of a reefer that 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 container material. Further research is investigating the usage of carbon nanotubes as insulation for reefers. However, hardware solutions have reached their potential limit, unless a major breakthrough occurs in material science.

Most reefer energy saving models relate to dealing with optimization of the software that runs the refrigeration unit. Sörenson (2013) has investigated the potentials for reducing energy consumption on a sample Star Cool reefer by introducing modern control methods, without compromising the quality of the transported goods. He has developed a non-linear dynamic simulation including a controller unit. He, finally, 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 the thermal inertia of cargo and the grating ventilation rate to determine the actual demand for the potential reduction in reefers' energy consumption. The most commercially successful energy saving model for reefers has been developed by Wageningen University in The Netherlands. This model is called QUEST, which 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 produce quality (Lukasse et al., 2011). A reefer unit is designed to both freeze and cool. Traditional non-Quest control in chilled mode runs the evaporator fans at maximum speed regardless of load. Therefore, it works less efficiently on partial loads, such as when cooling smaller amounts of

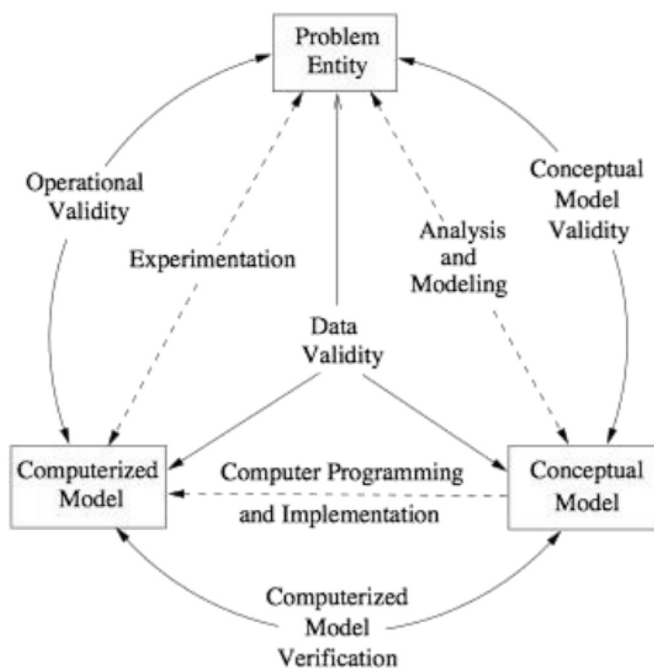


Fig. 3. Simplified model of the modelling process (Sargent, 2013).

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 the correct temperature, so that the quality is not impaired (Lukasse et al., 2011).

The two systems described are based on reefers' individual working. However, they do not take into account a system of reefers operating at terminals. For this, a system named Reefer Monitoring and Control System (REFCON) has been developed. An automated control system remotely monitors the conditions on reefer containers – during transportation on board of the container ship and during storage at the container terminal. A reefer with a modem communicates its status to a controller that sends the signal to a screen via a transmission cable (Emerson Climate Technologies, 2014). The temperature indicators – especially the return air temperature and the set point temperature – are displayed on the screen. When a large deviation of return air temperature from the set point is observed, the reefer handler will inspect it. This system enables safe transportation of cargo and transparency in shipping operations. Automated monitoring improves operational efficiency, reduces operating costs, and increases staff safety. Two-way communication takes place between the operator and every single reefer (Emerson Climate Technologies, 2014). Maersk Star Cool and Start Cool CA (WorldCargoNews, 2012) are examples of these dedicated air climate control systems. The CTAS reefer monitoring system (PEMA, 2016) is another remote reefer monitoring and control system for covering all aspects of cool container management within container terminals.

Peak shaving is a 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's electrical load. A generator can also be used to power non-critical loads during peak hours;
- Power sharing involves intermittent supply of power for reefers' cooling operations.

It is common for a facility utilizing peak shaving techniques to have net energy savings of 10%–30% of their electricity bill (Baldor Electric Company, 2005). Other industries such as smart homes (Costanzo et al., 2012; Cottone et al., 2015), transportation and smart grids (Zamani et al., 2010; Vazquez et al., 2010), and battery storage (Luo et al., 2015) are other good examples of peak shaving algorithms.

Modelling is frequently used to support 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 *general energy balance equation*. Using this as a foundation, several approaches such as spatial temperature difference models and heat flux models have been developed to gain an in-depth understanding of the reefer system (James et al., 2006).

Although there are several techniques available for determining energy consumption, the methodology adopted in this research is

simulation modelling. This is because simulation is a cost-effective way to understand the current system; it identifies the bottlenecks and suggests solutions to improve the results. Simulation also provides design tools capable of generating real-life experiments. Finally, simulation is often used when the system to be studied is complex with many interacting variables, the relation among the variables is non-linear, and output has to be visualized in an interactive way. These factors apply to reefer systems, and therefore simulation modelling is the preferred choice for studying reefer systems (Fishwick, 1995).

In simulation modelling, computational fluid dynamics (CFD) is the most widely used technique for modelling reefer energy consumption (James et al., 2006). Jedermann et al. (2013), however, follow a different approach. They have developed linear dynamic differential equations in Matlab software to study the energy consumption of reefers. Sörenson (2013) has used simulation environments such as TRNSYS, Matlab, and Simulink to model the complex reefer refrigeration system. These models, however, fail to determine the impact of energy consumption. Several simulation models have been developed to understand the complex terminal operations. Lutjen et al. (2013) have, for instance, used a network model to study the interactions between different agents of logistics such as vendors, distributors, and warehouses. 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. This model is built in the emPlant simulation software and captures the containers' logistical dynamics 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, these models focus on the logistics side; they ignore reefers' energy consumption.

Simulation models have also been developed to study energy consumption at terminals. Saanen et al. (2015) have used a heat mapping technique to simulate the CO₂ emissions at the rubber-tired gantry terminal. This is especially helpful for understanding the energy and environmental impacts of different terminal operation in much detail. However, this model, although extremely useful, deals with only large objects and focuses more on CO₂ emissions. Abadi et al. (2009) used an object-oriented simulation system developed in C++ programming language to develop a macroscopic model of terminals. It consists of objects such as the terminal itself, trucks, trains, and ships. Other minor objects such as various yards and different types of cranes are contained within the terminal object. However, this model does not track reefers' movements at terminals.

From the literature review, the authors have identified knowledge gaps regarding: a) the dynamic visualization of energy consumption by a system of reefers operating at terminals and b) appropriate peak shaving techniques to save on energy bills. Earlier studies emphasize the energy saving models for a single reefer and a reefer temperature control system at the terminal. They also provide a list of different peak shaving techniques. However, they lack the following elements that constitute the knowledge gap:

- Most of the models deal with reefers' energy consumption on an individual basis. REFCON provides mainly information about reefers' temperature system. There is therefore no detailed study on the energy consumption of a system of reefers connected at terminals. This includes the interconnection between the terminals' operations and reefers' temperature increases. For this, the research deals with terminal logistics, its impact on

reefer temperature, and therefore the energy consumption at terminals;

- Existing models do not take into account the sensitivity of various factors to reefers' energy consumption. Consequently, a sensitivity analysis is performed for a single reefer and for a system of reefers, thereby providing insight into the key decision variables for determining a reefer's energy consumption;
- Many studies confirm the occurrence of power peaks at terminals due to reefer operations. Several peak shaving techniques are available to reduce peak power demand, but there is little study on how to incorporate these peak shaving solutions. This research will provide details of reefers' peak power consumption and will suggest opportunities to reduce these peaks;
- Grid operators calculate the electricity price for container terminals partly on the basis of terminals' peak energy consumption. The greater the observed peak, the higher the energy cost. The challenge for container terminals is therefore to smooth their peak demand over time to prevent high peaks, thereby leading to energy bill savings. However, the financial savings due to peak reduction are unknown. This research, therefore, presents the savings that a terminal can achieve thanks to peak power reduction.

3. Conceptualisation, specification, and construction of the reefer energy consumption model

In order to determine the relationships between terminal logistics and reefer containers, it is important to identify all terminal processes; these are divided into three phases: incoming, dwell time, and outgoing. In the incoming phase, the ship carrying reefer containers arrives at the quay side. The reefers are then unplugged from the ships and transported to the terminals by means of quay cranes. During the dwell time phase, terminal equipment is used to stack the containers in reefer racks. The containers are then plugged into electrical sockets and checked that their temperature is set according to the bill of loading information supplied by the shipping line (Radu and Kruse, 2009). A continuous supply of electricity is ensured by plugging them into electrical sockets for their appropriate dwell time. Finally, in the last phase, they are unplugged, loaded onto trucks, trains, or barges, and transported to the hinterland. Of course, the process also takes place the other way round; therefore, the model can be easily adapted to sequencing differences (changing from import to export reefers).

3.1. Conceptualisation of reefer model during its unplugged time

Using IDEFO(Integration DEFINition for Function)-schemes (Sage and Armstrong, 2000), all terminal processes are identified concerning the handling of reefer containers. It is important to study the impact of these processes on reefer temperature. Fig. 4 shows the processes that are part of the model: transporting the reefer from quay to stack (A5), stacking the reefer (A6), plugging in the reefer (actual arrival of the reefer in the simulation model, A7), checking the temperature (A8), and unplugging the reefer (A9).

A description of the reefer processes helps to elucidate the temperature fluctuations in reefers. These fluctuations have a great impact on the reefers' initial power requirement. Fig. 5 gives a sample temperature profile for the transport of fish from Iceland to France. As seen, as the ship arrives at the terminal and the reefers are unplugged, there is a rapid increase in their temperature. This is because, for a certain time period, a reefer is without power supply (unplugged time), thereby affecting its temperature. In this case, the reefer's temperature increased from 0.5 °C to 6 °C for a period of eight hours without electric supply.

From the literature study, the most comprehensive equation (Formula (1)) to model the temperature increase is as follows

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

Temperature increase of reefer (Tran, 2012).where

$\Delta T(t)$ = Temperature effect in time (°C)

ΔT = Ambient temperature - Return air temperature (°C)

A = Surface area of reefer (m²)

K = Thermal insulation of reefer (W/m². °C)

t = Time before plugging in at reefer stack (s)

S = Exposed sun intensity (no dimension)

M = Mass of cargo (kg)

C_p = Specific heat of cargo (kJ/kg. °C)

As shown, Formula (1) covers different types of variables affecting reefers' energy consumption. This equation therefore includes the variables affecting the cooling power of reefers (see Formula (2)). Formula (1) gives the reefers' temperature rise during its unplugged time. Once the reefer arrives at its rack, it is plugged in, and the temperature settings are checked. The reefer starts consuming energy from this moment in line with the reefer management system.

3.2. Conceptualisation of the reefer model during its plugged-in time

With Formula (1), a reefer's temperature change is calculated before it is plugged in. Its return air temperature rises correspondingly during this period. Once a reefer arrives at its rack and is plugged in, the return air temperature may deviate from the recommended set point temperature. First, it is checked whether, because of temperature fluctuations, the return air temperature is outside the allowed bandwidth. This point is shown in Fig. 5. Three conditions are consequently possible:

3.2.1. Return air temperature is beyond the upper limit of the allowed bandwidth

In this case, there is a great risk of damage to the cargo due to overheating (Miller, 2012). Thus, the reefer urgently needs to be brought back to its set point temperature, and so the reefer is rapidly cooled to bring it down to this temperature. During this process, in addition to the usual auxiliary power, a maximum amount of cooling power is applied. The applied cooling power is calculated as follows:

$$Q = M * C_p * \Delta T / t \quad (2)$$

Cooling power of a reefer (Tran, 2012).where

Q = Cooling/Heating power (kW)

M = Mass of cargo (kg)

C_p = Specific heat of cargo (kJ/kg. °C)

ΔT = Temperature difference (°C)

t = Cooling time (s)

The combined use of auxiliary and cooling power causes an initial power pulse. This pulse is applied until 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 temperature.

3.2.2. Return air temperature is beyond the lower limit of the allowed bandwidth

In this scenario, there is a high risk of crystal formation,

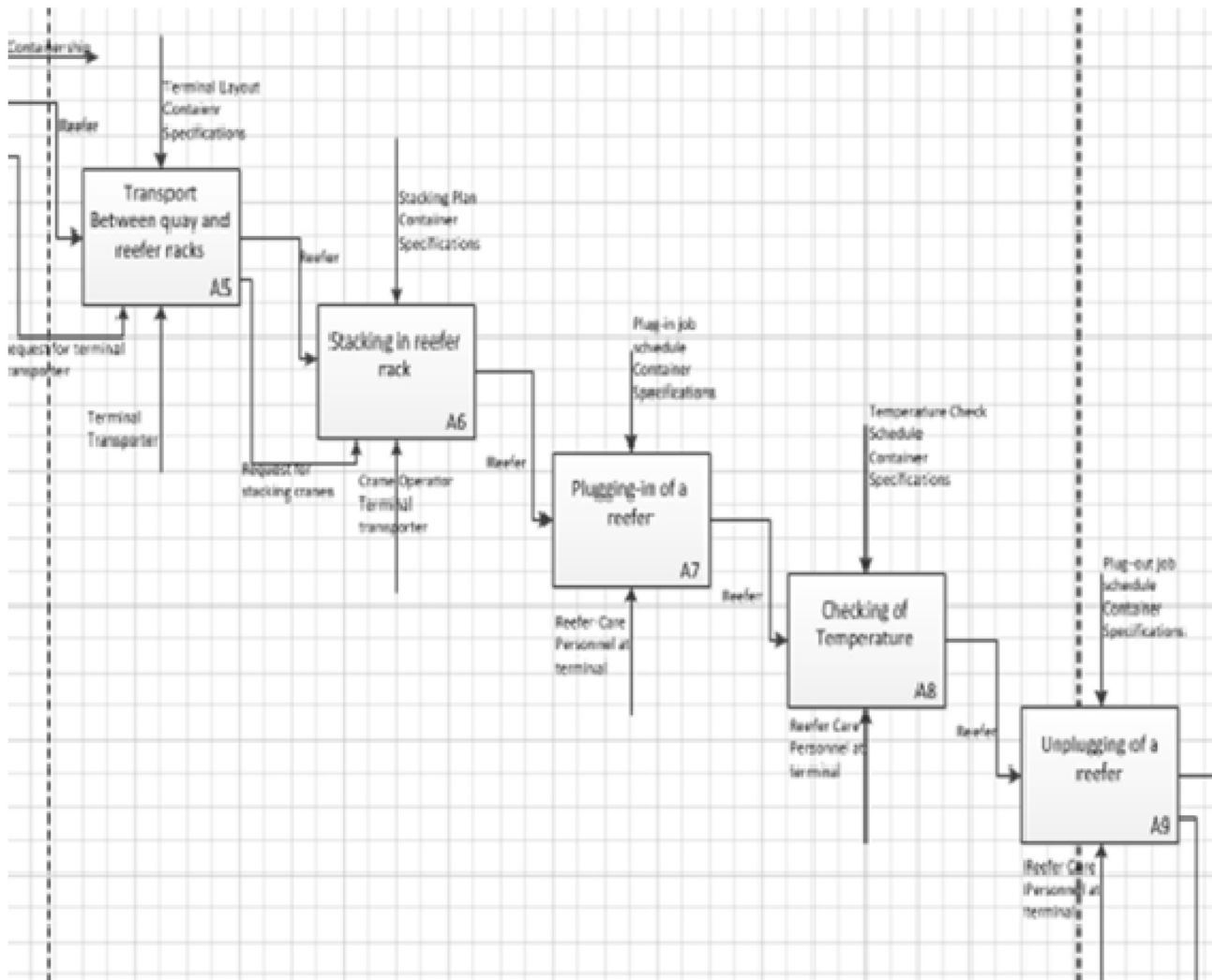


Fig. 4. IDEF scheme of reefer processes.

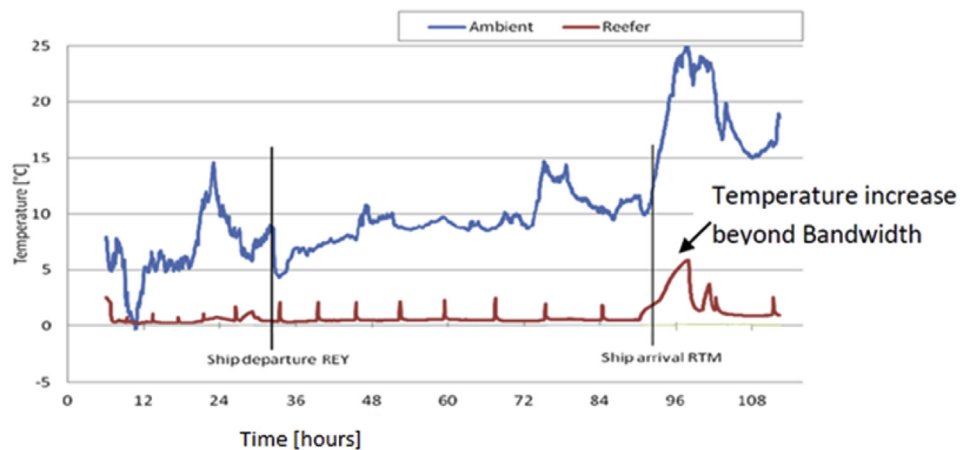


Fig. 5. A temperature profile of a reefer (Eliasson et al., 2013).

especially in meat products (Frozen Food Handling and Merchandising Alliance, 2009). The temperature therefore urgently needs to be brought back to its set point, and so the reefer is

heated until the set point is reached. Like in the previous scenario, there is an initial power pulse until the set point temperature is reached. Then the reefer operates in its usual on/off mode.



Fig. 6. Conceptual model for the power consumption of an individual reefer (Nafde, 2015).

3.2.3. 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 its usual on/off mode. Auxiliary power is used until the temperature has reached the upper limit/lower limit in the event of temperature rise/fall. After this, cooling/heating power is additionally used to bring down (up) the reefer to its set point. The conceptual model has been developed from the above description.

The model, as shown in Fig. 6, represents the events for a reefer during connection time.

3.3. Specification of the reefer energy consumption model

The conceptual model having been discussed, the data requirements for the simulation model are presented in this section. The main data required are divided into categories, as follows.

Data are needed about the arrival and departure schemes for the reefers at a terminal. ASEA Brown Boveri (ABB) provided this **reefer data**¹ for a terminal in Rotterdam Port for the period from 1 January

2014 to 29 January 2015. This data sheet also includes individual reefer-related information such as the type of cargo, the mass of cargo, the set point temperature, and the number of reefer plugs. The energy consumption is modelled for 61,321 reefers arriving and departing at the terminal over the same period. These reefers arrived in different periods of the year, had their distinguishable characteristic data, and carried various types of cargoes. These cargoes were of different weights and had varying amounts of dwell time. The terminal has around 1700 reefer slots. The original data are used as input for the deterministic simulation model. The number of reefers is sufficiently large to obtain reliable insights.

The **run length of the simulation period** is consistent with the size of the reefer data set, and therefore set to one year and one month, that is, 9480 h. The longest cycle time within the simulation model is the reefer with the highest dwell time. This value from data analysis is 12 days including 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, as the runtime is 33 times the longest cycle time. A time step of 1 min is used to simulate the temperature increase/decrease function. For peak power calculations, a 15-min time step is used. No warm-up period is used.

¹ The dataset used is available for reproducibility.

Other important data required here are the **delay time before a reefer is plugged in**, because this affects the reefer's temperature fluctuations. The delay time depends on whether a reefer is for import or export. For import, the reefer layout on the ship is an important factor determining delay time. A quay crane and a stacking crane take 10 min to bring the reefer from ship to reefer rack. On average, a container ship has 800 reefer plugs. In this case, it takes two hours for the last reefer to arrive at its rack. Once a reefer arrives at a rack, a job is sent to a reefer operator at the terminal to plug it in within one hour. However, in some extreme circumstances, a reefer might be unplugged for more than six hours. For an export reefer, the delay time is less because of the arrival of smaller numbers of reefers per time period. The trucks with export reefers arrive more equally distributed over a day.

Furthermore, data are needed to determine the temperature increase of a reefer in its unplugged and its auxiliary power state (see Formula (1)). The literature indicates that the lower the value of thermal insulation of a reefer, the better its resistance to temperature increase (Geysen and Verbeeck, 2011). This value depends

mainly on the reefer's age. The average life expectancy for a reefer is 12 years (Sørensen, 2013). Thus, as the reefer ages, its thermal insulation value increases. Table 2 gives the relation between the age of a reefer and its thermal insulation value.

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

A reefer's electric power consists of auxiliary and cooling power. From the literature, 2.5 kW of power is required by a reefer to run its basic components such as fans (Tran, 2012). With frozen cargo, the objective is to provide a circulation of cold air (blanket) around the cargo. Primarily, the air circulation between the cargo and the walls, floor, and roof will absorb any warm air that has entered through the insulation. The air in turn will carry the absorbed heat to the evaporator coil where this heat is absorbed and given off to the outside ambient air via the condenser. The cooling power depends on the set point temperature. The cooling capacity varies slightly depending on manufacture and the ambient temperature.

Electricity contracts between a utility company and a terminal are confidential, and so general electricity tariffs for industries in The Netherlands are used to calculate energy costs. Within these tariffs, only day, night, and peak prices are used. Other costs such as installation costs and maintenance costs are not considered. The final result provides day additional costs due to peak power demand, day and night time energy costs, and total energy costs. In

Table 2

Variation in reefer thermal insulation with age (Geysen and Verbeeck, 2011).

Age (years)	Thermal Insulation Value (W/m ² . °C)
0–4	0.5
5–8	0.6–0.7
9–12	0.8
>12	0.9

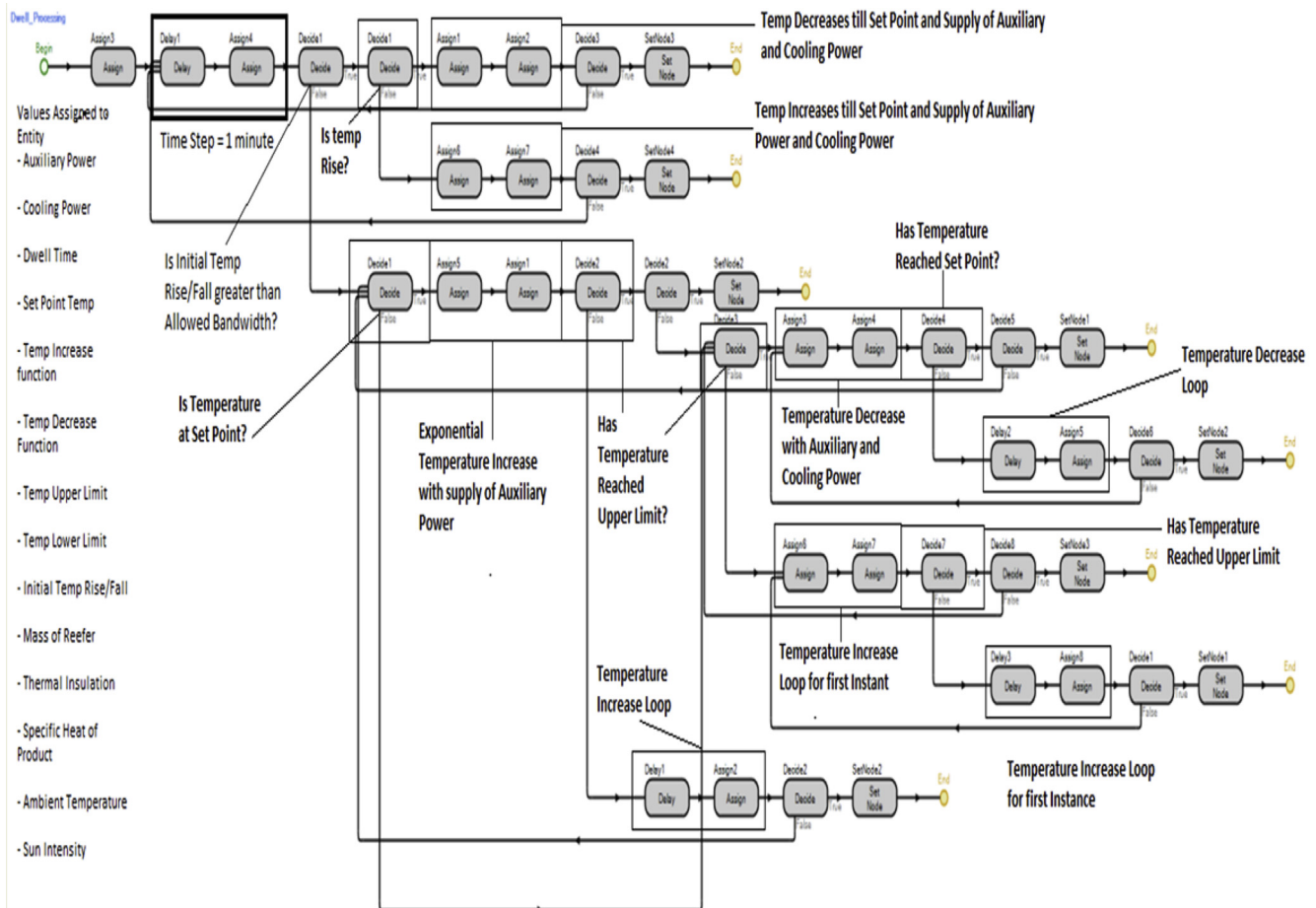


Fig. 7. Computerised energy demand model in Simio (Nafde, 2015).

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

3.4. The reefer energy consumption simulation model

Based on the conceptual model, the model specifications, and the above assumptions, the simulation model has been developed.

When a container ship carrying reefers arrives, each reefer is unplugged from its power source. It is then lifted by quay cranes and stacked into the reefer racks. Here, it is again plugged into a power source. In between this time, the reefer is without a power

supply. Depending on the conditions, its temperature may rise/fall to varying degrees. Once the reefer is plugged in, it operates in its usual on/off mode. Reefers with different set point temperatures arrive at the terminal. The above model is replicated for the different temperature classes of reefers available from the data sheet (see Table 1). These temperature classes consist of several individual entities. For all these entities, the only common attributes are surface area and auxiliary power. The rest of the data from the model specification vary for each entity. Every entity (reefer) is therefore unique in its own way.

Once these attributes were assigned to each of the 61,321 entities, the reefer model was developed (see Fig. 7). Its working is based on the conceptual model discussed in Fig. 5 and is applicable to all the entities.

3.5. Verification and validation of the reefer energy consumption model

The following verification test was conducted to check whether the model was working correctly (Kelton et al., 2011):

Test – energy patterns

For a reefer that is allowed only small temperature fluctuations,

Table 3
Sample reefer data (for verification).

Dimensions	Values
Initial temperature before plug-in	10.2 °C
Set point	10 °C
Allowed temperature, upper limit	10.5 °C
Allowed temperature, lower limit	9.5 °C
Auxiliary power	2.5 kW
Cooling power	10 kW

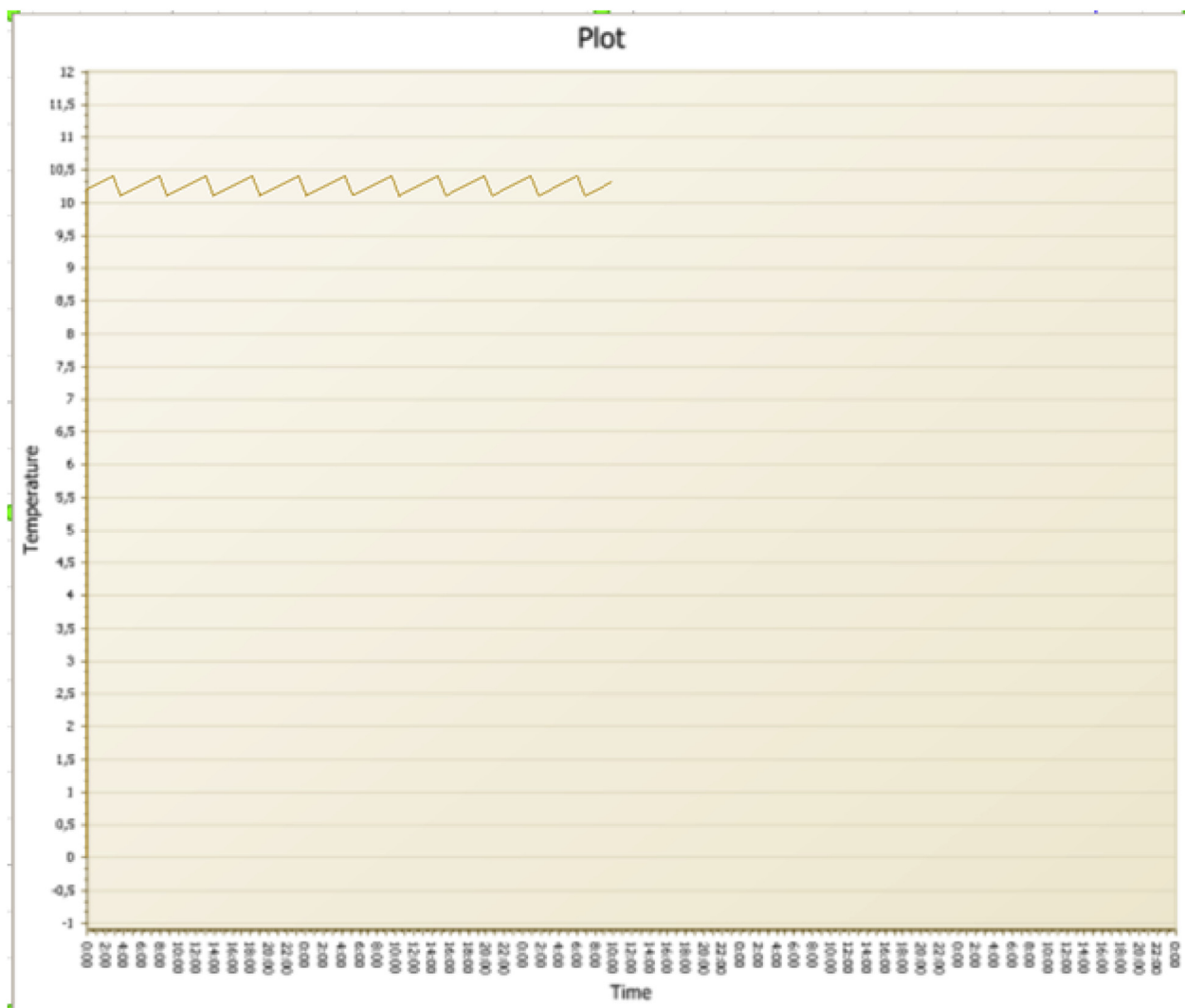


Fig. 8. Temperature fluctuations (°C) according the sample data (Table 3) during 5 days (Hours).

many power pulses should occur within a time period. However, the duration of these pulses should be small. Table 3 contains sample data for verification. Fig. 6 shows the temperature fluctuations of the sample reefer. 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. This energy profile for this temperature fluctuation is illustrated in Fig. 7.

Figs. 8 and 9 show that the number of power pulses corresponds with the number of cooling processes undergone by a reefer. Because of its narrow temperature bandwidth, the cooling process occurs many times within short time spans. Another experiment with a wide temperature bandwidth was executed and showed a few power pulses within large time periods. The model is therefore verified.

Validation of the model is concerned with its accurate representation of the real system. The authors have applied the following validation methods. The first part of the validation is a sensitivity analysis performed on a single reefer to determine important variables affecting its temperature. The variables taken into consideration are those affecting the reefer temperature in Eq. (1). Their base values and their corresponding deviations for sensitivity analysis are shown in Table 4.

As mass of cargo proved to be the most important factor

Table 4

Base values of reefer parameters and tested deviations for sensitivity analysis.

Variable	Constant Value	Sensitivity Analysis
Thermal insulation	0.7 W/m ² .°C	0.4–0.9 W/m ² .°C
Unplugged time	2 h	6 h
Mass	30,000 kg	5000 kg to 35,000 kg
Sun intensity	0.6	0 to 1

affecting temperature fluctuation, the results of the sensitivity analysis are shown in Figs. 10 and 11.

In our example it can be seen that identical reefer conditions with different weights manifest big differences in the duration of the switch-on/off times (i.e. varying between 6 and 34 for off hours and 1 and 6 h for on hours).

The cargo mass in the reefer is the most important factor affecting the reefer's temperature fluctuation. However, it is difficult for the terminal operator to have control over this factor. An earlier sensitivity analysis revealed that the thermal insulation of a reefer is the second important factor. The temperature of an older reefer rises more rapidly than that of a recently manufactured reefer. Sun intensity also plays an important role in a reefer's temperature increase. In conclusion, efforts should be made to minimize the impact of sensitive variables on reefer temperature.

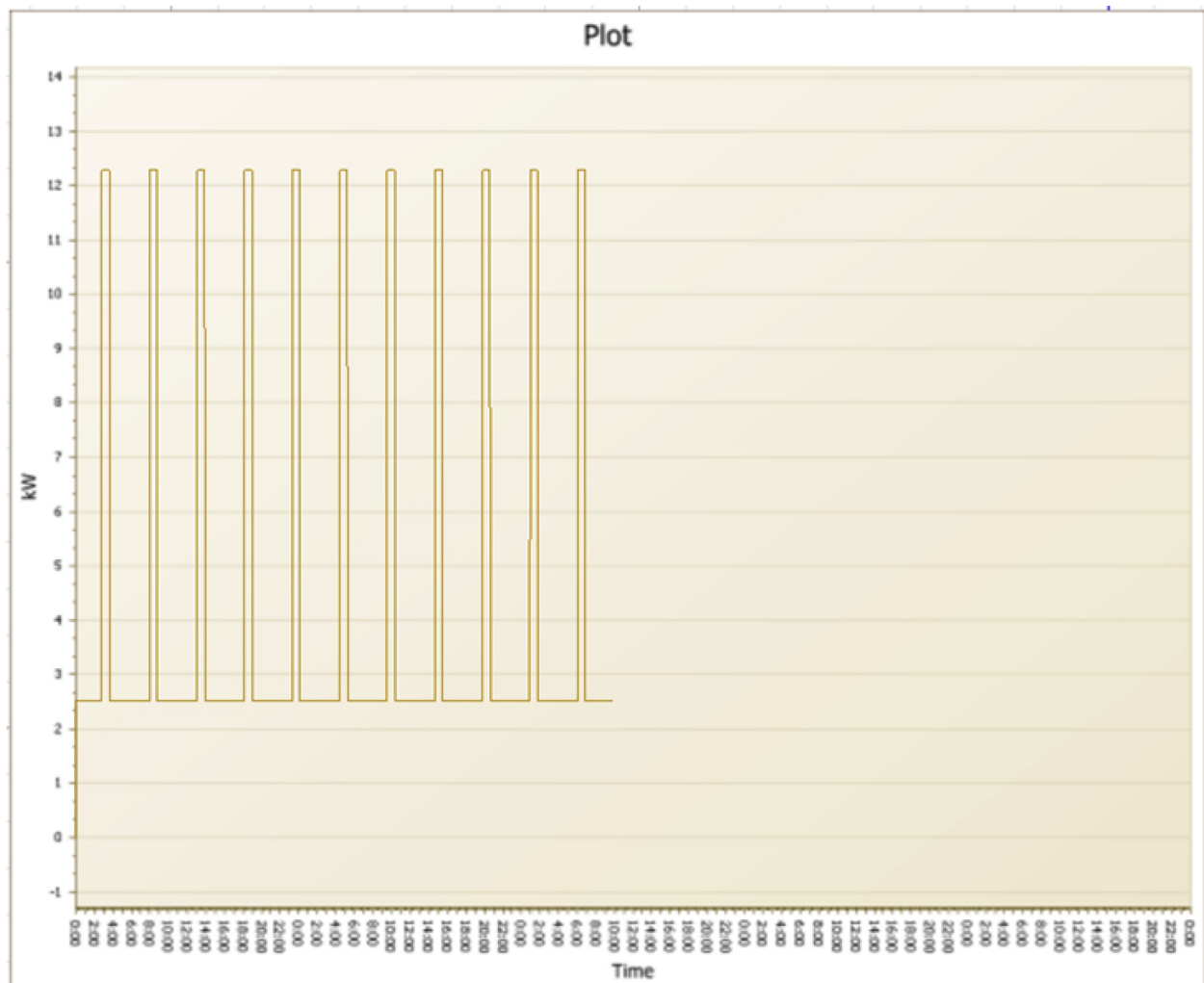


Fig. 9. Energy consumption pattern (kW) according the sample (Table 3) during 5 days (Hours).

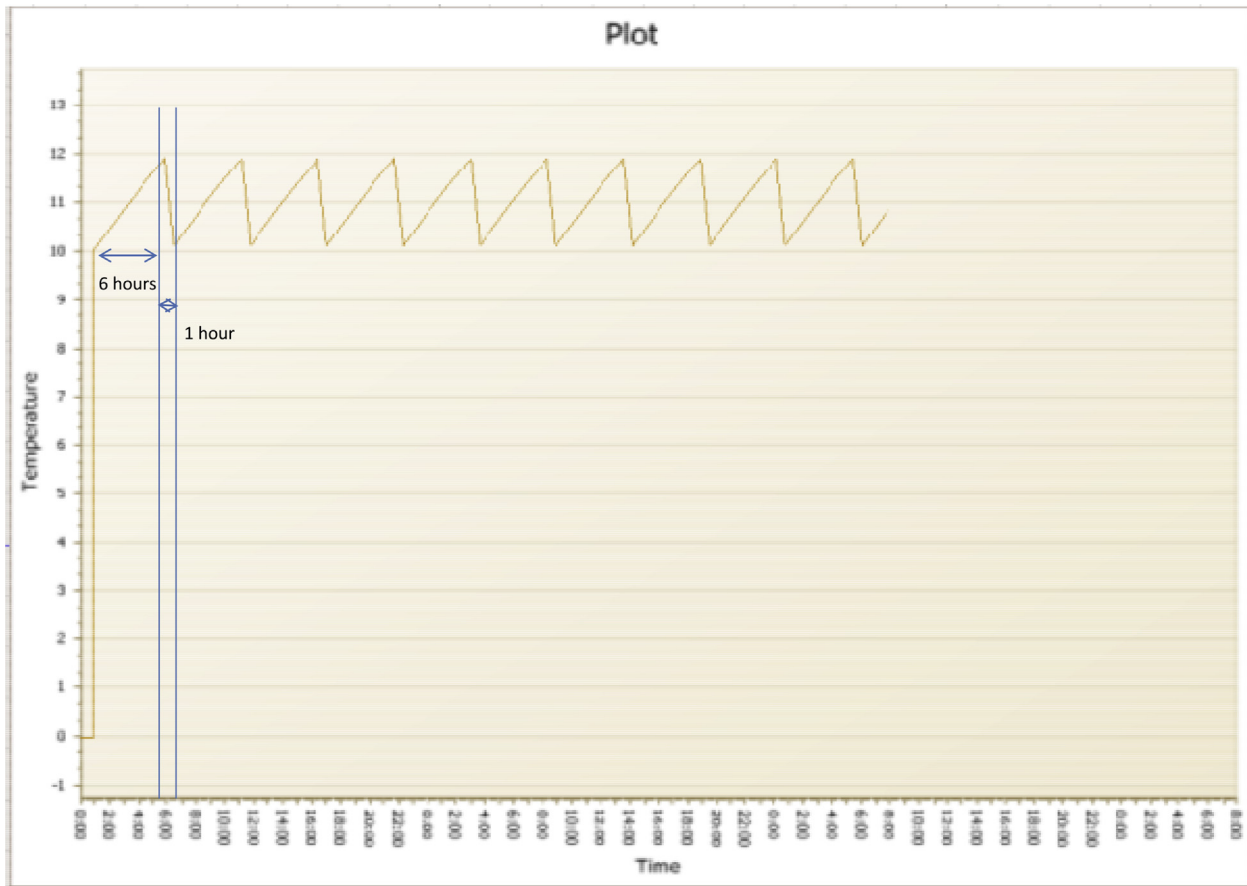


Fig. 10. Temperature fluctuations (°C) with mass – 5000 kg according the sample (Table 4) during 3 days (Hours).

A sample working model by Sørensen (2013), who is one of the leading researchers in the modelling of reefer refrigeration units, was compared to the model, with a set point for the sample reefer of -20°C . Temperature fluctuations and cooling power pulses displayed completely identical patterns. Also, Face Validation was conducted with experts in ABB and the Reefer Care Manager at a terminal in Rotterdam. Results of the face validation were also positive.

4. Modelling experiments

This section shows the results of the base case (current situation) and the results of two peak shaving alternatives.

4.1. Base case

Fig. 12A/B give the number of reefers simultaneously connected to reefer plugs at the terminal for the entire simulation period ($= 9480 \text{ h} = 1 \text{ year} + 1 \text{ month}$). The throughput of reefers during this period was 61,321, of which 45,923 carried frozen products and the rest carried chilled products. In the first quarter of 2014, fewer chilled and frozen reefers arrived at the terminal because of the seasonality of the reefer trade with Western European countries. Therefore, a small number of reefers were simultaneously connected to reefer plugs, leading to small spike heights.

In the month of April, large quantities of chilled products arrived at the terminal. This can be attributed to the seasonal arrival pattern of deciduous fruits from South Africa. However, the number of frozen reefers arriving in the same period was still small because

of the lack of sufficient cargo trade between South America and Western Europe. Thus, although the arrival of a large number of chilled reefers increased the height of the spike, it was still small as there were not a sufficient number of frozen reefers in port.

The largest consignment of chilled and frozen products arrived in the period from June to November. For chilled products, this reflects the seasonal export pattern of citrus fruits from South Africa. For frozen products, it reflects the seasonality of the meat trade between South America and Western Europe. Their combined effect led to a large number of reefers being simultaneously connected. This caused a large number of very high spikes as shown: in a three-month period starting in August, the limit of 14,000 kW was crossed six times (see Fig. 12B).

4.2. Peak shaving experiments

The solutions deal with changes in operational procedures to reduce the peak power demand. Two rules of operation are tested to analyze their effects on peak demands and temperature deviations:

4.2.1. Intermittent distribution of power among the reefer racks

Reefers are stored in separate reefer racks at terminals. Each rack consists of four rows, and each row further has multiple slots to store the reefer containers.² Each of these slots is provided with an electrical socket for the operational functioning of reefers. Large

² Reefer stack configurations can vary from terminal to terminal.

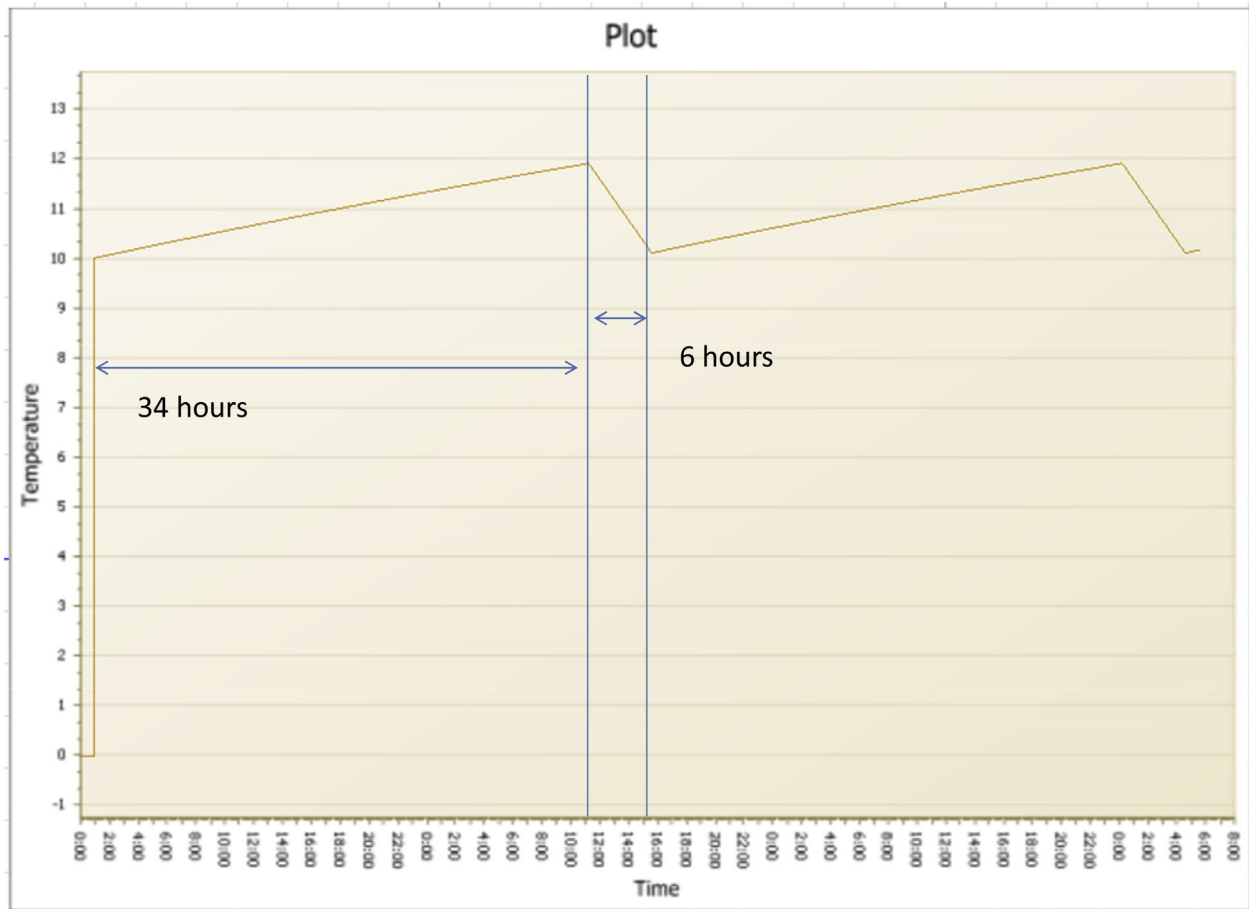


Fig. 11. Temperature fluctuations ($^{\circ}\text{C}$) with mass – 35,000 kg according the sample (Table 4) during 3 days (Hours).

numbers of reefers cooling simultaneously leads to a huge demand of power from the electrical network. This is the primary reason for terminals crossing the threshold of allowed peak power, but, if the power supply to these reefer racks is divided into appropriate timeslots, the simultaneous overlapping of cooling power can be avoided. Therefore, intermittent power supply is suggested for each pair of container racks with different timeslots of 5 and 15 min.

4.2.2. Restriction on peak power consumption among operating reefers

In this experiment, the power supply is restricted to a threshold value. This has consequences for the individual reefers. Each reefer will utilize its entire bandwidth of allowed temperature. This implies that, after reaching its upper temperature limit, cooling power is applied until the lower limit of the allowed temperature is reached. In such cases, the cooling power is applied for a longer duration. For a system of reefers operating simultaneously, this operation affects the probability of a cooling power overlap. The result is more impactful for reefers with a narrow bandwidth of allowed temperatures. Consequently, by changing the behaviour of power pulses, the cooling power overlap can be modified.

It has already been stated that reefers are responsible for approximately 30–35% of the total energy consumption at terminals (Green Cranes, 2013). Two cases of timeslots are considered (see Table 5). In the first case, the power is supplied in timeslots of 15 min. This reduces the peak demand to 8266 kW. In the second case, the power is supplied in 5-min timeslots. This leads to an even greater reduction in peak power demand to 2763 kW. In both cases,

total energy consumption and therefore energy cost are also reduced. This solution can result in annual savings of up to €1 million for a terminal. Its downside, however, is that it leads to an increase in reefer temperature during the power off mode. This temperature increase is smaller if shorter timeslots are used, so appropriate timeslots can reduce the risk of product damage in the reefers; in order to avoid product damage, proper precautions are required during implementation of this solution. In Table 5, it can be seen that the 5- and 15-min timeslots do cause a temperature increase/decrease in Frozen ($0.18/0.5^{\circ}\text{C}$) and Chilled ($0, 0.12\text{--}0.18^{\circ}\text{C}$). For Frozen, an increase of 0.5°C is not a big risk, but for Chilled it can have consequences for product quality.

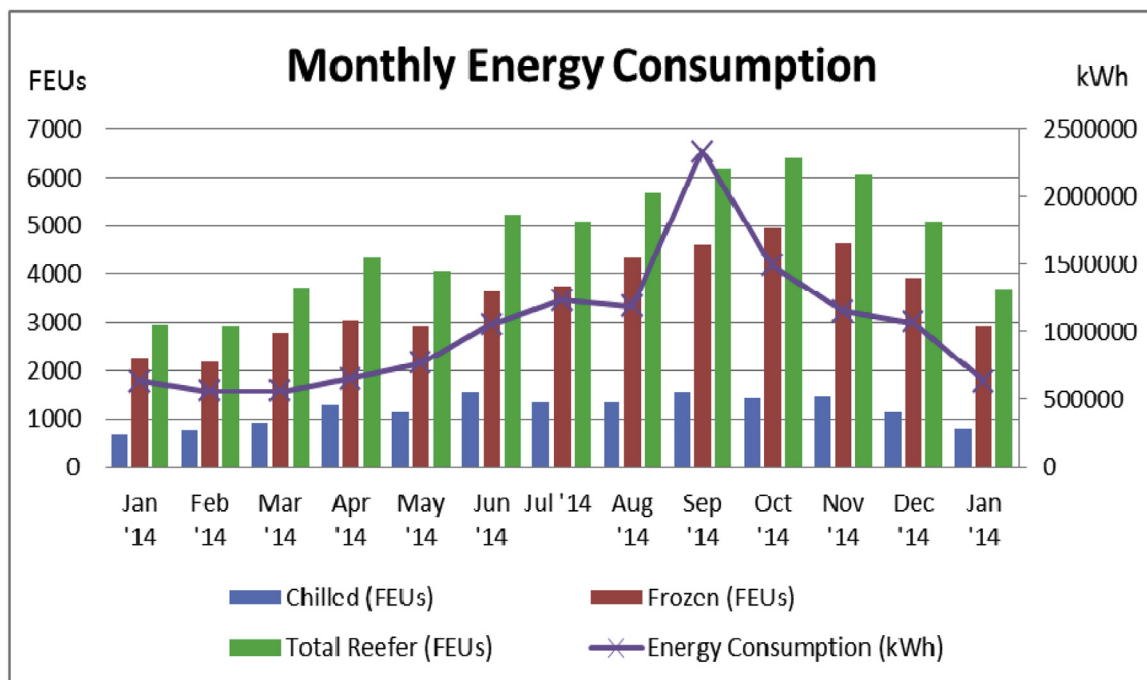
The differences in total energy demand between the 5- and 15-min timeslots can be explained by the fact that the 5-min timeslot is much more precise than the 15-min timeslot, and therefore it can be more precisely determined when energy needs to be delivered, and – more importantly – when not.

An experiment with a maximum power limit of 14,000 kW reduces peak power demand to 13,760 kW. This results in annual savings of more than a quarter of a million Euros. Furthermore, it has minimal impact on the temperature inside the reefer. Hence, this solution, although less impactful in terms of energy savings, is highly reliable with respect to controlling the temperature inside the reefer.

5. Conclusions

This paper describes the development of an energy

A



B

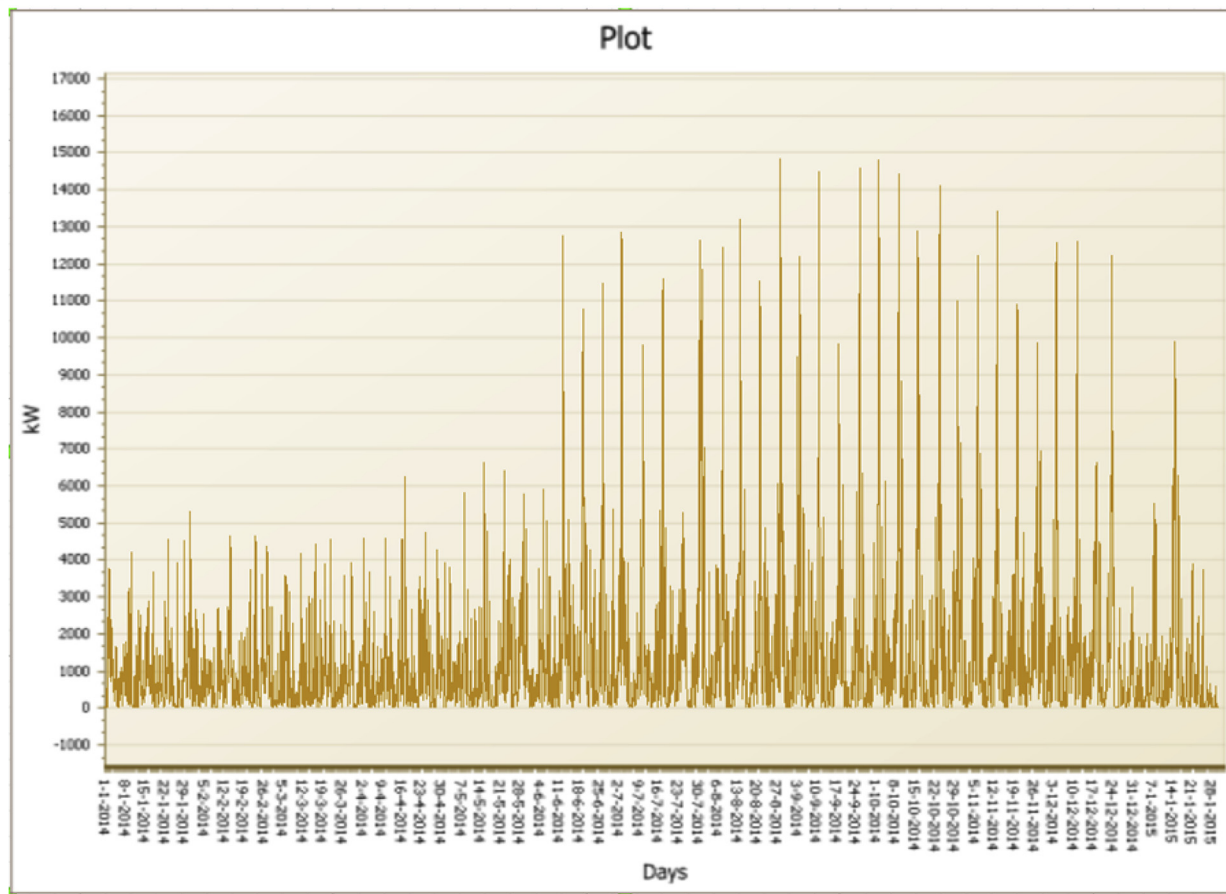


Fig. 12. A: Reefer arrival and monthly energy consumption – base case (Nafde, 2015). B: Energy consumption – base case (Nafde, 2015).

Table 5

Summary of the modelling results (annual).

	Energy Power Consumption			Energy Costs			Quality	
	Peak Power (kW)	Average Power Demand (kW)	Total Energy Demand (kW)	Peak Energy Costs (€)	Total Energy Costs (€)	Total Energy Savings (€)	Impact of Reefer Temperature Difference °C	Product Damage
Base Case	14,831	1275 ± 0.17	12.1 Million	250,000	1.09 Million	NA	NA	NA
Intermittent Power Supply 15 min Slots	8266 ± 201.5	544 ± 0.5	6 Million	0	40,000 –500,000	600,000 –700,000	Frozen: Max 0.5 Chilled: Max 0.12 Max –0.18	Extreme ambient T, high risk
Intermittent Power Supply 5 min Slots	2763 ± 80.3	186 ± 0.2	2 Million	0	100,000 –150,000	1 Million	Frozen: Max 0.18	Less product risk
Max threshold 14000 KW	13,760 ± 18.5	1340 ± 0.3	12.7 Million	0	850,000 –900,000	200,000 –250,000	No effect	No risk

consumption simulation model to research opportunities for container terminals to reduce their peak energy demand. With this model, two peak-shaving alternatives are evaluated with real reefer data (of 1 year and 1 month) in terms of energy savings, peak savings, and internal reefer temperatures. In conclusion, despite energy savings with intermittent distribution of power among the reefer racks, precautions have to be taken against temperature increases that can affect the quality of products in reefers. This can lead to additional insurance costs and, more importantly, affect the reputation of the terminal. In general, the shorter the timeslots, the lower the risk of product damage. It is therefore important to choose an appropriate size for the timeslot to have minimal temperature increases/decreases in reefers, thereby avoiding damage to products. A restriction on peak power is a more robust solution that leads to smaller energy savings and shows no consequences for internal temperatures.

From the sensitivity analysis, it is evident that the key variables affecting temperature changes in reefers are cargo mass and thermal conductivity. It is therefore recommended to develop and implement regulations to check the cargo mass in reefers and the quality of reefers operating at terminals. The next research step is to make reefers more intelligent (smart) by allowing internal communication between the reefers about their required energy demand. This study opens the discussion with terminal operators to reduce the energy consumption at terminals. They are still reluctant to change, because the current business models provide no incentives to change. However the demand for shorter dwell times for reefers is growing (especially for fruits & vegetables), and the port authorities are demanding more greening of the operations, therefore the authors foresee that this study fits well to the awareness of greening ports operations.

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