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Development of a holistic framework for shipyard energy management : a case study on production facilities and technology

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DEVELOPMENT OF A HOLISTIC FRAMEWORK FOR SHIPYARD ENERGY MANAGEMENT

A case study on production facilities and technology

By

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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Abstract

Title of Dissertation: Development of a holistic framework for shipyard energy management.

Degree: Master of Science

This dissertation examines how shipyards can reduce their greenhouse gas (GHG) emissions and at the same time become more resilient by operating in a more energy efficient and sustainable manner.

Due to the direct relationship to shipping, shipyards are directly affected by developments within the shipping industry. Shipyards need to continuously adapt their strategies to remain competitive. Working efficiently and cost effective within shipyards has become increasingly important, especially during volatile market conditions. Shipyards which are not adequately prepared, especially during periods of recession, will not have the required resilience to make it through such challenging times. Additionally, combating climate change is high on the agenda for the majority of countries and can no longer be ignored. Even though shipyards are not governed by International Maritime Organization (IMO) regulations, they have a responsibility to contribute to the Nationally Determined Contributions (NDCs) of the country within which the shipyard is located, as required by the Paris Agreement which was adopted on the 12th of December 2015 by the Conference of Parties (COP) at its 21st Session (COP 21).

Shipbuilding is an energy intensive industry and hence shipyard activities have a high electricity demand, thereby contributing substantially to the emission of greenhouse gasses, depending on the source of electricity. This is further compounded by emissions released by shipyard activities not depending on electricity such as gas cutting, operating fuel oil or gas driven vehicles, painting and blasting. The higher the energy consumption the higher the operating costs and the higher the effects of the externalities on the environment.

In this dissertation shipyard sustainability is discussed specifically in relation to shipyard energy management. A holistic framework for shipyard energy management is proposed upon which shipyards can focus for effective energy management. The proposed holistic framework is comprised of 7 pillars which include; 1) renewable energy employment, 2) compliance, 3) production facilities and technology, 4) process improvement, 5) integrated hull, outfitting and painting process (IHOP), 6) project management and 7) shipyard layout. A case study on a significant energy user, the compressor, within the production facilities and technology pillar was analysed. A model to calculate the energy consumption of this significant energy user was created and optimization software was used to facilitate the decision making process with regards to improved energy consumption measures. The total energy savings along with carbon dioxide (CO_2) emissions reductions and energy cost savings per annum was calculated and shown. The interrelation between the 7 pillars of the proposed holistic framework is also explained. Furthermore, the importance of all components and role players is discussed and how they contribute to a successful and sustainable shipyard energy management system.

Keywords: GHG, Emissions, Sustainability, Climate Change, NDCs, Maritime, Energy Management, Compressor

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List of Abbreviations

˚C	Degrees Celsius
ΔP	Difference in Pressure
CAD	Computer Aided Design
CAD	Compressed Air Demand
CAM	Computer Aided Manufacturing
CAP	Compressed Air Produced
CAS	Compressed Air System
CNC	Computer Numerically Controlled
CO_2	Carbon Dioxide
COP	Conference of Parties
CPM	Critical Path Method
CSP	Concentrated Solar Power
CT	Cycle Time
DOE	Department of Energy
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EnMS	Energy Management System
ESPO	European Sea Ports Organisation
EU	European Union
FSD	Fixed Speed Drive
GDRC	Global Development Research Centre
GERT	Graphical Evaluation and Review Technique
GHG	Green House Gases
HBCM	Hull Block Construction Method
Hr	Hour
IHOP	Integrated Hull Outfitting and Painting
IMO	International Maritime Organization
ISO	International Standards Organization

Kg	Kilogram
kW	Kilowatt
kWh	Kilowatt Hour
kWp	Kilowatt Peak
LF	Load Factor
M^3	Cubic Meter
Min	Minutes
NC	Number of Cycles
NDC	Nationally Determined Contributions
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
PC	Personal Computer
PDCA	Plan Do Check Analyse
PEL	Power and Energy Logging
PERT	Program Evaluation and Review Technique
Pload	Loaded Power Demand
PPFM	Pipe Piece Family Manufacturing
Punload	Unloaded Power Demand
PV	Photovoltaic
PWBS	Product Work Breakdown Structure
SC	Specific Capacity
SD	Secure Digital
Sec	Seconds
SEEMP	Ship Energy Efficiency Management Plan
SEU	Significant Energy User
SMART	Specific, Measurable, Appropriate, Realistic & Time-bound
SPC	Specific Power Consumption
Tl	Load Time
Tu	Unload Time
UN	United Nations

UNEP	United Nations Environment Programme
UNSDGs	United Nations Sustainable Development Goals
USEPA	United States Environmental Protection Agency
Vs	Air Storage Tank Volume
VSD	Variable Speed Drive
WMO	World Meteorological Organization
X	Utilization Factor
ZOFM	Zone Outfitting Method
ZPTM	Zone Painting Method

Chapter 1: Introduction

Chapter 1.1 – Background

The accumulation of greenhouse gasses in the atmosphere is resulting in severe climate change with disastrous and far reaching consequences. This is painstakingly evident when reading the World Meteorological Organization's (WMO) statements on the state of the global climate.

As per the 2017 WMO Statement on the State of the Global Climate, 2017 was the costliest hurricane season on record, the second year of major bleaching in the Great Barrier Reef was experienced, more than 41 million people were affected by floods in South Asia, approximately 30 percent of the world population faced extreme heat waves and more then 892 000 drought related internal displacements occurred in Somalia.

"2018 was the fourth warmest year on record. 2015–2018 were the four warmest years on record as the long-term warming trend continues. Ocean heat content is at a record high and global mean sea level continues to rise. Arctic and Antarctic sea-ice extent is well below average. Extreme weather had an impact on lives and sustainable development on every continent Average global temperature reached approximately 1° Celsius (°C) above pre-industrial levels" (WMO, 2018). These extracts from the last two WMO statements on the state of the global climate clearly highlights the catastrophic global effects of anthropogenic greenhouse gas emissions and the urgent mitigating action required by all.

On the 12th of December 2015 the Paris Agreement was adopted by the Conference of Parties (COP) at its 21st Session (COP 21) with a specific goal of keeping global warming well below 2°C compared to pre-industrial levels and with the ultimate aim of limiting global warming to 1.5°C. However, efforts have largely been inadequate to achieve these targets. Current commitments expressed in the NDCs are inadequate to bridge the emissions gap in 2030. Technically, it is still possible to bridge the gap to ensure global warming stays well below 2°C and 1.5°C, but if NDC ambitions are not increased before 2030, exceeding the 1.5°C goal can no longer be avoided. Now more than ever, unprecedented and urgent action is required by all nations (UNEP, 2018).

Figure 1.1 shows the current global greenhouse gas emissions from 2015 to 2018 and the future predicted global greenhouse gas emissions under different NDC scenarios as well as the growing emissions gap between different NDC scenarios and the 1.5 and 2 degree targets up to 2030.

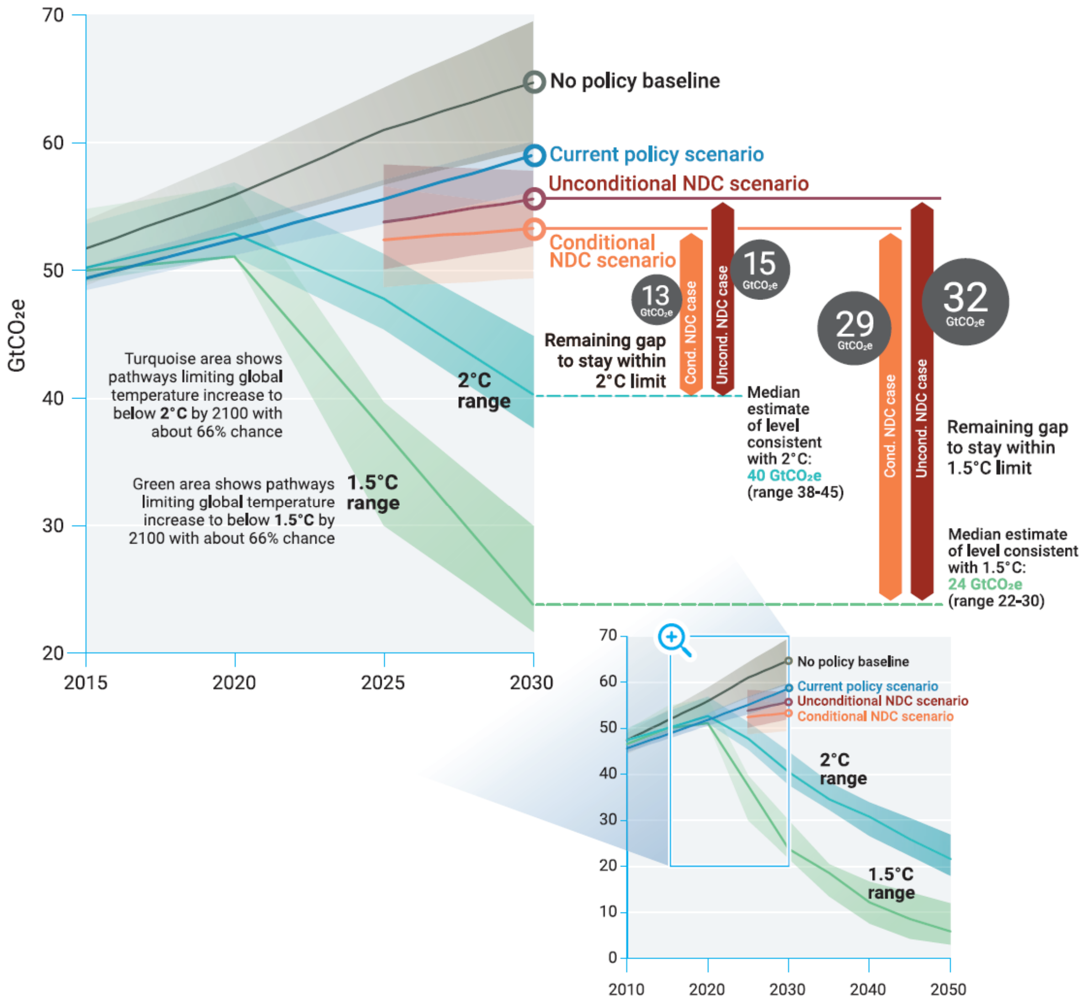

Figure 1. 1 - Global greenhouse gas emissions under different scenarios and the emissions gap in 2030 *Source: UNEP, 2018*

Non-state and subnational action plays an important role in delivering national pledges (UNEP, 2018). Therefore, it is essential for the main emissions contributors from the energy, industry, forestry, transport, agriculture and building sectors to strengthen their commitment towards reduced GHG emissions to bridge the emissions gap. This can largely be achieved through improved energy management. Energy management is also essential for the achievement of United Nations (UN) Sustainable Development Goals (UNSDGs), and in particular Goal 7: ensure access to affordable, reliable, sustainable, and modern energy for all; Goal 12: ensure sustainable consumption and production patterns; Goal 13: take urgent action to combat climate change and its impacts (Ölçer, A., Kitada, M., Dimitrios, D & Ballini, F, 2018).

Chapter 1.2 – Problem Statement

The emission of greenhouse gasses into the atmosphere and its impact on global climate can no longer be ignored. Regulations within the shipping environment are becoming increasingly stringent, as part of the transition to a more energy efficient and potentially GHG emissions free future. In response to GHG emissions reduction from ships and improved energy efficiency, the IMO introduced the mandatory Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). Similarly, figure 1.2 shows how the environmental priorities of ports evolved over time. Air quality being ports' top priority since 2013 and energy consumption being the second most important priority since 2016.

Source: European Sea Port Organisation (ESPO), 2018.

Figure 1. 2 - Evolution of Ports' Environmental Priorities over time Source: ESPO, 2018

Shipyards can adopt a similar approach, as used onboard ships or within ports. Taking a holistic approach to ship construction could give the shipbuilding industry the opportunity of not only setting its own environmental agenda (rather than be forced by government or public pressure) but to also deal with such impacts more effectively, and perhaps even benefit commercially from associated innovations (OECD, 2010).

Due to shipyard operations being highly energy intensive, energy consumption represents extremely high overhead costs. Many shipyards perceive energy consumption costs to be a given operational expenditure over which they have limited or no control over. High energy consumption is also directly related to high levels of GHG emissions into the atmosphere, especially where the primary source is fossil fuel based.

Chapter 1.3 – Aim and Objectives

The primary aim is to develop a holistic shipyard energy management framework upon which shipyards can focus on to facilitate energy use, energy consumption and energy efficiency improvements. The secondary aim is to illustrate how energy consumption and associated CO_2 emissions can be reduced when utilizing the proposed holistic shipyard energy management framework.

To achieve these aims the objectives are to:

- Describe the relationship between shipyards, sustainability and energy management
- Outline the proposed holistic shipyards energy management framework
- Briefly describe each component of the proposed holistic shipyard energy management framework
- Identify significant energy users within shipyards
- Show how existing energy performance can be assessed
- Develop baselines from collected data for existing energy consumption, energy cost and CO_2 emissions
- Develop an energy consumption calculation model for a significant energy user and utilize an optimization tool to facilitate in making recommendations on improvements which will result in the reduction of energy consumption, energy cost and CO_2 emissions

- Compare the baseline energy consumption, energy cost and CO_2 emission figures to the optimized results to show the potential saving

This dissertation will be limited to energy performance improvement for electricity use within shipyards, with the aim to reduce operating costs and specifically CO_2 emissions into the atmosphere. Emissions of other GHGs like methane, nitrous oxide and fluorinated gases will not be considered. This study will not include any potential health and safety impacts associated with shipyard activities or emissions from other energy sources such as gas or direct use of liquid fuels.

Research Questions:

1. What is the relation between shipyards and sustainability?
2. Through which ways can shipyards manage and improve their energy utilization, performance and efficiency?
3. Which are shipyards' most significant energy users?
4. How can energy consumption from a significant energy user be improved?
5. By how much can energy consumption, CO_2 emissions and energy costs for this significant energy user be reduced by?

Chapter 1.4 – Dissertation Outline

Chapter 2 describes sustainability within a shipyard context, in particular the relationship between the environment and economy aspect in relation to shipyard energy management. The contributory role of shipyards towards the achievement of the UNSDGs and the NDCs of the country within which they operated is also described.

In chapter 3 a holistic shipyard energy management framework consisting of 7 pillars is proposed. Each pillar is briefly discussed including how each can contribute to reduced energy use, energy costs and CO_2 emissions.

Chapter 4 introduces a case study on a compressor, with a complete analysis and associated baseline calculations for annual energy consumption, CO_2 emissions and energy costs. An energy consumption calculation model for the compressor is created and the optimization function, OptQuest, within the Oracle Crystal Ball software application is used to establish the optimal compressor specific capacity (SC) and air storage tank volume (Vs) for the subject facility. Energy savings, CO_2 emissions reduction and energy costs savings is then shown on relation to the baseline figures.

The conclusion to the dissertation is presented in Chapter 5, including further research recommendation.

Chapter 2: Shipyards' Role Towards Sustainability

Chapter 2.1 – Sustainable Development

Sustainable development is defined as the; ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). The report by Gro Harlem Brundtland, "Our Common Future", also highlighted three core parts to sustainable development namely economic growth, environmental protection and social equity. This dissertation will deal with the interrelation between the economic and environmental aspect, specifically from an energy management perspective within shipyards. A safe and sustainable energy pathway is crucial to sustainable development (Brundtland, 1987).

The Venn diagram, figure 2.1, shows this interrelation between the economic, social, and environmental aspects. Better known as the triple bottom line, as conceptualized by John Elkington.

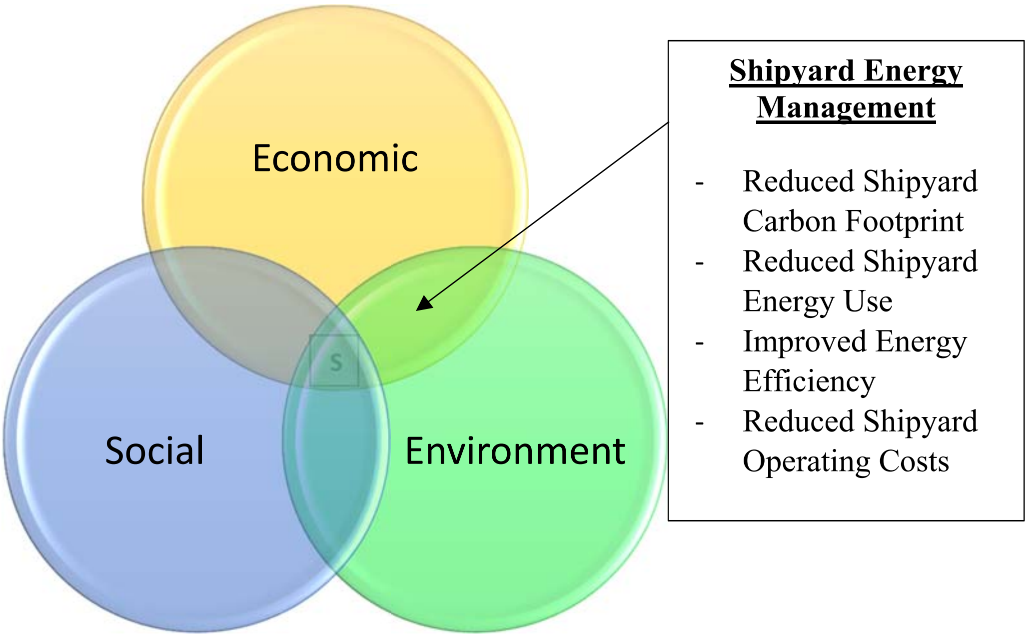

Figure 2. 1 - Triple bottom line Source: Author

Placing the emphasis solely on the single bottom line of profit is no longer adequate and neither sustainable. For a company to be truly sustainable, the company must make a constructive and continuous contribution to environmental and social aspects, while continuing to be profitable. The concept may be hard to grasp at first and is often seen as an extra burden and unnecessary expense, but research has shown that positively contributing to both the social and environmental aspects can significantly improve a company's social acceptance and stakeholder perception and as a result the overall profitability. Depending on the investment type, a major barrier might sometimes be the total initial financial outlay, especially for environmental initiatives. However, in such cases proper assessment and financial viability analyses needs to be done, as the return on investment period for certain projects is longer than others. Long term benefits assessment is important in this regards. For example, energy management investments to achieve GHG emission reduction targets it is not only advantageous to the company and local stakeholders but also has global beneficial effects. Companies should show genuine care and concern when it comes to dealing with the people and environmental aspects. Actions taken should not be once off, short terms, a public perception strategy or merely a balancing act with the economic perspective. Social and environmental aspects should be ingrained within the company's culture, daily operational planning and annual budgeting. Achieving set goals and targets in relation to the social and environmental aspects should be just as important as achieving profit goals and targets. Therefore, it is essential to also measure the social and environmental performance over time so ensure focus is maintained and short comings are addressed accordingly. In some countries reporting on these two aspects might also be a norm or legal requirement, which also needs to be taken into consideration. To ensure focus is maintained on these two aspects, the organizational structure within a company should make allowance for the employment of suitably qualified personnel to manage these aspects effectively.

Chapter 2.2 – Sustainable Development Goals

December 2015 all United Nations Member states adopted the sustainable development goals (SDGs) better known as the 2030 Agenda for Sustainable Development. There are a total of 17 sustainable development goals and 169 targets, measurable through 232 indicators. The agenda covers all three pillars of sustainable development; environment, people and economics, as mentioned in chapter 2.1. The intended application is global, for both developed and developing countries, who contribute through their own Nationally Determined Contributions (NDCs). The SDGs provide a framework for settings the NDCs which should follow a bottom-up approach, achieved through localizing the SDGs to ensure effective implementation at subnational level by local and regional governments and multi-stakeholder inclusion. Ownership, accountability and commitment from all the stakeholders, including shipyards, is essential to the successful achievement of the nationally set goals and targets.

The SDGs can be divided up into 5 thematic areas, commonly known as the 5 Ps;

1. People
    - SDG 1: No Poverty
    - SDG 2: Zero Hunger
    - SDG 3: Good Health and Well-being
    - SDG 4: Quality Education
    - SDG 5: Gender Equality
2. Prosperity
    - SDG 7: Affordable and Clean Energy
    - SDG 8: Decent Work and Economic Growth
    - SDG 9: Industry, Innovation and Infrastructure
    - SDG 10: Reduced Inequalities
    - SDG 11: Sustainable Cities and Communities
3. Peace
    - SDG 16: Peace, Justice and Strong Institutions
4. Partnerships
    - SDG 17: Partnerships for the goals
5. Planet
    - SDG 6: Clean Water and Sanitation
    - SDG 12: Responsible Consumption and Production

- SDG 13: Climate Action
- SDG 14: Life Below Water
- SDG 15: Life on Land

Figure 2.2 indicates the 5 P's, as mentioned above.

Figure 2. 2 - 5 P's of the Sustainable Development Goals. Source: GDRC

Most companies or institutions can incorporate the majority or all 17 SDGs successfully within their operations. However, contributions by shipyards to the SDGs from the perspective of this dissertation will help address specifically the following sustainable development goals and targets.

- SDG 7, target 7.3: By 2030, double the global rate of improvement in energy efficiency (UN, 2015).
- SDG 8, target 8.4: Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead (UN, 2015).
- SDG 9, target 9.4: By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater

adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities (UN, 2015).

- SDG11, target 11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management (UN, 2015).
- SDG 12, target 12.1: Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries (UN, 2015).
- SDG 13, target 13.2: Integrate climate change measures into national policies, strategies and planning (UN, 2015).

Chapter 2.3 – Summary

Long-term shipyard sustainability can only be ensured through an inclusive and strategic vision, supplemented by carefully set measurable objectives, goals and targets, which not only includes financial performance, but also social and environmental performance. Constant performance measurement, reporting and mitigation is essential in remaining on track and identifying short comings. Suitably qualified personnel should be employed to concentrate on these matters.

Shipyards have an important role to play in achieving the NDCs of the country within which it operates. Due regards should be paid to national, regional and international regulatory requirements, stakeholder interests and industry standards. Effective energy management within shipyards goes a long way in meeting many of shipyard obligations towards environmental sustainability, in particular continually reducing the emission of greenhouse gasses from their activities. Thus a holistic energy management framework upon which shipyards can focus to help achieve these goals and targets is required.

Chapter 3: Shipyard Energy Management

Energy management within shipyards facilitates the reduction of existing energy consumption through implementing more energy efficient operations, processes and systems. Energy consumption reduction can be achieved through several approaches, either directly or indirectly. The direct focus of some of these approaches might be specifically on cost, cycle time and man-hour reduction, which indirectly results in decreased energy consumption. Research and publications on these approaches has primarily been performed separate from each other, resulting in fragmented information being available to shipyards. For example:

- In a paper C. Gasparotti (2006) discussed the shipbuilding process from a project management perspective,
- Storch. L, Hammon. C, Bunch. H and Moore.R (1995) in their Ship Production (2nd Edition) publication covers the shipbuilding management theory, product orientated work breakdown structure (PWBS), shipyard layout, planning, scheduling and production control,
- Trygg. L, Thollander. P and Broman. G evaluated industrial energy audits in small and medium enterprises in a paper,
- Kolich. D, Sladic. S and Storch. L (2017) discussed lean integrated hull, outfitting and painting (IHOP) transformation of shipyard erection block construction in their paper and
- Ozkok. M and Helvacioglu. H (2012) discussed A Continuous Process Improvement Application in Shipbuilding in their paper

Therefore, the aim of this chapter is to bring together the relevant approaches which can affect the energy performance within shipyards and propose a holistic shipyard energy management framework consisting of 7 pillars.

Chapter 3.1 – Proposed main pillars of Shipyard Energy Management

The proposed main pillars of energy management within shipyards are:

- Compliance
- Production Facilities and Technology
- Process Improvement
- IHOP
- Project Management
- Shipyard Layout
- Renewable Energy Employment

Each of these pillars can contribute to energy savings within a shipyard. The right combination and level of implementation of the pillars will vary from yard to yard and it is up to the management team to find the appropriate balance to make it yard specific, adapted to its operating conditions, area of operation, applicable regulations and available finances.

Figure 3.1 shows how these proposed 7 pillars to shipyard energy management relates to shipyard sustainability and the triple bottom line, as discussed in the previous chapters. The overlapping circles indicates the interrelation between the 7 pillars.

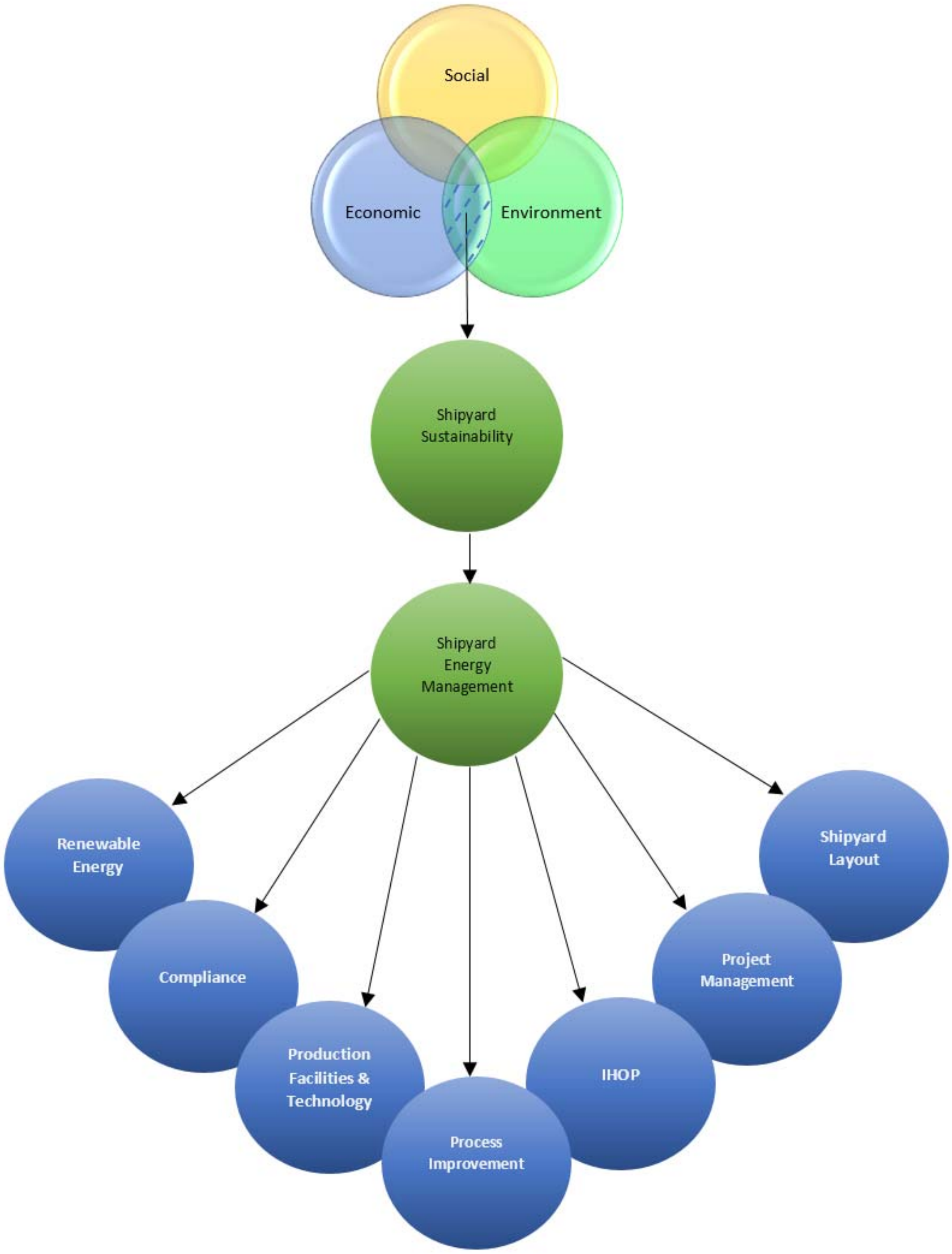

Figure 3. 1 – Proposed holistic framework for shipyard energy management   Source: Author

Chapter 3.1.1 – Compliance

Compliance in this case does not necessarily only mean legal compliance due to government regulations, as legal requirements varies from country to country and are limited or absent in most countries from a shipyard energy management perspective. Thus compliance from this perspective includes complying with industry standards, the shipyard's own energy management system or international standards such as the International Organization for Standardization (ISO) 50001:2018.

The implementation of international standards such as ISO 50001:2018 will facilitate the establishment of an energy management system (EnMS) within the shipyard. In complying with the EnMS, shipyards will be able to continually improve their energy performance, energy efficiency, energy consumption and energy use. The success of the EnMS is reliant on the support and commitment of top management including all employees of the shipyard. Proper implementation of the EnMS will result in energy management to become part of the culture of the shipyard. Requirements of an EnMS includes the development and implementation of a shipyard specific energy policy, along with objectives, targets, which are specific, measurable, appropriate, realistic and time-bound (SMART) and action plans in relation to energy efficiency, use and consumption. The EnMS includes inspection, review, audit and certification programs to demonstrate compliance to ensure the system is being implemented properly and continual improvement is being achieved.

Shipyards not adopting international standards such as the ISO 50001:2018 standard should still implement a shipyard specific energy management system which takes into consideration and complies with all industry standards and legal requirements. As with ISO 50001:2018, the Plan, DO, Check, Analyze (PDCA) cycle should be central to the shipyard specific energy management system. This will allow the shipyard to have a structured approach towards energy management and that continual improvement initiatives to ensure minimal energy and energy efficiency is used for the shipyard activities. A properly implemented shipyard energy management system will allow the shipyard to fully map and better understand its energy flow and energy costs. It will help to identify all the significant energy users and to establish relevant baselines which will provide a point of reference for target setting and future comparison.

Fig 3.2 shows the PDCA cycle as per ISO 50001:2018

Figure 3. 2 – PDCA Cycle Source: ISO 50001:2018

Chapter 3.1.2 – Production Facilities and Technology

Mechanization and automation increases productivity levels, throughput and repeatability, but can be costly initial investments. Upgrade decisions depend on available financial resources, shipbuilding order book, and cost of labour in comparison to mechanization and/or automation and ultimately the Net Present Value (NPV) of the investment. Over time large successful shipyards evolved from basic and manual production systems to shipyards employing state of the art shipbuilding technology through increased automation, the use of robotics, computer aided design and manufacturing (CAD/CAM), ultra-heavy lifting appliances and 5 dimensional computer numerically controlled (CNC) machinery. Thus, resulting in industry leading processes, systems and facilities.

Outdated facilities and equipment are generally much more energy intensive when compared to newer technology. When upgrading and purchasing new manufacturing equipment energy consumption should be an important deciding factor and requirements should be specified clearly in any purchase order. The viability of upgrading or replacing older equipment with newer and more energy efficient production should be properly analyzed and decided upon. Replacements should be planned and budgeted for accordingly. This is especially important for significant energy consumers. Energy consumption can be drastically reduced by using energy more efficiently for processes such as lightning, ventilation and compressed air by employing newer, more optimal and more energy efficient technology. Additionally, energy consumption on idle equipment and in unoccupied work spaces should also be controlled.

Chapter 3.1.3 – Process Improvement

Continual process improvement is an important aspect for shipyards. Process improvement allows shipyards to decrease their cycle times, electricity consumption, GHG emissions, environmental impact and overhead costs. To facilitate this a lean approach to shipyard operations needs to be implemented. This involves eliminating the 7 deadly wastes from shipyard operations by focusing on lean principles and value from the customers' perspective. These wastes, also known as "Mudas", was devised by Japanese industrial engineer Taiichi Ohno.

In any production process there are value adding activities and non-value adding activities. The seven wastes refer to these non-value adding activities. Non value activities are those activities encountered or performed within the shipyard which the customer does not pay for. Thus, directly affecting the profit and overall energy consumption of the project.

The 7 deadly wastes are as discussed below:

Transport Waste: Involves the multiple, time consuming and unnecessary wasteful movement of sub-assemblies, block assemblies, steel plates, piping, fabrication material, fabricated parts, outfitting materials and consumables. This results in wasting of energy and an increase in costs due to liquid fuels and electricity to operate vehicles, forklifts, cranes and other hoisting equipment being used more than actually required.

Inventory Waste: Keeping excess steel plates, pipping, outfitting materials, fabrication materials, parts and consumables in the inventory results in wasting of energy as described above under transport waste. Excessive inventory levels result in cluttering of storage and buffer areas, requiring constant re-organising to gain access to required items. Apart from energy waste, the inventory costs money which simply sits on shelves or in storage with the risk of getting damaged each time it gets moved.

Motion Waste: Relates to the unnecessary motion of both workers and machinery, resulting in excessive energy consumption and increased wear and tear over time. This can be a result of poor ergonomics, improper machine operation or setup causing longer then required running times.

Waiting Waste: Relates to the disruption in the process flow of the shipyard. Excessive waiting times can result in overall project delay if the lost time is not made up through working overtime, especially in shipyard operations where the are many inter and successive dependencies. Working overtime means extra man-hours and energy consumption to complete a specific task. For instance, where 1 persons using one welding machine may have normally been required to complete a welding task an extra person using a second welding machine is put on the delayed job. Thus extra costs are incurred due to extra man-hours and energy consumption from the second person and welding machine being utilized.

Over-processing Waste: Within the shipyard this can relate to using oversize equipment to perform lesser activities, performing work above and beyond the scope or customer requirements and working within too tight tolerances. This results in increased energy consumption and cost because larger equipment uses more energy and more working hours and energy use is required to perform extra and higher specification work.

Over-production Waste: This relates to producing too many fabricated components, piping parts, sub-assemblies, main unit assemblies or orthogonal/non-orthogonal assemblies too early. This leads to available space being occupied by items not required at that point in time. This makes it difficult perform other tasks and store items required for upcoming tasks. This contributes to the transport, inventory and waiting wastes and associated extra costs and energy use.

Defects Waste: Any re-work that needs to be performed within the shipyard is considered as defect waste. This results in the wasting of resources and the increase of costs and energy consumption for the task which required re-work. Any re-work can result in delaying subsequent activities and increases the waiting waste.

These seven wastes are highly interrelated with one potentially effecting the other, compounding the wastages, associated costs, energy consumption and negatively affecting the actual value adding activities. Additionally, these wastes are also interrelated the pillars of the proposed shipyard energy management framework. Focusing on the pillars of the proposed shipyard energy management framework will help to eliminate these 7 deadly wastes, through proper planning, scheduling, production control, accuracy control, IHOP, production facilities, technology and shipyard layout.

Chapter 3.1.4 – IHOP

To enable a shipyard to become more competitive, reduce cycle time and to convert the extremely complex shipbuilding process into a simpler and more manageable process, the overall construction needs to be broken up into smaller components to allow for better focus, understanding and integration. Thus an integrated hull, outfitting and painting process (IHOP) needs to be adopted. The level of IHOP implementation varies from yard to yard. Improving and perfecting the implementation level and process allows the further reduction of the total time spent per vessel built (cycle time), thus not only savings costs on man-hours but also on electricity consumption due the more efficient process being followed. The aim is to minimize the amount of outfitting and painting done while the vessel under construction is on the slipway, in dry dock or alongside. Blocks constructed must have their associated fittings and painting job scopes close to full completion, allowing for minimal work to be performed once the blocks are welded together. The main idea is that there needs to be more overlapping of work and work done in tandem as opposed to first fully completing the steel assembly before moving to outfitting (Rubeša. R, Fafandjel. N & Kolic. D, 2011).

IHOP achieves improved efficiency and increased throughput by facilitating automation and allowing workers to have better access to cranes and appliances to aid their job scope. Workers can complete their assigned tasks in more comfortable working position, because overhead work is minimized and in most cases eliminated while working on the blocks or sub-assemblies. This results in the work being completed faster and being of better quality. There is also a reduction of staging requirements which involves a lot of setup and dismantling time. Any staging which may be required can be shared by the different workers. Competition of workers for space, overcrowding and cluttering of the vessel by routing of welding cables, temporary ventilation ducting, compressed air hoses and electrical cables as is normally the case in on-board work is eliminated. Cycle time is greatly reduced by the overlapping stages of production. All work done at early stages requires less man-hours compared to work performed at a later stage.

The IHOP involves hull construction, outfitting and painting, thus integrates the Hull Block Construction Method (HBCM), the Zone Outfitting Method (ZOFM), the Zone Painting Method (ZPTM) and Pipe Piece Family Manufacturing (PPFM) method. Importantly, a Product Work Breakdown Structure (PWBS) needs to be implemented to enable the integration of the four aforementioned methods successfully.

PWBS comprises of three main classifications.

1. To integrated all the of the above methods, PWBS divides the ship construction process into three work types, namely: Hull construction, outfitting and painting, each of which is further subdivided into fabrication and assembly. The assembly subdivions are linked to zones to tie in with the zone orientated production of the other production methods as previously discussed.

2. The product resources are classified into the material to be utilized for production, the facilities to be applied for production, the manpower and expenses to be charged for production.
3. Classification is made according to four product aspects namely; System, which is a structural or operational function of a product (e.g . ballast water system); Zone – which is a geographical division of a product (e.g. engine room or bridge, including the sub-divisions and combinations); Area – the division of the production process into work probelms of similar type (e.g physical feature, quality or quantity) and Stage which allows the sequencing of the production process (e.g on-unit, on-block and on-board outfitting and the steel construction process).

Together this allows the effective control of the production process and enables the manufacturing of parts and subassemblies for a coordinated and time scheduled outfitting of units and structural blocks, including the simultaneous utilization of indivual production processes for the requirements of separate systems. However the full and effective implementation of IHOP is not easy to achieve, especially for smaller shipyards. A high level of accuracy control, project management, expertise and integration is required to prevent costly mistakes.

Chapter 3.1.5 – Project Management

To ensure an efficient and successful project, facilities, man power, capital, information and material needs to be managed and coordinated properly. Initially the basic management cycle needs to be followed to perform the identification and priority setting of independent jobs or activities. This will create the platform for the application of commonly used methods, such as the Critical Path Method (CPM), Program Evaluation or Review Technique (PERT).

The Basic Management Cycle: The basic management cycle is shown in the figure 3.3 (Storch. R, Hammon. C, Bunch. H & Moore. R, 1995). Zone, Area, Stage and System relates to what was discussed under IHOP/PWBS. Production cannot start without effective planning, which is then followed by scheduling. Planning and scheduling is based on the build strategy and is integral to deciding on the sequence and time period within which the vessel will be constructed. Planning involves listing all the jobs as per PWBS, determining manpower and facility requirements, which jobs must be sequenced and cost estimation. Following this, design and engineering schedules are formulated, which includes the scheduling of the order in which all jobs must be performed, complete with start and stop times for each job. Material and manpower requirements for each stage is also included. Decisions on what build processes can be started and what needs to be purchased can then be made. Ordering of materials should be such that the materials are delivered as per schedule, or just on time, to avoid delaying build processes and taking up valuable storage space. During production control in the execution phase, actual progress monitored and consistently compared against the planned schedule. If there are any deviations, which can result in delays, then corrective action plans with schedules needs to be implemented to ensure set targets are not surpassed.

Planning, scheduling, execution and production control requires total integration with other shipbuilding functions to fully benefit from group technology, as discussed under IHOP.

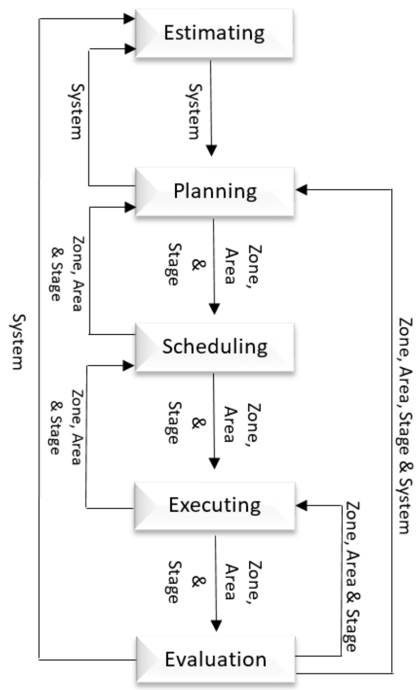

Figure 3. 3 – Management Cycle Source: Storch, R et.el, 1995.

PERT and CPM: The Program Evaluation and Review Technique (PERT) is often used together with the Critical Path Method (CPM). Both are network-based techniques.

PERT allows the analysis of all tasks, established using PWBS, involved within the shipyard project. This is achieved by either estimating the activity durations for each task using historical productivity indices or by using engineering labour standards, should productivity indices not be available. This will then allow the shipyard to establish the total time required to complete the project as a whole (cycle time).

CPM utilizes only one time and one cost estimation, where in comparison; PERT includes no cost estimation, but multiple time estimations like optimistic, pessimistic, most likely and expected time to complete a task.

CPM allows for a critical path to be established. The critical path is the path that takes the most time to complete, therefore leads to the expected project completion time.

The above only describes some of the available project management techniques. Shipyards may opt to use other techniques like Gantt Charts, Line of Balance or the Graphical Evaluation and Review Technique (GERT). Describing each technique is not the objective. The objective is to emphasize the importance of proper project management and the structured approach it provides. A lack of project management can cause disarray and will result in excessive re-work, increased man-hours and ultimately projects not being completed on time. The knock-on effect of this is the wasting of resources, increased energy consumption, increased GHG emissions and increased operational costs. Thus to ensure an on-budget, on-time and energy efficient project, effective project management is of critical importance. It will ensure that proper planning and scheduling is performed and any bottlenecks are identified and eliminated. It will also ensure materials are ordered and delivered on time, effective communication between all departments are maintained, outfitting opportunities are utilized at the maximum possible level at early stages and the integration between various shipbuilding functions is achieved.

Chapter 3.1.6 – Shipyard Layout

Energy savings, which directly relates to GHG emissions reductions and cost savings, from a shipyard layout perspective comes from deciding on and implementing the optimal shipyard layout to ensure an efficient production process that results in the lowest possible production times and least transportation distance and time.

Shipyard layout considerations are more applicable during the shipyard design process for new yards, but can be equally important to existing shipyards which need to adapt, expand and improve their layout, either of the entire yard or certain facilities to take advantage of process improvements, including bulk same or similar type vessel orders or build contract. It is possible to convert an existing shipyard into a third-generation shipyard by a careful application of modern computational tools and through the adoption of an innovative approach (Obadasi. A, Alkaner. S, Ölçer. A, & Sukas. N, 1997).

Deciding on the optimal shipyard layout is a complex decision, factors which needs to be taken into consideration include:

- Location factors with regards to region, community and site
- Layout factors from an energy consumption, operating cost and production time minimization perspective:

    - For steel stockyards – easy and quick access from the road and sea to ensure no time is wasted offloading new steel supplies with a direct supply of steel from the storage areas to the preparation shops. Plate stacking orientation should be adapted to the materials handling method to be employed, with sufficient access between piles. There should be designated piles for standard steel plates, high turnover steel, steel that needs to go to preparation machines, weekly loads and priority steel. Storage areas should have sufficient holding capacity to avoid overflow, clutter, confusion while allowing appropriate access.
    - For section preparation areas – The need to backtrack should be eliminated. Flow of material should be orderly and sequential, without interference between cropping, marking, bending and straighten or camber flow lines. Spatial planning should allow for sufficient allocation for scrap skips/containers, walkways, driveways for forklifts and buffer areas next to work sites.
    - For fabrication areas – These should be divided into the appropriate sub-assembly, main unit assembly which include flat unit assemblies,

curved unit assemblies, three dimensional assemblies and block assemblies, as well as orthogonal assemblies or non-orthogonal assemblies to ensure a structured and efficient workflow. Fabrication areas should be ergonomically designed with easy and quick access to the required fabrication tools and equipment.

Efficient transport of heavy materials and supplies within the shipyard is directly related to the materials handling equipment installed. Careful consideration should be made with regards to the amount, locations, safe working load, expected utilization rate, speed of operation and utility of lifting appliances to be installed. Lifting appliances to be installed should be of adequate capacity so that it is neither under size nor excessively oversized for the area within which it is installed.

Throughput should be maximized by deciding upon the appropriate main horizontal, vertical or linear, workflow to be utilized for each facility within the shipyard and whether the layout will be by process, by product or mixed layout. It is important that the optimal overall shipyard layout is implemented from the onset, as shipyard layout can result in increased transport, motion and waiting wastages, as discussed under process improvement. This equates to increased energy consumption, production times and GHG emissions. Fixing layout problems can be extremely costly and disruptive to the operation. Therefore, all available means for verification and validation including modern computer simulation tools should be utilized to obtain an optimal and future proof layout for the shipyard based on all available factors as there is no universal best shipyard layout.

Chapter 3.1.7 – Renewable Energy Employment

Shipyards can install renewable energy to reduce their reliance on the national grid or become self-sufficient and at the same time drastically reduce their CO_2

emissions. Alternatively, depending on the country within which the shipyard is located, the shipyard can also opt to buy green energy from renewable sources.

Installing renewable energy will involve installing a hybrid micro-grid system. Depending on the extend of renewable energy employment, hybrid micro-grid is a power generation system which incorporates at least two types of power technologies to supply power to local loads with the ability to operate either grid-connected or stand-alone (Fathima. A & Palanisamy. K, 2015).

Due to high and cyclic power demand from shipyard activities operating in stand-alone mode can be costly and not feasible for most shipyard. Firstly, most shipyards simply won't have the required space to install the required amount of solar panels and/or wind turbines to meet the peak cyclic loads of shipyard activities. Secondly, both solar panels and wind turbines have periods during which they will produce no electricity, i.e. during periods of no sunlight for solar panels and during periods of too low or too high wind speeds for wind turbines in relation to cut-in and cut-out wind turbine specific parameters. Thus to continue supplying electricity to the shipyard demands, a backup battery storage system will need to be also employed. The capacity of which will also have to be large enough to meet the peak and cyclic demands of shipyard activities.

Possible power generation capacity from solar and wind renewable sources is dependent on the efficiency of the installed unit and location of the shipyard, which needs to be taken into consideration and employing renewable energy sources.

Figure 3.4 shows the global wind power density. The colours on the global chart are linked to the colour scale shown in figure 3.5 indicating the amount of watts that can be produced per square meter. The selected layer is for a reference height of 100m, but can be selected for 50 or 200m as well. Countries like Argentina, Norway, Greenland, Iceland, Scotland and Namibia shows wind power densities in the range of 800 to more than 1300 W/m^2, indicating their high wind power potential.

Information from the chart and the downloadable area specific wind climate data files can be used to determine wind resources potential in the country within which a shipyard is located when making feasibility analysis and decisions. The generalized wind climate file, also known as a wind atlas file, contains the sector-wise frequency of occurrence of the wind (the wind rose) as well as the wind speed frequency distributions in the same sectors (as Weibull A- and k-parameters). The wind climates are specified for a number of reference roughnesses (roughness classes) and heights above ground level (Wind Atlas webpage, 2019).

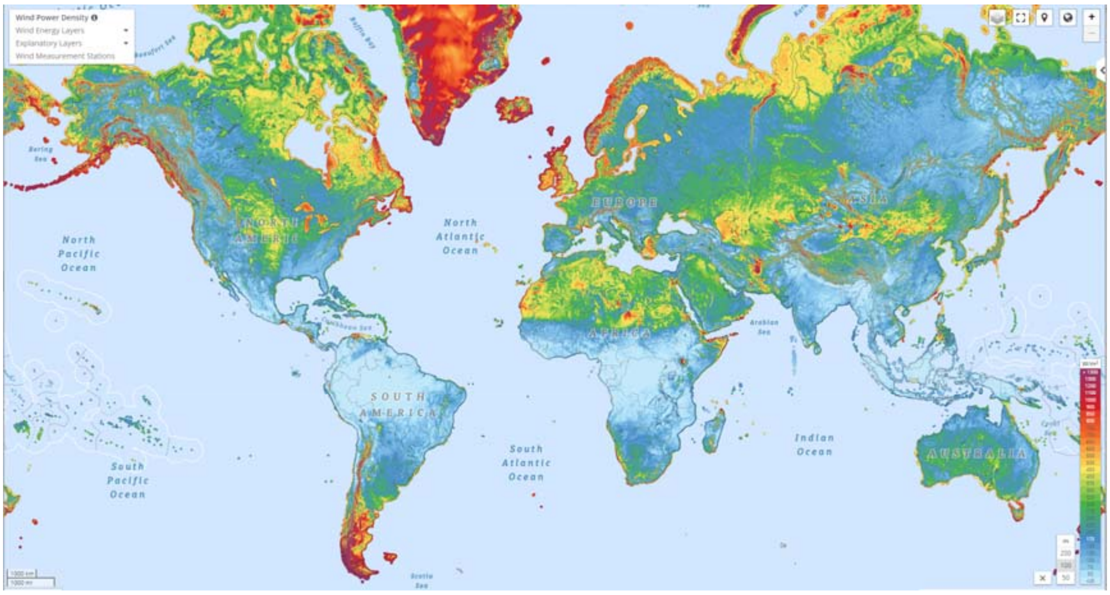

Figure 3. 4 - Global Wind Power Density Chart Source: Global Wind Atlas

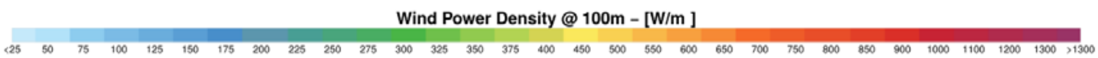

Figure 3. 5 - Wind Power Density Scale (W/m2) Source: Global Wind Atlas

Figure 3.6 shows the: PVOUT (PV Electricity output): Amount of energy, converted by a PV system into electricity [kWh/kWp] that is expected to be generated according to the geographical conditions of a site and a configuration of the PV system. Three configurations of a PV system are considered: (i) Small residential; (ii) Medium-size commercial; and (iii) Ground-mounted large scale (Global Solar Atlas, 2019). This information can be used by a shipyard when making feasibility analysis and decisions on installation of photovoltaic systems within a micro grid.

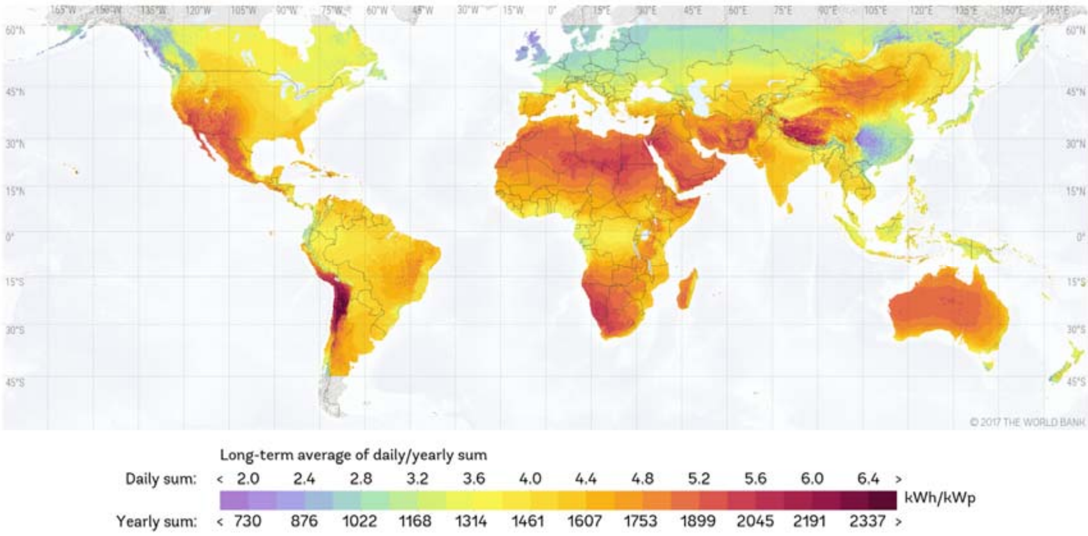

Figure 3. 6 - PV Power Potential Chart   Source: Global Solar Atlas

Compared to Concentrated Solar Power (CSP), Photovoltaics (PV) is the most commonly used. Figure 3.7 shows the globally installed capacity of PV and CSP systems.

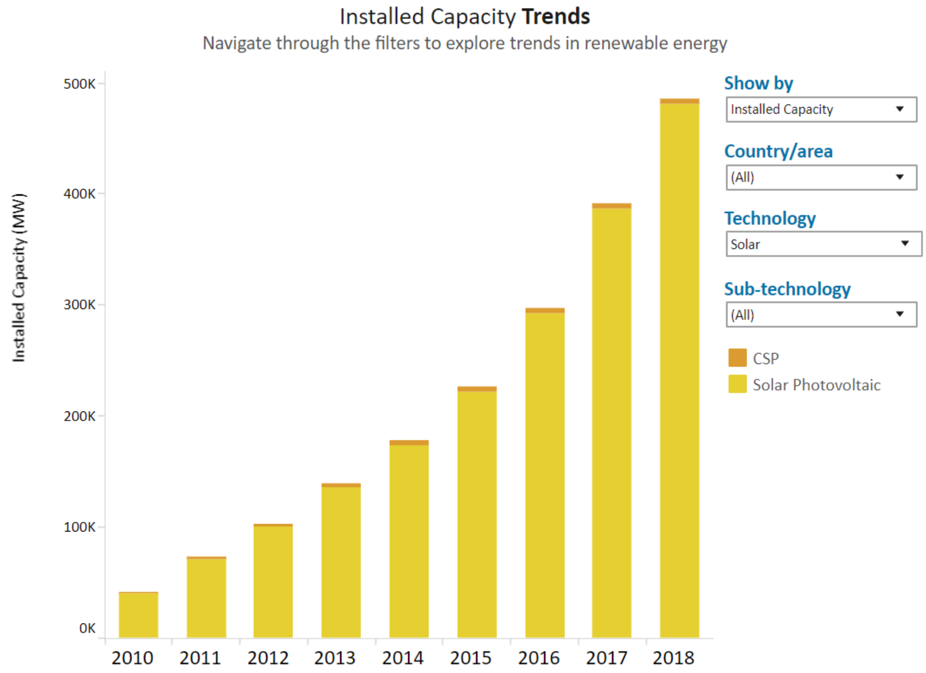

Figure 3. 7 - Globally installed Solar Capacity Source: Irena

Apart from solar and wind energy, renewable energy also includes bioenergy, geothermal energy, hydropower and ocean energy. Hydropower can't be directly employed by a shipyard, except through national grid supply. Like hydropower power, biomass can be obtained through the national grid instead of being directly employed by the shipyard. However, shipyards can resort to utilizing of liquid bio-fuel as a replacement to power their internal combustion engine transport and equipment. Geothermal energy can also be obtained through the national grid. However geothermal heat pumps can be utilized for the heating or cooling of shipyard office spaces and buildings. Ocean waves, tides or current can be harnessed to generate renewable energy. However, this technology is still under development and not fully mature or suitable at this stage for consideration by shipyards. The type or mix of the national grid energy source is dependent on the country and area within which the shipyards are located.

Chapter 4 – Case Study - Production Facility and Technology Pillar

Chapter 4.1 - Introduction & Methodology

The main energy sources for shipyards are electricity (either fossil fuel or renewable supply), gas and liquid fuel. Electricity is responsible for approximately 75 – 80 percent of a shipyards annual energy budget (USEPA, 2007). Figure 4.1 shows the total electricity consumption of the main electricity consumers for the construction of a 76 000 dead weight (DWT) bulk carrier (Kameyama. M, Hiraoka. K, Sakurai. A, Naruse. T & Tauchi. H, 2000).

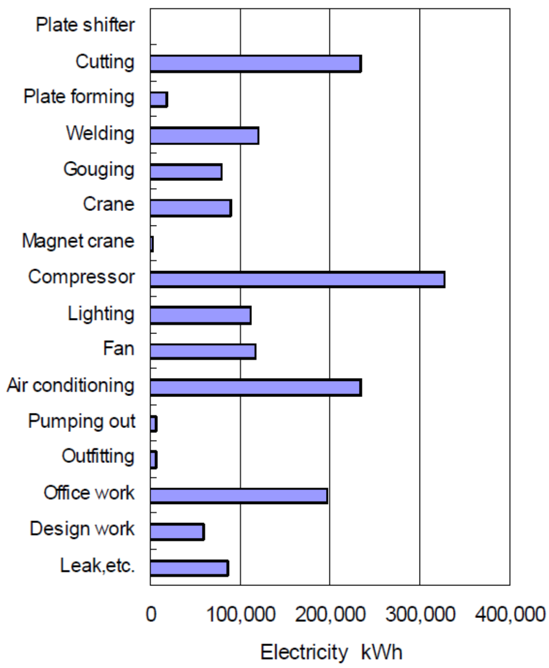

Figure 4. 1- Electricity consumption by source to build a 76 000 DWT bulk carrier Source: Kameyama. M. et.al., 2000)

A total of 1.7 million kWh of electricity was consumed during the project, with consumption from the associated compressor totalling 325 000 kWh, 19% of the overall electricity consumption. Thus making the compressor the most significant energy user within that shipyard. The compressed air system (CAS) is an essential production support system upon which production processes rely to maintain the production flow. Thus compressed air is an essential commodity within a shipyard with the continued and appropriate supply at all costs often taking preference over an optimal and energy efficient supply. Inefficient use and supply amounts to significantly extra CO_2 emissions into the atmosphere and large amounts of lost revenue.

Hence, the focus of this chapter will be on an approach to improving the energy consumption of compressed air systems within shipyards. The following methodology will be followed:

- Describing the CAS
- Analyzing the data collected from a compressed air system within a marine production facility
- Producing a compressed air demand profile
- Producing a baseline for the energy consumption, CO_2 emissions and energy cost from the analyzed data
- Identify areas of concern within the CAS
- Give recommendations on reducing the energy consumption, CO_2 emissions and energy cost.
- Produce a deterministic model for calculating the total shift energy consumption of the compressor
- Use the "OptQuest" function of the Oracle Crystal Ball software add-in within Microsoft Excel to optimize the total shift energy consumption based on variables related to the data analysis findings and recommended system improvements.
- Compare the results from the optimization to the baseline figures

Chapter 4.2 - The Compressed Air System

The compressed air system consists of two sides, namely the demand side and the supply side. The demand side includes end users, storage and distribution components. Whereas the supply side includes the actual compressor and associated air treatment equipment (DOE, 2003).

Fig 4.2 shows the typical components of an Industrial Compressed Air System.

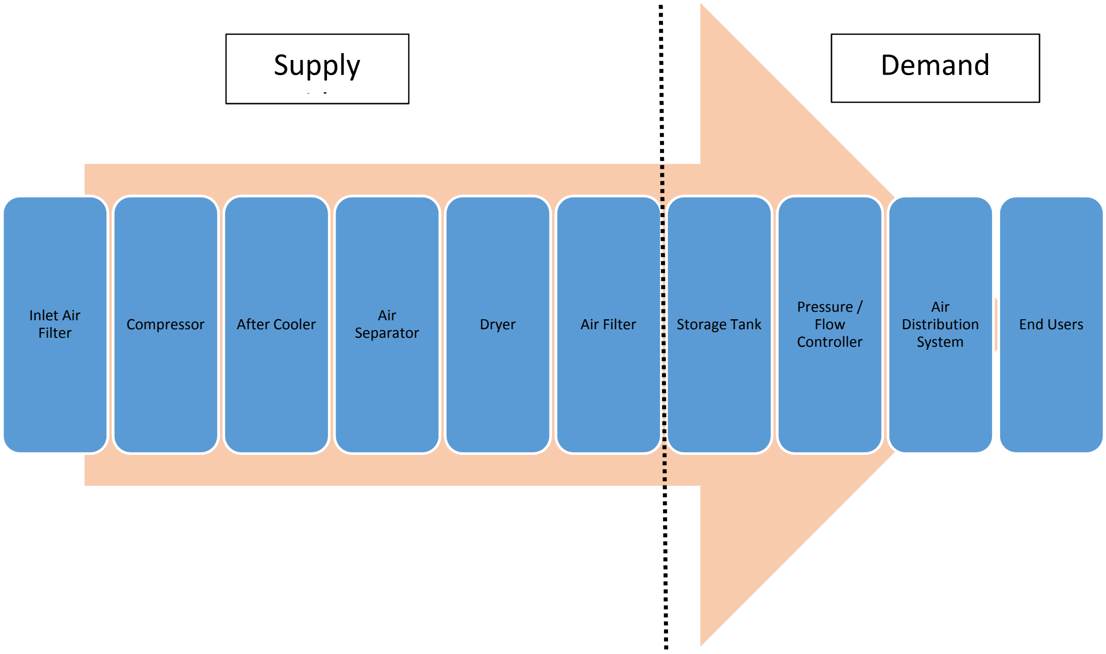

Figure 4. 2 – Components of an Industrial CAS Source: Author

Chapter 4.2.1 - Supply Side

Inlet Air Filter: Cleans the intake air to the compressor from damaging particles.

Compressor: The compressor is the main component of the compressed air system. It is a mechanical device which takes in atmospheric air and reduces its volume through an increase in pressure. There are typically 2 types of compressors, positive displacement and dynamic compressors. Positive displacement compressors include reciprocating and the rotary type compressors. Dynamic compressors include the centrifugal and axial type compressors.

After Cooler: Decreases the temperature of the output air after the final compression stage.

Air Separator: Separates any liquid or moisture that may be contained within the output air.

Dryer: Dries the saturated air coming from the separator. Saturated air leaving the separator can become condensed and moisturized if it is further cooled while travelling along the air distribution system. The supply of dry air to the end users is essential to prevent corrosion, damage to and malfunction of end user equipment.

Air Filter: Further cleans the air from contaminants before entering the air receiver/storage tank. Contaminants include particles from the preceding components and distribution system, lubricants and condensate. Different types of filters are available depending on the filtration requirement.

Chapter 4.2.2 - Demand Side

Air Receiver/Storage Tank: Provides the ability to store the compressed air produced by the compressor, allowing peak demand periods to be satisfied. Air receivers are essential in systems where the compressed air demand is not consistent, like in shipyards.

Pressure/Flow Controller: This component is not compulsory, but can be used in conjunction with the integrated compressor control system to stabilize the final output pressure into the air distribution system.

Air Distribution System: Piping system network responsible for connecting all the components of the compressed air system and transporting the compressed air to each end user location.

Filter/Regulator/Lubricator: Final air filter before the end user. Output pressure also get further regulated as per end user requirement. Lubrication can also be applied at this point.

End Users: This is where the produced compressed air is actually consumed. End users in shipyards include, but is not limited to: Pneumatic tools, air hoists, actuators, air pumps, blowers, automated equipment, grid blasters, spray painting equipment, hydro blasters and manufacturing and production equipment requiring compressed air for certain functions.

To avoid interruptions to shipyard operations, the supply side must at all-time be capable of satisfying the compressed air demand from the production systems. To achieve this the compressor air system must be properly specified to meet the associated shipyard compressed air demand. Sufficient storage capacity must be provided to ensure the compressor runs efficiently and to cater for the fluctuating compressed air demand normally experienced with shipyard compressed air utilizing activities.

Chapter 4.3 – Energy audit and findings of a compressed air system within a subject marine production facility

To assess the performance, confirm the operating parameters and conditions of a compressed air system you first need to familiarize yourself with the entire system. Following that, an energy audited can be performed on the system. Using the collected data, baseline operational performance levels can be established. After proper analysis of the collected data, factual recommendations can be made on potential system improvements to save on energy consumption and to reduce CO_2 emissions.

The CAS energy audit forms part of the overall shipyard energy audit program, as shown in the figure 4.3.

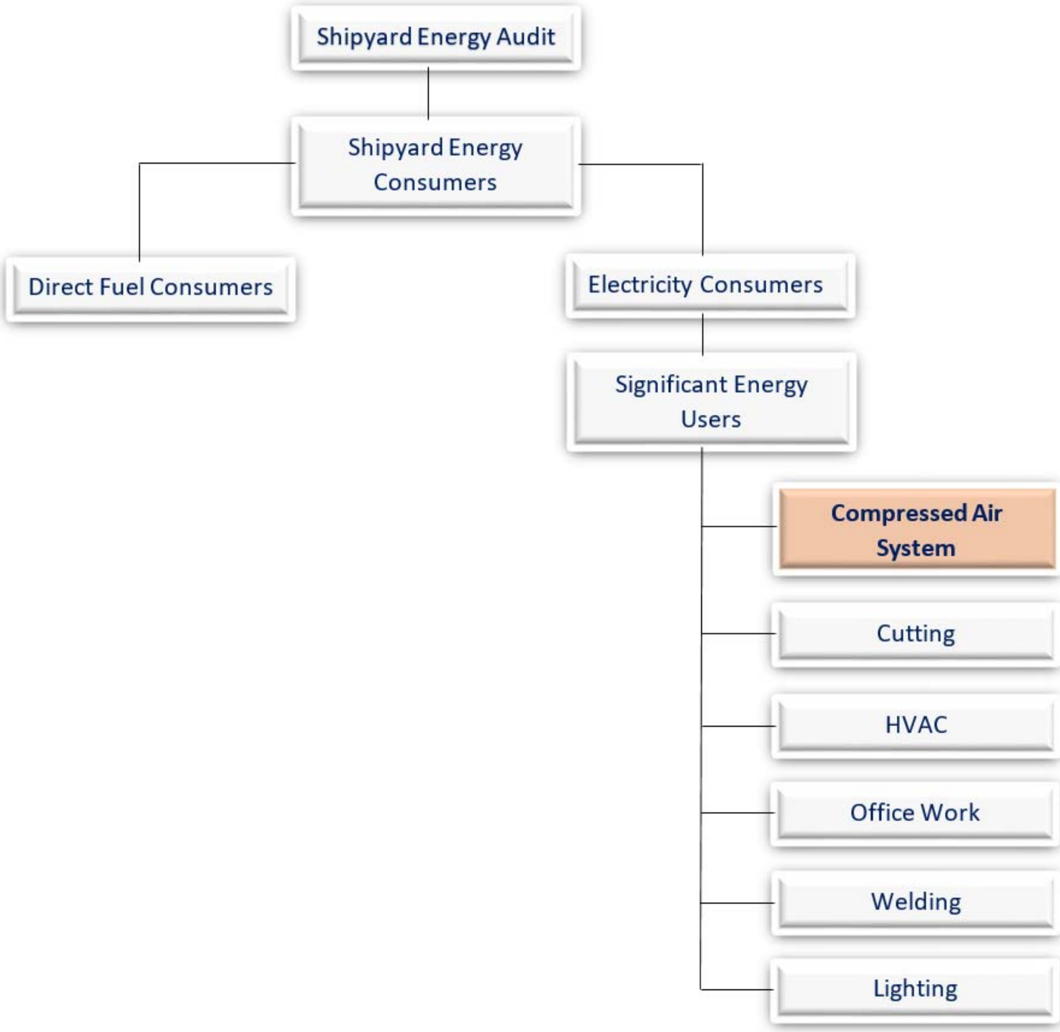

Figure 4. 3 - Shipyard Energy Audit Scheme Source: Author

The SEUs indicated above only serves as a guide. SEUs will differ from yard to yard as it depends on their operations, various equipment being utilized, mechanization in relation to man power utilization and the amount of work being outsourced. Thus to fully comprehend their own energy consumption, it is important that each shipyard do their energy mapping and energy audits.

To achieve the remaining objectives of this chapter, CAS information and data logged by Uyan, E (2019) at a marine production facility will be utilized. Additionally, the following information will be presented:

- The specifications of the compressor, air storage tank, upper and lower activating pressure settings
- A description the data logging process employed
- A summary of the logged data results
- A table with the data logged
- A compressed air demand (CAD) profile graph
- Analysis of results
- Conclusions from analysis

Table 4.1 shows the specifications of the dayshift compressor.

Type	Positive displacement, rotary screw
Drive	Fixed Speed Drive (FSD)
Control Method	Load / Unload with overrun timer
Power Rating	55 kW
Specific Capacity (SC)	10.153 m^3/min
Specific Power Consumption (SPC)	0.1595 m^3 kW/min

Table 4. 1- Specifications of dayshift air compressor Source: Compiled by author from Uyan, E, 2019.

The storage tank size coupled to the above compressor is 2m^3. The lower activating pressure for the compressor is set at 6.5 bars and the upper activating pressure is set at 7.5 bars, in accordance with the facility equipment requirements to ensure proper operation and to prevent equipment damage.

Chapter 4.3.1 - Description of the data logging process

A Chauvin Arnoux power and energy data logger (PEL) 103 was used to perform the power and energy measurements on the compressed air system for a single dayshift period. A power and energy meter is an instrument that measures the current and voltage flowing through an electric system (O'Driscoll and O'Donnell, 2013). Before the power and energy meter was used it was connected to a personal computer

(PC) installed with the PEL software application. The power and energy meter was then configured with the appropriate setting with regards to plant electricity distribution system, nominal voltage and voltage ratios, nominal frequency, current measurement and sampling period. Three voltage clips and three current probes were used due to the 3 phase power system. The voltage clips and current probes were attached at the input power supply box of the compressor. The voltage clips were attached to the screws of the electric input terminal boards and the current probes, which work on magnetic fields, were attached around the power cables. Data was then logged for the required time period. Logged data was stored on a SD card within the PEL 103 power and energy meter. Once the data logging process was complete the meter was disconnected from the compressor's input power supply box and connected to the PC installed with the PEL software application. The logged data was then imported and for analysis.

Chapter 4.3.2 - Data Logging Results

In summary, the data retrieved showed the following:

- The total number of cycles the compressor performed during the logging period
- The compressor power demand profile showing the power demand during each load and unload mode per cycle performed by the compressor

To get a clear overview of all the cycles performed by the compressor during the data logged period a table was compiled from the data collected by Uyan, E (2019). Table 4.2 shows extracts of the compressor operational data, with the complete table presented in Appendix 1. The table includes the cycle sequence, load time, power demand for each mode, unload time and cycle time for each of the 467 cycles. The load factor (LF), compressed air produced per cycle (CAP/cycle) in cubic meters, compressed air demand rate per cycle (CAD rate/cycle) in cubic meters per minute was calculated for each cycle.

Cycle time is the sum of the load and unload time.

Cycle Time = load time + unload time (Equation 4.1

The load factor (L.F) was calculated using the below formula and expressed as a percentage:

$$Load\ Factor, LF\ (\%) = \frac{load\ time}{load\ time + unload\ time}$$

(Equation 4.2

The compressed air produced per cycle (CAP/cycle (m^3)) was calculated using the below formula:

CAP/cycle (m^3) = SPC * $P_{average\ load}$ * t_{load} (Equation 4.3

SPC = Specific power consumption (m3. kW/min) of the compressor

$P_{average\ load}$ = Average power demand in kW

t_{load} = load time

The compressed air demand rate per cycle (CAD rate/cycle (m^3/min)) was calculated using the below formula:

$$CAD_{cycle}\ (m^3/min) = \frac{CAP_{cycle}}{cycle\ length}$$

(Equation 4.4

Table 4.2 (Appendix 1).

Time Interval	Cycle #	a	b	c	d	e	f		g	h	i	j
		Load Time (sec)	Power Demand in Load Mode (kW)	Unload Time (Sec)	Power Demand in Unload Mode (kW)	Cycle Time (Sec)	Cycle Time (Min)		Load Factor	CAP/cycle (m3)	CAD rate/cycle (m3/min)	CAD rate/cycle (m3/sec)
						e=a+c	f=e/60		LF%=Ltime/(Ltime+Ultime)	CAP=SPC*Pl+Tload(min) CAP=SPC*b*(a/60)	CAD=CAP/Cycle Time (min) CAD=h/f	CAD=i/60
08:35-0900	1	12	63.91	13	35.47	25	0.42		48.00%	2.04	4.89	0.08
08:35-0900	2	15	63.91	12	35.47	27	0.45		55.56%	2.55	5.66	0.09
08:35-0900	3	13	63.91	35	35.47	48	0.80		27.08%	2.21	2.76	0.05
08:35-0900	4	10	63.91	49	35.47	59	0.98		16.95%	1.70	1.73	0.03
08:35-0900	5	9	63.91	59	35.47	68	1.13		13.24%	1.53	1.35	0.02
08:35-0900	6	11	63.91	65	35.47	76	1.27		14.47%	1.87	1.48	0.02
08:35-0900	7	11	63.91	56	35.47	67	1.12		16.42%	1.87	1.67	0.03
08:35-0900	8	12	63.91	42	35.47	54	0.90		22.22%	2.04	2.27	0.04
08:35-0900	9	11	63.91	74	35.47	85	1.42		12.94%	1.87	1.32	0.02
08:35-0900	10	10	63.91	48	35.47	58	0.97		17.24%	1.70	1.76	0.03
08:35-0900	11	13	63.91	66	35.47	79	1.32		16.46%	2.21	1.68	0.03
08:35-0900	12	11	63.91	72	35.47	83	1.38		13.25%	1.87	1.35	0.02
08:35-0900	13	12	63.91	62	35.47	74	1.23		16.22%	2.04	1.65	0.03
08:35-0900	14	12	63.91	59	35.47	71	1.18		16.90%	2.04	1.72	0.03
08:35-0900	15	11	63.91	61	35.47	72	1.20		15.28%	1.87	1.56	0.03
08:35-0900	16	11	63.91	61	35.47	72	1.20		15.28%	1.87	1.56	0.03
08:35-0900	17	12	63.91	73	35.47	85	1.42		14.12%	2.04	1.44	0.02
08:35-0900	18	11	63.91	73	35.47	84	1.40		13.10%	1.87	1.33	0.02
08:35-0900	19	12	63.91	38	35.47	50	0.83		24.00%	2.04	2.45	0.04
09:00-09:30	20	10	63.63	39	35.79	49	0.82		20.41%	1.69	2.07	0.03
09:00-09:30	21	16	63.63	48	35.79	64	1.07		25.00%	2.71	2.54	0.04
09:00-09:30	22	16	63.63	15	35.79	31	0.52		51.61%	2.71	5.24	0.09
09:00-09:30	23	10	63.63	45	35.79	55	0.92		18.18%	1.69	1.85	0.03
09:00-09:30	24	11	63.63	63	35.79	74	1.23		14.86%	1.86	1.51	0.03
09:00-09:30	25	11	63.63	71	35.79	82	1.37		13.41%	1.86	1.36	0.02

Break. Complete table is shown in Appendix 1

16:00-16:45	437	20	63.52	30	35.75	50	0.83		40.00%	3.38	4.05	0.07
16:00-16:45	438	11	63.52	21	35.75	32	0.53		34.38%	1.86	3.48	0.06
16:00-16:45	439	17	63.52	46	35.75	63	1.05		26.98%	2.87	2.73	0.05
16:00-16:45	440	11	63.52	40	35.75	51	0.85		21.57%	1.86	2.19	0.04
16:00-16:45	441	11	63.52	60	35.75	71	1.18		15.49%	1.86	1.57	0.03
16:00-16:45	442	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	443	14	63.52	58	35.75	72	1.20		19.44%	2.36	1.97	0.03
16:00-16:45	444	11	63.52	20	35.75	31	0.52		35.48%	1.86	3.60	0.06
16:00-16:45	445	12	63.52	64	35.75	76	1.27		15.79%	2.03	1.60	0.03
16:00-16:45	446	11	63.52	39	35.75	50	0.83		22.00%	1.86	2.23	0.04
16:00-16:45	447	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	448	14	63.52	56	35.75	70	1.17		20.00%	2.36	2.03	0.03
16:00-16:45	449	11	63.52	45	35.75	56	0.93		19.64%	1.86	1.99	0.03
16:00-16:45	450	13	63.52	66	35.75	79	1.32		16.46%	2.20	1.67	0.03
16:00-16:45	451	11	63.52	72	35.75	83	1.38		13.25%	1.86	1.34	0.02
16:00-16:45	452	11	63.52	39	35.75	50	0.83		22.00%	1.86	2.23	0.04
16:00-16:45	453	12	63.52	73	35.75	85	1.42		14.12%	2.03	1.43	0.02
16:00-16:45	454	11	63.52	74	35.75	85	1.42		12.94%	1.86	1.31	0.02
16:00-16:45	455	11	63.52	35	35.75	46	0.77		23.91%	1.86	2.42	0.04
16:00-16:45	456	17	63.52	17	35.75	34	0.57		50.00%	2.87	5.07	0.08
16:00-16:45	457	11	63.52	73	35.75	84	1.40		13.10%	1.86	1.33	0.02
16:00-16:45	458	11	63.52	66	35.75	77	1.28		14.29%	1.86	1.45	0.02
16:00-16:45	459	13	63.52	73	35.75	86	1.43		15.12%	2.20	1.53	0.03
16:00-16:45	460	11	63.52	45	35.75	56	0.93		19.64%	1.86	1.99	0.03
16:00-16:45	461	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	462	16	63.52	36	35.75	52	0.87		30.77%	2.70	3.12	0.05
16:00-16:45	463	11	63.52	57	35.75	68	1.13		16.18%	1.86	1.64	0.03
16:00-16:45	464	11	63.52	69	35.75	80	1.33		13.75%	1.86	1.39	0.02
16:00-16:45	465	11	63.52	76	35.75	87	1.45		12.64%	1.86	1.28	0.02
16:00-16:45	466	12	63.52	83	35.75	95	1.58		12.63%	2.03	1.28	0.02
16:00-16:45	467	11	63.52	78	35.75	89	1.48		12.36%	1.86	1.25	0.02
	Totals	5904		23301		29205	486.75					
	Average	12.64	63.69	49.90	35.60	62.54	1.04		20.22%	2.14	2.56	0.04

Table 4. 2 – Complete compressor operational data
Source: Compiled by author from Uyan, E, 2019.

Fig 4.4 - Compressed Air Demand (CAD) Profile – Dayshift

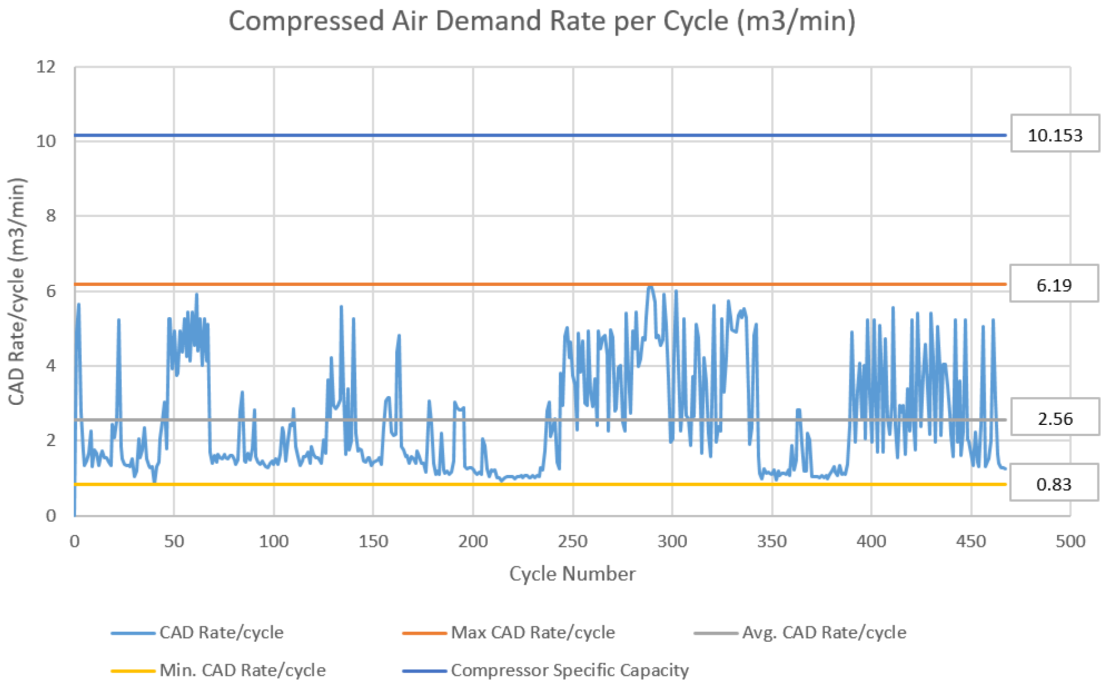

Figure 4. 4 – CAD Profile for the dayshift Source: Author from data Uyan. E, 2019

Figure 4.4 was compiled after the calculation of the CAD during each of the 467 cycles. It shows the CAD for each cycle along with the compressor specific capacity, maximum, average and minimum CAD in m^3.

Chapter 4.3.3 - Analysis of results

After analysis of the logged data it could be seen that there is a continuous power demand from the compressor throughout the entire data logging period, alternating from approximately 66 kW to 33 kW as the compressor cycles through load and unload mode. The 66 kW is more than the 55 kW rating for the motor, however, this is a norm for compressors operating with load and unload modes; a compressor with this control type draws about 105-115% of its power rating in load-mode and about 20-60% in unload-mode (Schmidt and Kissock, 2005). Not once during the data logging period did the power demand drop to zero kW power demand, which is normally the case when the compressor auto shuts off during a long unload period, as set in the compressor parameters, a function with which this compressor is equipped.

The following can be seen in figure 4.6, the maximum CAD for the entire shift was 6.19 m^3/min, the minimum CAD is 0.83 m^3/min, the average CAD is 2.56 m^3/min. The erratic compressed air demand during the shift can also be clearly seen in figure 4.4. Fig 4.5 is a summary of the data shown in figure 4.4. The dayshift period was divided into nine intervals of one hour each and the maximum compressed air demand along with the average compressed air demand during each one-hour period is shown, including the compressor specific capacity.

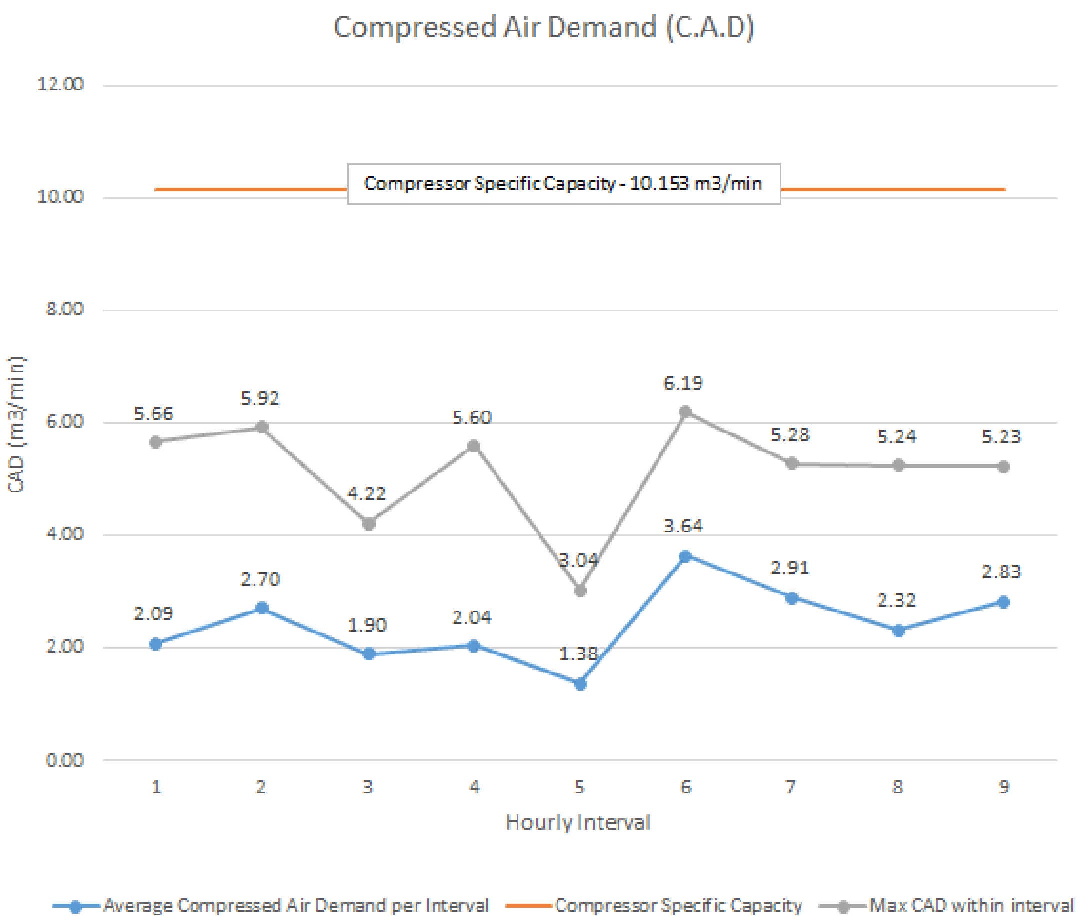

Figure 4. 5 – C.A.D Profile per 1 hour interval Source: Author from data Uyan. E, 2019

Table 4.3 shows the number of cycles during each one-hour interval. The first interval shows significantly less cycles than the rest of the intervals, because the compressor only started up at 08:35, as air was still being consumed from the storage tank. The compressor went through a total of 467 cycles during the shift when the compressor was stopped at 17:45. Total actual running hours for the shift is 8.11 hours, derived from the load and unload time data.

	DATA SUMMARY						
	Number of Cycles	Cumulative Load time for Load Cycles (sec)	Cumulative UnLoad time for Unload Cycles (sec)	Average Load Time (sec) - Tload	Average Unload Time (sec) - Tunload	Average Power Consumption during Load Cycle	Average Power Consumption during UnLoad Cycle
1st Hour (08:00-09:00)	19	219	1018	11.53	53.58	65.11	35.47
2nd Hour (09:00 - 10:00)	66	833	3079	12.62	46.65	63.84	35.59
3rd Hour (10:00-11:00)	48	571	2650	11.90	55.21	63.57	35.87
4th Hour (11:00-1200)	54	633	2972	11.72	35.45	63.81	35.45
5th Hour (12:00-13:00)	40	442	3174	11.05	79.35	63.50	35.04
6th Hour (13:00-14:00)	76	1091	2523	14.36	33.20	63.71	36.26
7th Hour (14:00-15:00)	62	809	2841	13.05	45.82	63.85	35.09
8th Hour (15:00-16:00)	53	661	2958	12.47	55.81	63.51	35.53
9th Hour (16:00-17:00)	49	645	2086	13.16	42.57	63.52	35.75
Totals	467	5904	23301				
Shift Running Hours		1.64	6.4725				
Total Shift Running Hours		8.11					

Table 4. 3 – Summarized compressor operational data Source: Author

Chapter 4.3.4 - Conclusions from the energy audit and analysis

After the analysis of the logged data it could be concluded that:

1. The storage tank size is too small
2. The compressor is too large for the application.

The reasons for these conclusion are elaborated on below.

When a storage tank is too small it results in the compressor constantly cycling through load and unload mode to satisfy the compressed air demand. The air in the storage tank gets consumed in a short period of time, causing the compressor to be switched to load mode at the lower activating point of 6.5 bars shortly after going into unloads mode. This is clearly evident in this scenario; the average unload time is only 49.9 seconds. This leads to this undesirable scenario called short-cycling (Bierbaum, U & Hütter, J., 2004). Short cycling is evident because of the following:

Compressor electrical motor running above the maximum allowable cycles per hour

For an electrical motor to run efficiently and to prevent long term damage to the motor it should not run more then a certain amount of cycles per hour. Figure 4.6 shows the allowed number of cycles for an electric motor depending on the power rating (Bierbaum and Hütter, 2004)

Motor power rating (kW)	Allowed cycles/h Al(1/h)
4-7.5	30
11-22	25
30-55	20
65-90	15
110-160	10
200-250	5

Figure 4. 6 – Max allowable cycles per hour for an electric motor
Source: (Bierbaum and Hütter, 2004)

The subject compressor's electrical motor has a 55 kW power rating. Thus the maximum allowed cycles per hour is 20. The compresor completed a total of 467 cycles during 8.11 hours of running time. This equates to an average of 57.6 cycles per hour. The number of cycles per hour for each hour interval, as discussed earlier, is shown in figure 4.7.

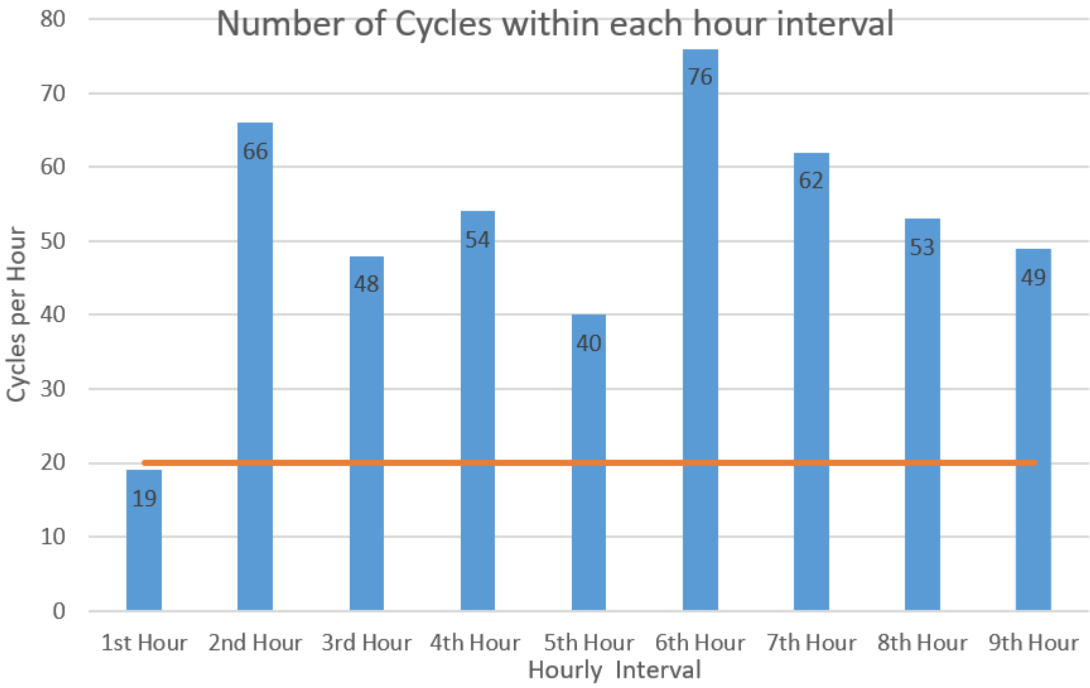

Figure 4. 7 – Number of cycles per hour Source: Author

The orange line represents the maximum allowable cycles per hour for this compressor. As can be seen, apart from the 1st hour interval, every other hour interval significantly exceeded the maximum allowable cycles per minute. The only reason the 1st hour interval is below the maximum allowable cycles per minute is because the 1st cycle only started at 08:35.

Auto-shutdown never activates on the compressor

This means the unload period is too short for the auto-shutdown function to perform an actual compressor shutdown and enter into the 0 kW demand, energy saving state. If the compressor would enter the shutdown state during a long unload period, then the compressor power demand graph should be similar to the graph in figure 4.8. Figure 4.8 shows a power demand of 0 kW during long unload periods, whereas information from the logged data showed that the power demand never dropped below 33 kW during the entire data logging period.

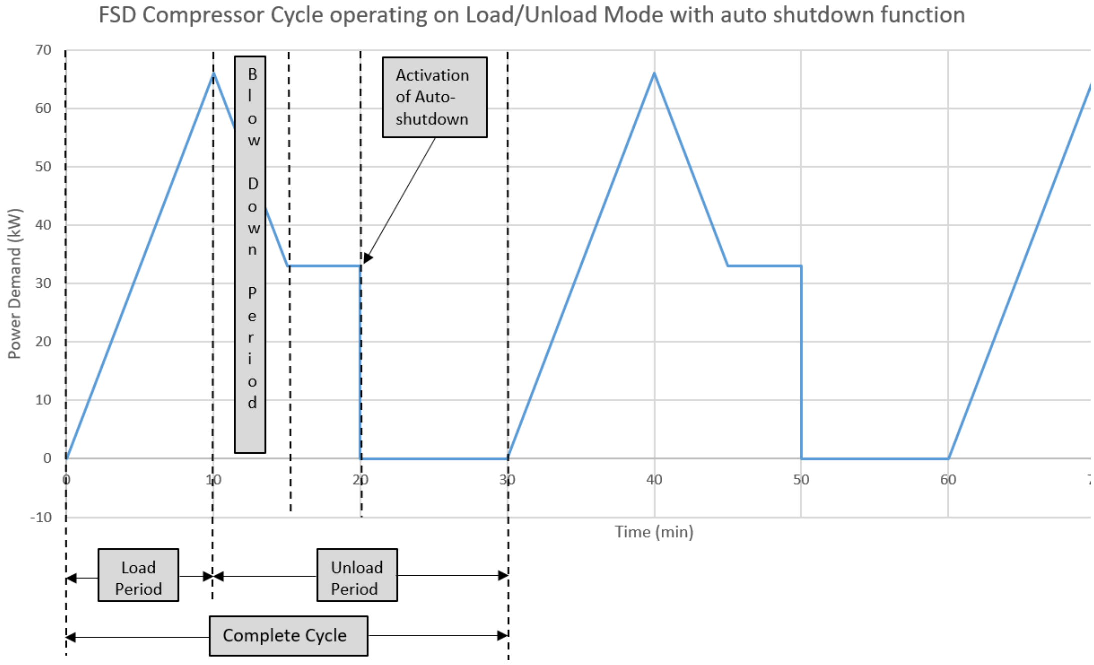

Figure 4. 8 – Load/Unload mode on FSD Compressor with auto shutdown. Source: Author

Sufficiently long unload periods will allow auto-shutdown to be activated (depending on the time period setting), provided an appropriate size storage tank is fitted.

The equation to calculate the appropriate storage tank size to fit, as a minimum, taking into consideration the max cycles per hour is given below (Agricola et al., 2003):

$$V_S = \frac{SC * 60 * [x - x^2]}{NC_{max} * \Delta P} \quad (m^3)$$

(Equation 4.5

Where:

V_s – Required air storage tank volume (m^3)
SC – Specific capacity of the compressor (m^3/min)
x – Utilization factor
ΔP – Pressure difference between the upper and lower activation point
NC_{max} – Maximum allowable cycles per minute

The utilization factor is calculated by using the below equation:

$$x = \frac{CAD_{max} - CAD_{avg}}{SC}$$ (Equation 4.6

CAD_{max}, CAD_{avg} and SC was given earlier as;

CAD_{max}	= 6.19 m^3/min
CAD_{avg}	= 2.56 m^3/min
SC	= 10.153 m^3/min

Thus x = (6.16-2.35)/10.153 = 0.36

The upper and lower pressure activation points, are 7.5 bars and 6.5 respectively. The NC_{max} is 20 cycles per minute.

Thus the minimum required air storage tank volume is:

Vs = (10.153*60(0.36))/(20*(7.5-6.5) = 7 m^3

Note: Since NC_{max} is in hours, thus the SC value needs to be multiplied by 60 to convert it to hours as well.

This shows that the currently installed air storage tank volume of 2 m^3 is not sufficient, resulting in the severe short cycling of the compressor.

CAD

As shown previosly in figure 4.6 and 4.8, the maximum CAD experienced during the entire data logging period was 6.19 m^3/min, while the average CAD is 2.56 m^3/min. Genenerally a safety margin of 20% is applied on top of the maximum CAD to allow for any CAD spikes and for possible future CAD increase within the facility. In this case a 64% safety margin is in use, thus the compresor is oversized.

Load times and Load Factor

The load times represent the time that the compressor actually perform usefull work by adding compressed air to the system. During unload time no compressed air is addd to the system, thus no usefull work is being done. Thus to improve the utilization of the compressor the load times needs to be longer. The avaerage load time for this compressor is 12.62 seconds while the average unload time is 49.9 seconds. Thus this compresser does more time adding no value compared to actuall value addition work. This is shown by the avarage load factor of 20.2%. Showing that the compressor is only used for 20.2% of the total time to actually generate compressed air.

The load times for this comprezsor is short because of its high specific capacity of 10.153 m^3/min in relation to the small storage tank volume. Thus, once the lower activation is activated at 6.5 bars it only takes on avaerage 12.62 seconds to fill the air storage and reach the upper activation point of 7.5 bars, returtning to the unload state.

Finally, to reduce the energy consumption of the compressed air system, specifically from the compressor and air storage tank perspective;

1) the tank size needs to be increased if the existing compressor is to be retained or

2) a new compressor along with an approproately sized air storage tank needs to be installed.

Chapter 4.4 - Compressor Energy Consumption and CO_2 Emissions baseline

To provide a basis for comparison to assess system recommended improvements in relation to energy consumption and CO_2 emissions, a baseline needs to be established based on the current system performance.

To calculate the actual power consumption of the compressor for the entire shift, the operational data from table 4.2 was divided into nine intervals of one hour each, 08:00 to 09:00, 09:00 to 10:00, 10:00 to 11:00, 11:00 to 12:00, 12:00 to 13:00, 13:00 to 14:00, 14:00 to 15:00, 15:00 to 16:00 and 16:00 to 17:00. As an example, table 4.4 shows the compressor operational data for the hour interval from 08:00 to 09:00.

Time Interval	Cycle #	a	b	c	d	e	f
		Load Time	Power Demand in Load Mode	Unload Time	Power Demand in UnLoad Mode	Cycle Time	Cycle Time
		(sec)	(kW)	(sec)	(kW)	(sec)	(min)
08:00-0900	1	12	63.91	13	35.47	25	0.42
08:00-0900	2	15	63.91	12	35.47	27	0.45
08:00-0900	3	13	63.91	35	35.47	48	0.80
08:00-0900	4	10	63.91	49	35.47	59	0.98
08:00-0900	5	9	63.91	59	35.47	68	1.13
08:00-0900	6	11	63.91	65	35.47	76	1.27
08:00-0900	7	11	63.91	56	35.47	67	1.12
08:00-0900	8	12	63.91	42	35.47	54	0.90
08:00-0900	9	11	63.91	74	35.47	85	1.42
08:00-0900	10	10	63.91	48	35.47	58	0.97
08:00-0900	11	13	63.91	66	35.47	79	1.32
08:00-0900	12	11	63.91	72	35.47	83	1.38
08:00-0900	13	12	63.91	62	35.47	74	1.23
08:00-0900	14	12	63.91	59	35.47	71	1.18
08:00-0900	15	11	63.91	61	35.47	72	1.20
08:00-0900	16	11	63.91	61	35.47	72	1.20
08:00-0900	17	12	63.91	73	35.47	85	1.42
08:00-0900	18	11	63.91	73	35.47	84	1.40
08:00-0900	19	12	63.91	38	35.47	50	0.83
	Total	219		1018		1237	20.62
	Average	11.53	63.91	53.58	35.47	65.11	1.09

Table 4. 4 – Hour Interval (08:00 to 09:00) compressor operational data Source: Author

The total cycles, cumulative and average load times, cumulative and average unload times, average power demand in load mode and average power demand in unload mode was then transferred to table 4.5. Table 4.5 shows the summarized data for each of the 9 one hour intervals. The power consumption per one-hour interval was then calculated using the below formula:

Power consumption (kWh) = [average load time (h)* average load mode power demand (kW)] + [average unload time (h)* average unload mode power demand (kW)] (Equation 4.6

Note: The load and unload times given in seconds were divided by 3600 to convert the seconds into hours.

The power consumption for each one-hour period was then added to give the total power consumption for the entire dayshift period.

	DATA SUMMARY							
	Number of Cycles	Cumulative Load time for Load Cycles (sec)	Cumulative UnLoad time for Unload Cycles (sec)	Average Load Time (sec) - Tload	Average Unload Time (sec) - Tunload	Average Power Consumption during Load Cycle	Average Power Consumption during UnLoad Cycle	Power Consumption (kWh)
1st Hour (08:00-09:00)	19	219	1018	11.53	53.58	65.11	35.47	13.99
2nd Hour (09:00 - 10:00)	66	833	3079	12.62	46.65	63.84	35.59	45.21
3rd Hour (10:00-11:00)	48	571	2650	11.90	55.21	63.57	35.87	36.49
4th Hour (11:00-1200)	54	633	2972	11.72	35.45	63.81	35.45	40.49
5th Hour (12:00-13:00)	40	442	3174	11.05	79.35	63.50	35.04	38.69
6th Hour (13:00-14:00)	76	1091	2523	14.36	33.20	63.71	36.26	44.72
7th Hour (14:00-15:00)	62	809	2841	13.05	45.82	63.85	35.09	42.04
8th Hour (15:00-16:00)	53	661	2958	12.47	55.81	63.51	35.53	40.86
9th Hour (16:00-17:00)	49	645	2086	13.16	42.57	63.52	35.75	32.10
Totals	467	5904	23301					334.57
Shift Running Hours		1.64	6.4725					
Total Shift Running Hours		8.11						

Table 4. 5 – Summarized compressor operational data with power consumption
Source: Author

The baseline figures for total shift energy consumption, monthly energy consumption, annual energy consumption, annual energy cost and annual CO_2 emissions is given in table 4.6.

Baseline Figures		
Shift Energy Consumption	334.57	kWh
Monthly Energy Consumption	10,177.62	kWh
Annual Energy Consumption	122,118.05	kWh
Annual Energy Cost	37,856.60	Euro
Annual CO2 Emmisions	54,953.12	Kg-CO2

Table 4. 6 – Baseline Figures Source: Author

Notes:

- Monthly running hours and monthly energy consumption is based on 30.42 days per month
- Annual energy consumption is based on an assumed 365 operating days per year
- Energy cost is based on a rate of 0.31 Euro/kWh.
- CO_2 emissions calculations is based on an EU emissions factor of 0.45 $kgCO_2/kWh$ (Ecometrica, 2011).

Chapter 4.5 – Oracle Crystal Ball software optimization for possible system improvements

As stated earlier, either:

1) the tank size needs to be increased if the existing compressor is to be retained

or

2) a new compressor along with an approprately sized air storage tank needs to be installed.

Instead of using a trial and error approach, it was decided to utilize the Oracle Crystal Ball software optimization tool to help make the right decision on the optimal air storage tank volume and compressor specific capacity. Oracle Crystal Ball software is an add-in to Microsoft Excel which allows the replacement of single values with probability distribution and the random simulation of a model. This is achieved through the "OptQuest" optimization tool within the Oracle Crystal Ball software add-in. To perform the optimization using "OptQuest" the following was done:

1. Build a model in Microsoft Excel to calculate the total power consumption
2. Define the variables in Oracle Crystal Ball software add-in
3. Define the constraints within the "OptQuest" optimization tool
4. Define the objective within the "OptQuest" optimization tool
5. Choose how many iterations must be run and simulation method to be used
6. Select the type of optimization, stochastic or deterministic
7. Select other options as may the required and run the optimization model

The model built was named the single FSD compressor energy consumption minimization model, as it is limited to a single FSD compressor along with the associated air storage tank volume.

Variables within the Oracle Crystal Ball add-in can either be a decision variable or an assumption variable. Decision variable are quantities over which the user has control and can be set by clicking on the relevant cell in the model table where the variable needs to be set. The "define decision variable" option on the task bar is used to perform the definition by setting the appropriate bound, type and step size. Decision variable cells are highlighted in yellow. To introduce uncertainty into the model assumption variables can be set using the "define assumption" option on the task bar. The relevant probability distribution is then selected and with settings as may be required. Assumption cells within the model table are highlighted in green.

Objective setting for the optimization requires that a forecast must first be defined using the "define forecast" option on the task bar which is then indicated by a blue highlighted cell within the model table. Only after this can the "OptQuest" option on the task bar be utilised. Within "OptQuest" the following can be done:

- Setting the objectives. Each optimization model must have at least one objective.
- Setting the requirements if required
- Reviewing the decision variables
- Setting the constraints if required
- Selecting the required options as mentioned in points 5, 6 and 7 above.

When using the deterministic optimization option, all input data is constant or assumed to be known with certainty. When using stochastic optimization option, some of the model data are uncertain and are described with probability distributions, using the assumptions feature.

Once everything is properly defined the optimization model can be run. "OptQuest" will run through random values within the set bounds of the variables and return the optimal value of the set objective which satisfies the constraints.

Chapter 4.5.1 - Single FSD Compressor energy consumption minimization model

To build the required model, a CAD profile for the data logging period was created by dividing the CAD values for each cycle of the collected data, as calculated earlier in table 4.2 (Appendix 1), into 12 C.A.D. intervals. For example, all CAD values bigger or equal to 0.5, but less than 1 m^3/min (0.5<=CAD<1.0) was grouped in one interval and the average value calculated and shown in the subsequent column. The process was then repeated for the other CAD intervals. All CAD intervals can be seen in Table 4.7.

For easy reference, the table columns of the model were lettered from “a” to “u”, as seen in figure 4.9.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
CAD Interval	Average CAD	Original Cycles	Cycles (NC) =total ct/(tu+tl)	Specific Capacity (SC)	Tank Volume (Vs)	Motor Rating	Upper Presure Limit	Lower Pressure Limit	ΔP	Unload Time (tu)	Shutdown Timer Setting	Zero Power Shutdown time	Unload Time (tu)	Load Time (tl)	Load Time (tl)	Total Cycle Time (CT)	Loaded Power Demand (Pload)	Unloaded Power Demand (Punload)	Estimated Power Consumption	Corrected Power Consumption
m3/min	m3/min			m3/min	m3	kW	bar	bar	bar	min	min	min	hrs	min	hrs	min	kW	kW	kWh	kWh

Figure 4. 9 – Model Headers Source: Author

Each column from “a” to “u” is elaborated on below:

Column “a” – 12 CAD intervals

Column “b” – Average CAD of all CAD values within the associated CAD interval

Column “c” – Number of compressor cycles within the CAD interval as per original data logging results

Column “d” – Calculated number of cycles within the new reference period due to the change in variable values. It is calculated by using the following formula:

$$NC = \frac{reference\ time}{cycle\ time}$$ (formula 4.7

The reference time being the total cycle time (CT) from column “s” and the cycle time being the sum of the load (column “q”) and unload time (column “m”).

Column “e” – Specific capacity (SC) of the compressor in m^3/min

Column "f" – Total storage volume of the air storage tank/air receiver in m^3.

Column "g" – Power rating in kW of the compressor motor, as given by the manufacturer

Column "h" – Upper pressure activating point setting as per facility requirement.

Column "i" – Lower pressure activating setting as per facility requirement.

Column "j" – Difference in pressure (ΔP) between the upper and lower pressure activating point setting.

Column "k" – Unload time (t_u) in minutes, calculated using the following formula (Agricola et al., 2003):

$$t_u = \frac{Vs \text{ x } \Delta P}{CAD}$$

(formula 4.8

Column "l" – Power saving shutdown timer setting of the compressor. It indicates after how many minutes the compressor will shut down automatically while in unload mode.

Column "m" – Time the compressor actually spends in the zero power consumption state after being automatically shut down. It is zero when equal to or less than 5 and calculated as the difference between the total unload time and the shutdown timer setting, provided the unload time is larger than the auto-shut down timer setting. The "MAX" excel function was used for this purpose.

Column “n” – Unload time expressed in hours. i.e. Unload time in minutes (column “k”) divided by 60.

Column “o” – Load time (t_l) in minutes, calculated using the following formula (Agricola et al., 2003):

$$t_l = \frac{Vs \text{ x } \Delta P}{SC - CAD}$$ (formula 4.9

Column “p” – Load time expressed in hours. i.e. Load time in minutes (column “o”) divided by 60.

Column “q” – Total cycle time in minutes. Calculated by adding the load and unload times and multiplying it by the number of cycles.

Column “r” – Power demand from the compressor motor while in loaded mode (P_{load}).

Column “s” – Power demand from the compressor motor while in unloaded mode (P_{unload}).

Column “t” – Estimated power consumption based on the calculated values within the model. Calculated by multiplying the load mode power demand with the load time and adding it to the product of unload mode power demand and the unload time. i.e. Estimated power consumption = P_{load}*t_{load} + P_{unload}*t_{unload}

Column “u” – Corrected power consumption. A correction factor of 21.1% is applied to the estimated power consumption values to obtain the corrected power consumption values. The model values will invariably be different from the actual data logged values as they are calculated values based on formulas. Thus to obtain the correction factor the current facility CAS information;

compressor specific capacity, air storage tank volume and average power demand in load and unload mode, was entered into the model to obtain the total estimated power consumption for the shift (424.08 kWh). The difference between this value and the actual shift power consumption value calculated in table 4.5, 334.57 kWh) was calculated and divided by the estimated power consumption value.

i.e. Correction Factor = (424.08-334.57)/424.57 = 0.211069 (21.1%)

Table 4.7 shows the complete model, with the information as described above.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
CAD Interval	Average CAD	Original Cycles	Cycles (NC) =total ct/(tu+tl)	Specific Capacity (SC)	Tank Volume (Vs)	Motor Rating	Upper Presure Limit	Lower Pressure Limit	ΔP	Unload Time (tu)	Shutdown Timer Setting	Zero Power Shutdown time	Unload Time (tu)	Load Time (tl)	Load Time (tl)	Total Cycle Time (CT)	Loaded Power Demand (Pload)	Unloaded Power Demand (Punload)	Estimated Power Consumption	Corrected Power Consumption
m3/min	m3/min			m3/min	m3	kW	bar	bar	bar	min	min	min	hrs	min	hrs	min	kW	kW	kWh	kWh
0.5 <= CAD < 1.0	0.94	7	7	10.153	2	55	7.5	6.5	1	2.12	5	0.00	0.04	0.22	0.0036	16.38	63.69	35.60	10.43	8.23
1.0 <= CAD < 1.5	1.25	145	145	10.153	2	55	7.5	6.5	1	1.61	5	0.00	0.03	0.22	0.0037	265.33	63.69	35.6	172.67	136.23
1.5 <= CAD < 2.0	1.69	85	85	10.153	2	55	7.5	6.5	1	1.18	5	0.00	0.02	0.24	0.0039	120.63	63.69	35.6	80.98	63.89
2.0 <= CAD < 2.5	2.24	47	47	10.153	2	55	7.5	6.5	1	0.89	5	0.00	0.01	0.25	0.0042	53.91	63.69	35.6	37.54	29.62
2.5 <= CAD < 3.0	2.79	39	39	10.153	2	55	7.5	6.5	1	0.72	5	0.00	0.01	0.27	0.0045	38.59	63.69	35.6	27.85	21.97
3.0 <= CAD < 3.5	3.22	23	23	10.153	2	55	7.5	6.5	1	0.62	5	0.00	0.01	0.29	0.0048	20.93	63.69	35.6	15.52	12.25
3.5 <= CAD < 4.0	3.75	20	20	10.153	2	55	7.5	6.5	1	0.53	5	0.00	0.01	0.31	0.0052	16.92	63.69	35.6	12.96	10.23
4.0 <= CAD < 4.5	4.20	23	23	10.153	2	55	7.5	6.5	1	0.48	5	0.00	0.01	0.34	0.0056	18.68	63.69	35.6	14.70	11.60
4.5 <= CAD < 5.0	4.80	30	30	10.153	2	55	7.5	6.5	1	0.42	5	0.00	0.01	0.37	0.0062	23.71	63.69	35.6	19.32	15.24
5.0 <= CAD < 5.5	5.26	35	35	10.153	2	55	7.5	6.5	1	0.38	5	0.00	0.01	0.41	0.0068	27.61	63.69	35.6	23.08	18.21
5.5 <= CAD < 6.0	5.73	10	10	10.153	2	55	7.5	6.5	1	0.35	5	0.00	0.01	0.45	0.0075	8.01	63.69	35.6	6.87	5.42
6.0 <= CAD < 6.5	6.09	3	3	10.153	2	55	7.5	6.5	1	0.33	5	0.00	0.01	0.49	0.0082	2.46	63.69	35.6	2.15	1.70
																		Total	424.08	334.57

Table 4. 7 - Single FSD Compressor energy consumption minimization model
Source: Author

Chapter 4.5.2 - Optimizing Air Storage Tank Volume (Vs)

To ascertain which storage tank volume will result in the least energy consumption, while will utilizing the existing compressor the model inputs were set as follows:

- Model Objective: The total value of corrected power consumption was set as the forecast, with an objective of minimizing the final value of the power consumption and a requirement that the final value of the power consumption must be bigger than zero, as shown in Figure 4.10.

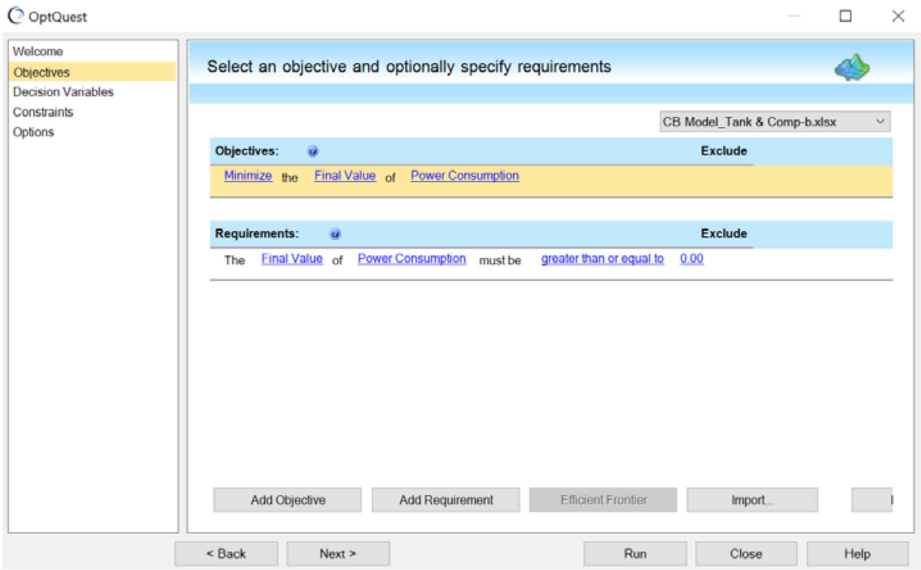

Figure 4. 10 – OptQuest objective and requirement

- Model Variable: Decision Variable – Air Compressor Tank Size (Vs). The lower bound was set at the existing air storage tank size of 2m^3 and the upper bound at 10 m^3, with discrete steps of 0.1 m^3, as shown in figure 4.11. The upper bound was selected based on the largest air storage tanks normally offered by manufacturers. Figure 4.12 shows the decision variable within OptQuest.

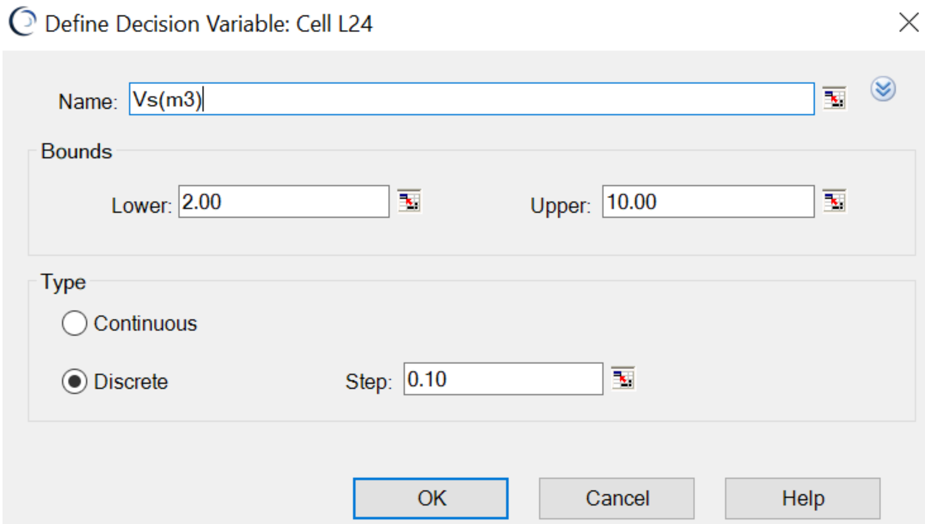

Figure 4. 11 – Air Storage Tank Decision Variable

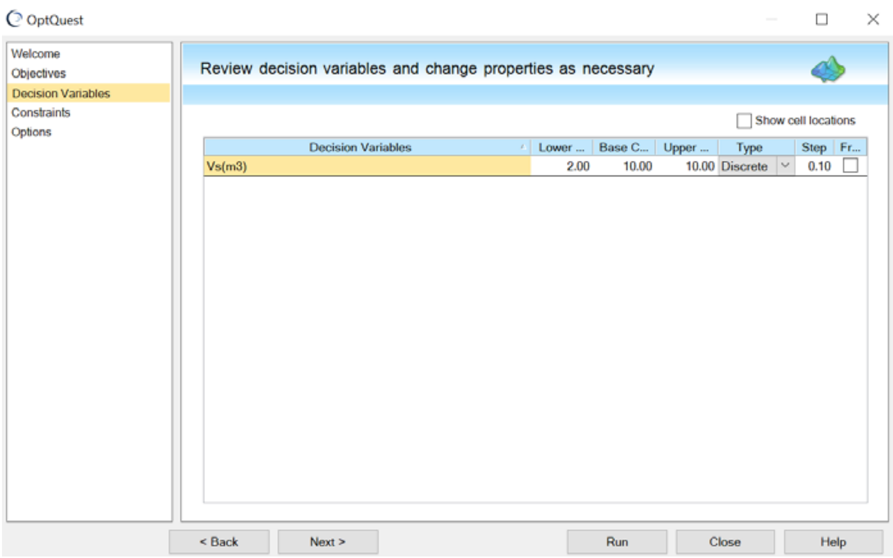

Figure 4. 12 – Decision Variable – Vs within OptQuest

- Model Constraints: For each of the 12 compressed air demand intervals, constraints were entered to reject any simulation values which return power consumption values of less than zero, as shown in figure 4.13. Negative values cannot be returned when only optimizing tank size, but can be returned when optimizing compressor specific capacity, specifically when the compressor specific capacity is less than the average of the compressed air demand interval.

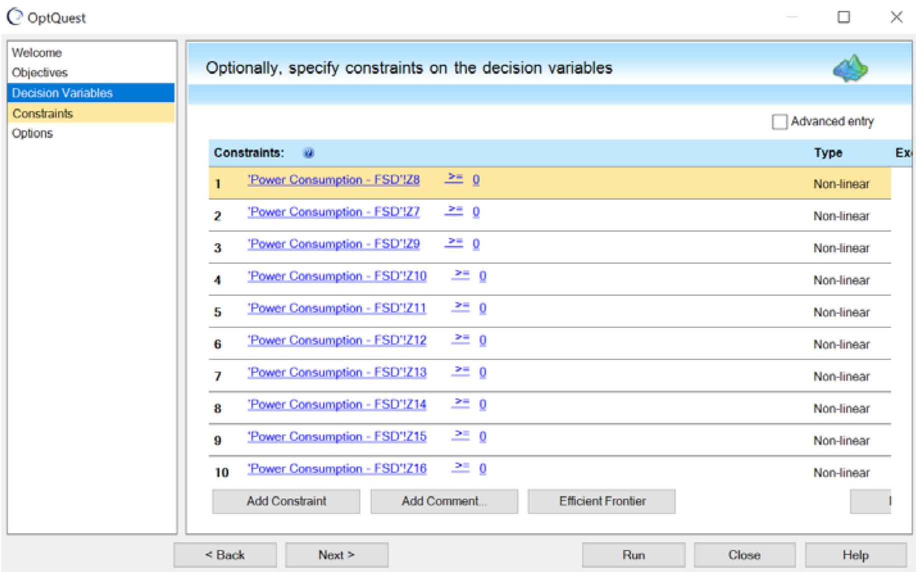

Figure 4. 13– OptQuest constraints

- Model Constant Inputs:
    - Motor power rating = 55 kW, as the installed compressor is being utilized
    - Upper pressure limit = 7.5 bars, as per facility requirements
    - Lower pressure limit = 6.5 bars, as per facility requirements
    - Auto shutdown timer setting = 5 minutes (assumed)
    - Loaded Power consumption = 63.69 kW, this is the calculated average from the logged data for this compressor
    - Unloaded power consumption = 35.6 kW, this is the calculated average from the logged data for this compressor

The run options selected were Monte Carlo simulation and deterministic optimization, as there is no uncertainty introduced into the model through set assumptions.

Discussion of results

Figure 4.14 shows the results from the simulation. The optimal air storage tank volume returned is 10 m^3, which was the upper limit of the bound. This was expected, as the larger the air storage tank volume the longer the compressor will remain in a 0 kW demand state in unload mode. This shows that the model is working as intended.

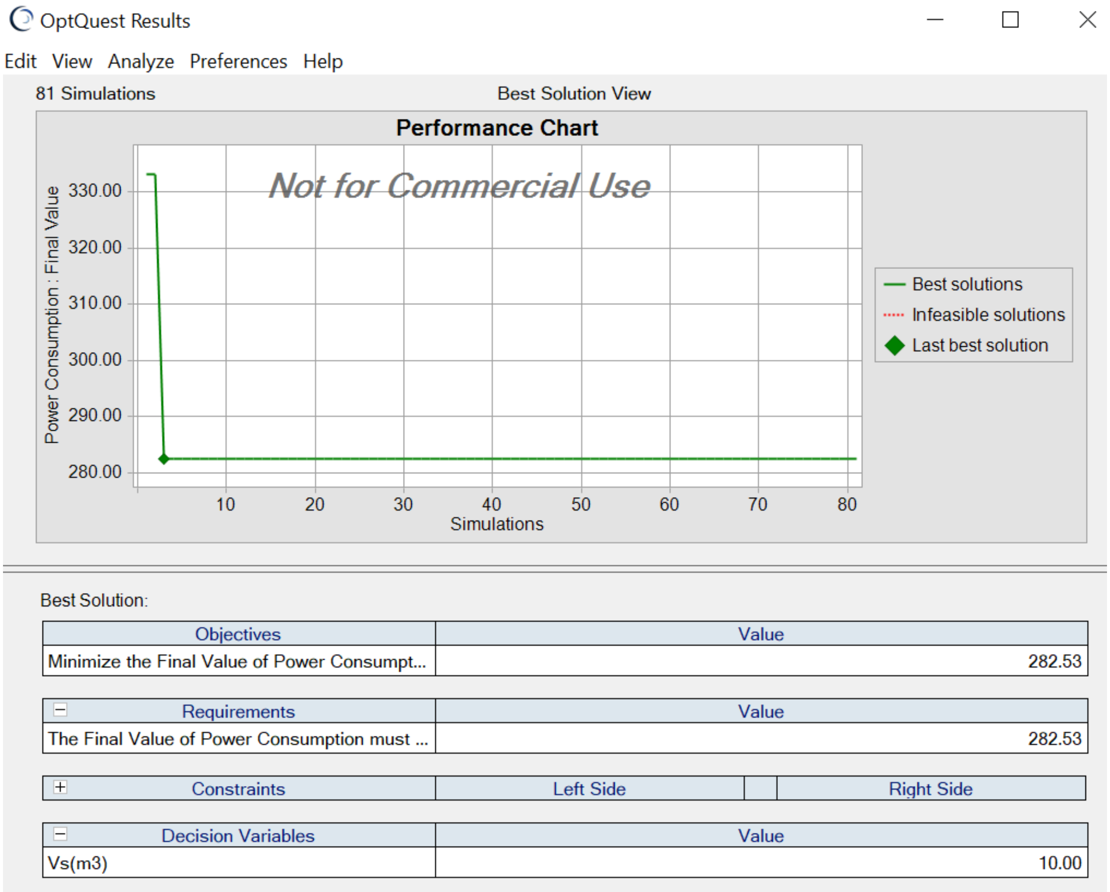

Figure 4. 14 – OptQuest results for optimized Vs

Table 4.8 shows the model with the optimal air storage tank size.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
CAD Interval	Average CAD	Original Cycles	Cycles (NC) =total ct/(tu+tl)	Specific Capacity (SC)	Tank Volume (Vs)	Motor Rating	Upper Presure Limit	Lower Pressure Limit	ΔP	Unload Time (tu)	Shutdown Timer Setting	Zero Power Shutdown time	Unload Time (tu)	Load Time (tl)	Load Time (tl)	Total Cycle Time (CT)	Loaded Power Demand (Pload)	Unloaded Power Demand (Punload)	Estimated Power Consumption	Corrected Power Consumption
m3/min	m3/min			m3/min	m3	kW	bar	bar	bar	min	min	min	hrs	min	hrs	min	kW	kW	kWh	kWh
0.5 <= CAD < 1.0	0.94	7	1.4	10.153	10	55	7.5	6.5	1	10.61	5	5.61	0.18	1.09	0.0181	16.38	63.69	35.6	5.77	4.55
1.0 <= CAD < 1.5	1.25	145	29	10.153	10	55	7.5	6.5	1	8.03	5	3.03	0.13	1.12	0.0187	265.33	63.69	35.6	120.59	95.14
1.5 <= CAD < 2.0	1.69	85	17	10.153	10	55	7.5	6.5	1	5.91	5	0.91	0.10	1.18	0.0197	120.63	63.69	35.6	71.76	56.61
2.0 <= CAD < 2.5	2.24	47	9.4	10.153	10	55	7.5	6.5	1	4.47	5	0.00	0.07	1.26	0.0211	53.91	63.69	35.6	37.54	29.62
2.5 <= CAD < 3.0	2.79	39	7.8	10.153	10	55	7.5	6.5	1	3.59	5	0.00	0.06	1.36	0.0226	38.59	63.69	35.6	27.85	21.97
3.0 <= CAD < 3.5	3.22	23	4.6	10.153	10	55	7.5	6.5	1	3.11	5	0.00	0.05	1.44	0.0240	20.93	63.69	35.6	15.52	12.25
3.5 <= CAD < 4.0	3.75	20	4	10.153	10	55	7.5	6.5	1	2.67	5	0.00	0.04	1.56	0.0260	16.92	63.69	35.6	12.96	10.23
4.0 <= CAD < 4.5	4.20	23	4.6	10.153	10	55	7.5	6.5	1	2.38	5	0.00	0.04	1.68	0.0280	18.68	63.69	35.6	14.70	11.60
4.5 <= CAD < 5.0	4.80	30	6	10.153	10	55	7.5	6.5	1	2.08	5	0.00	0.03	1.87	0.0312	23.71	63.69	35.6	19.32	15.24
5.0 <= CAD < 5.5	5.26	35	7	10.153	10	55	7.5	6.5	1	1.90	5	0.00	0.03	2.04	0.0340	27.61	63.69	35.6	23.08	18.21
5.5 <= CAD < 6.0	5.73	10	2	10.153	10	55	7.5	6.5	1	1.75	5	0.00	0.03	2.26	0.0376	8.01	63.69	35.6	6.87	5.42
6.0 <= CAD < 6.5	6.09	3	0.6	10.153	10	55	7.5	6.5	1	1.64	5	0.00	0.03	2.46	0.0410	2.46	63.69	35.6	2.15	1.70
																		Total	358.12	282.53

Table 4. 8 – Optimization model results for Vs Source: Author

Further analysis was done by extracting the results for air storage tank size versus shift power consumption and plotting it on a graph. Figure 4.15 shows the relationship between the two.

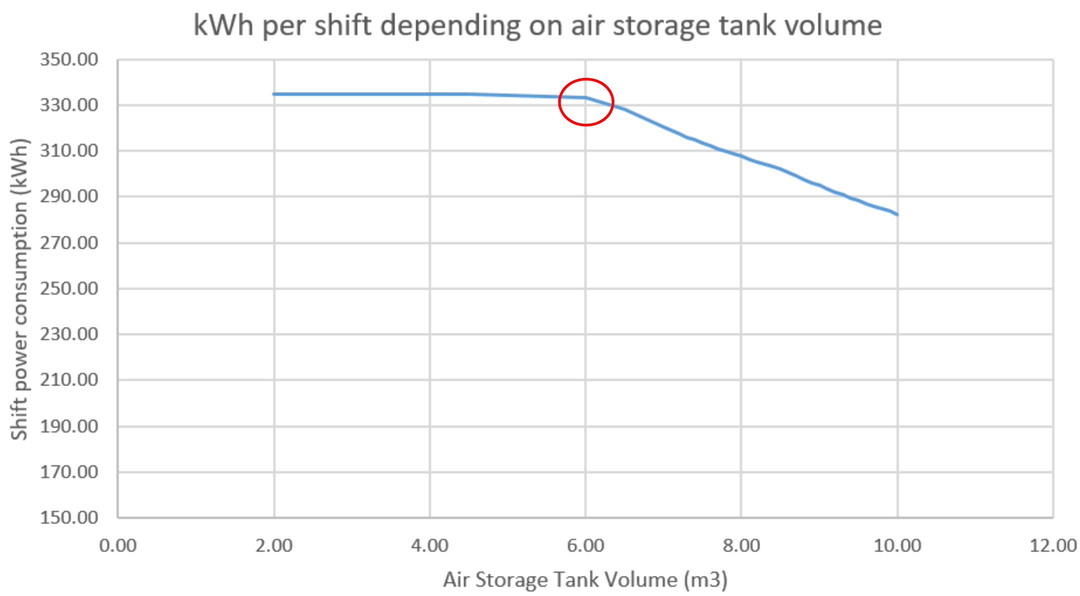

Figure 4. 15 – Relationship between Vs and shift power consumption Source: Author

From this graph it can be concluded that from a 6 m^3 tank volume and upwards, shift power consumption will continue to decrease. Thus the facility is limited only by the maximum air storage tank volume that they can install. However, as described earlier, to avoid short cycling a tank volume smaller then $7m^3$ should not be installed for this specific compressor. The facility is not limited to only a single air storage tank, a secondary air storage tank can also be installed within the compressed air system. Thus, instead of installing a single 10 m^3 air storage tank, a 5 m^3 air storage tank can be installed within the compressor room and a secondary $5m^3$ air storage tank can be installed in an area close where high intermittent C.A.D is normally experienced. This will assist in controlling large C.A.D spikes and pressure changes within the entire system which can result in other end users being negatively affected by reduced air supply. The actual size and location of the secondary air storage tank needs to be decided upon after careful data analysis.

Sufficient compressed air storage is essential to ensure optimal performance, service delivery and efficiency of the compressed air system.

Chapter 4.5.3 - Optimizing compressor specific capacity (SC) and air storage tank size (Vs)

To ascertain which combination of compressor specific capacity and air storage tank volume will result in the least energy consumption, the model inputs were set as follows:

- Model Objective: Remains the same as before. The total value of corrected power consumption was set as the forecast, with an objective of minimizing the final value of the power consumption and a requirement that the final value of the power consumption must be bigger than zero
- Variable 1: Decision Variable - Air Compressor Tank Size (Vs): The lower bound was set at the existing air storage tank size of $2m^3$ and the

upper bound at 10 m^3, with discrete steps of 0.1 m^3, as shown on figure 4.16.

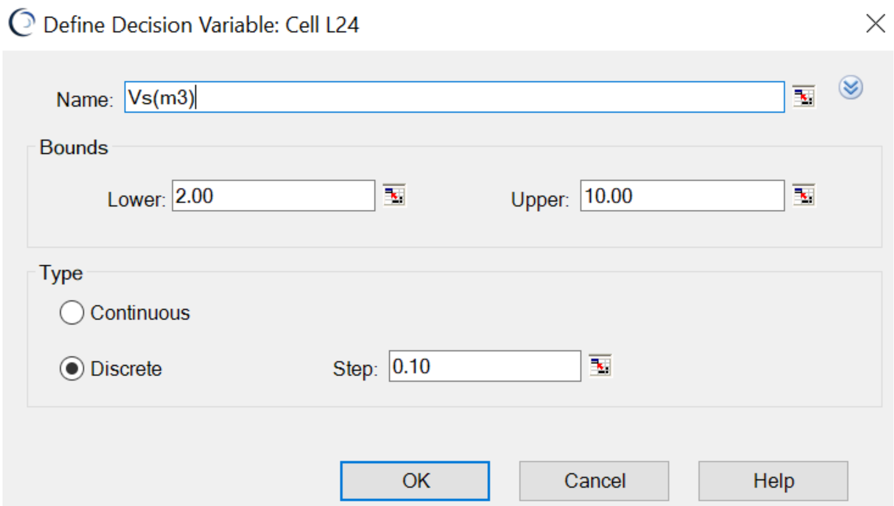

Figure 4. 16– Air Storage Tank (Vs) Decision Variable

- Variable 2: Decision Variable - Compressor Specific Capacity (SC): The lower bound was set at 5 m^3/min and the upper bound at 10.15 m^3/min, with continuous increments as shown in figure 4.17. See note below on SC values.

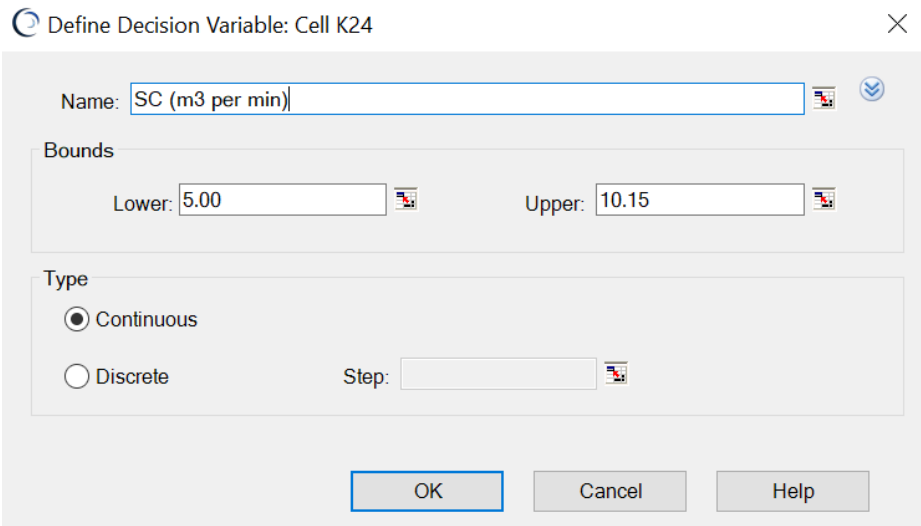

Figure 4. 17 – Specific Capacity (SC) Decision Variable

- Model Constraints: The model constraints remain the same as before and as shown in figure 4.13.

- Constant Inputs:

    - Motor power rating = This value alternates and is based on the specific capacity of the compressor. Following an assessment on motor power ratings in relation to specific capacity of FSD compressors with maximum operating pressure of 8.5 bars (other available maximum pressure ratings of 12 and 15 bars is too high for this specific application), the following motor power ratings were incorporated into the model:

        - 55 kW if the SC is larger than 8.5 m^3/min but smaller than or equal to 10.14 m^3/min
        - 45 kW if the SC is smaller than or equal to 8.5 m^3/min, but larger than 6.5 m^3/min
        - 37 kW if the SC is smaller than or equal to 6.5 m^3/min, but larger than 5.79 m^3/min

    Note: SC value less than the average of the CAD interval along with the associated motor kilowatt rating will automatically be rejected by the constraints set within the model simulation, as any SC value less than the average of the CAD interval will result in negative load and unload times to be returned. These values were included in the model for possible future expansion and to serve as a validation check on the proper functioning of the model.

The “IF” function within Microsoft excel was used in the model to ensure the appropriate compressor motor kW rating is used in relation to the specific capacity.

- Upper pressure limit = 7.5 bars, as per facility requirements
- Lower pressure limit = 6.5 bars, as per facility requirements
- Auto shutdown timer setting = 5 minutes (assumed)
- Loaded Power consumption = Since different compressors capacities will be used in the optimization, for which no data was collected for, the loaded power demand is considered to be the maximum possible. i.e. 115% of the compressor motor power rating.
- Unloaded power consumption = Since different compressors capacities will be used in the optimization, for which no data was collected for, the unloaded power demand is considered to be the maximum possible. i.e. 60% of the compressor motor power rating.

The run options selected were Monte Carlo simulation and deterministic optimization, as there is no uncertainty introduced into the model through set assumptions.

Chapter 4.5.4 - Discussion of results

Figure 4.18 shows the results from the optimization. The optimal specific capacity is 8.5 m^3/min and the associated air storage tank size is 10 m^3. The next step is to check the manufacturers’ catalogue and see which one offers a FSD compressor with a SC closest to 8.5 m3/min, along with a motor power rating of 45 kW, maximum air pressure rating of 8.5 bar and working pressure rating of 7.5 bar. The actual SC value can then be entered into the model to obtain the shift power consumption figure.

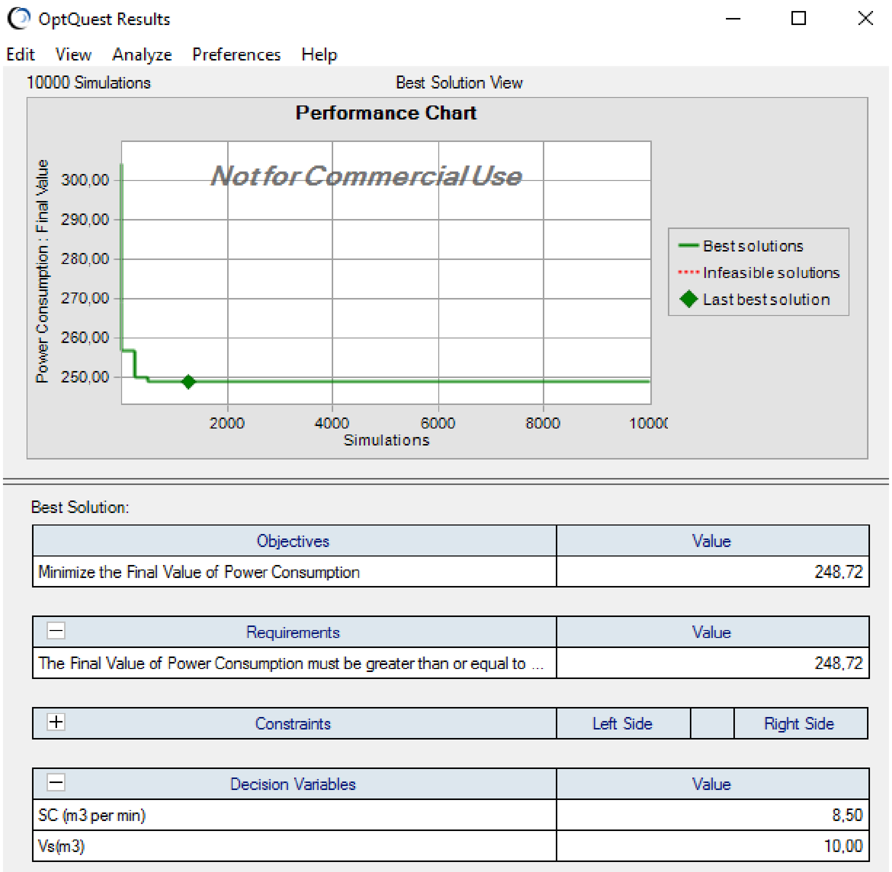

Figure 4. 18 – OptQuest results for optimized Vs and SC

Table 4.9 shows the model with the optimal specific capcity (SC) along with the air storage tank size (Vs), as per OptQuest result.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
CAD Interval	Average CAD	Original Cycles	Cycles (NC) =total ct/(tu+tl)	Specific Capacity (SC)	Tank Volume (Vs)	Motor Rating	Upper Presure Limit	Lower Pressure Limit	ΔP	Unload Time (tu)	Shutdown Timer Setting	Zero Power Shutdown time	Unload Time (tu)	Load Time (tl)	Load Time (tl)	Total Cycle Time (CT)	Loaded Power Demand (Pload)	Unloaded Power Demand (Punload)	Estimated Power Consumption	Corrected Power Consumption
m3/min	m3/min			m3/min	m3	kW	bar	bar	bar	min	min	min	hrs	min	hrs	min	kW	kW	kWh	kWh
0.5 <= CAD < 1.0	0.94	7	1.4	8.500	10	45	7.5	6.5	1	10.61	5	5.61	0.18	1.32	0.0221	16.71	51.75	27.00	4.75	3.75
1.0 <= CAD < 1.5	1.25	145	29	8.500	10	45	7.5	6.5	1	8.03	5	3.03	0.13	1.38	0.0230	272.75	51.75	27.00	99.73	78.68
1.5 <= CAD < 2.0	1.69	85	17	8.500	10	45	7.5	6.5	1	5.91	5	0.91	0.10	1.47	0.0245	125.51	51.75	27.00	59.78	47.16
2.0 <= CAD < 2.5	2.24	47	9.4	8.500	10	45	7.5	6.5	1	4.47	5	0.00	0.07	1.60	0.0266	57.04	51.75	27.00	31.86	25.13
2.5 <= CAD < 3.0	2.79	39	7.8	8.500	10	45	7.5	6.5	1	3.59	5	0.00	0.06	1.75	0.0292	41.65	51.75	27.00	24.37	19.23
3.0 <= CAD < 3.5	3.22	23	4.6	8.500	10	45	7.5	6.5	1	3.11	5	0.00	0.05	1.89	0.0316	23.00	51.75	27.00	13.94	11.00
3.5 <= CAD < 4.0	3.75	20	4	8.500	10	45	7.5	6.5	1	2.67	5	0.00	0.04	2.10	0.0351	19.09	51.75	27.00	12.06	9.52
4.0 <= CAD < 4.5	4.20	23	4.6	8.500	10	45	7.5	6.5	1	2.38	5	0.00	0.04	2.33	0.0388	21.65	51.75	27.00	14.16	11.17
4.5 <= CAD < 5.0	4.80	30	6	8.500	10	45	7.5	6.5	1	2.08	5	0.00	0.03	2.71	0.0451	28.72	51.75	27.00	19.62	15.48
5.0 <= CAD < 5.5	5.26	35	7	8.500	10	45	7.5	6.5	1	1.90	5	0.00	0.03	3.08	0.0514	34.90	51.75	27.00	24.61	19.41
5.5 <= CAD < 6.0	5.73	10	2	8.500	10	45	7.5	6.5	1	1.75	5	0.00	0.03	3.60	0.0601	10.70	51.75	27.00	7.79	6.14
6.0 <= CAD < 6.5	6.09	3	0.6	8.500	10	45	7.5	6.5	1	1.64	5	0.00	0.03	4.15	0.0692	3.48	51.75	27.00	2.59	2.05
																		Total	315.27	248.72

Table 4. 9 – Optimization model results for Vs and CS combined Source: Author

Figure 4.19 is from a manufacturers catalogue for a FSD compressor with the SC closest to 8.5 m3/min, along with a motor power rating of 45 kW, maximum air pressure rating of 8.5 bar and working pressure rating of 7.5 bar.

Working pressure	Flow rate *) Overall package at working pressure	Max. operating pressure	Rated motor power	Dimensions W x D x H
bar	m³/min	bar	kW	mm
7.5 10 13	8.26 6.89 5.50	8.5 12 15	45	1760 x 1110 x 1900

Figure 4. 19 – Manufacturer FSD compressor details Source: Kaeser

Table 4.10 shows the model with the closest available SC value to the optimal SC value, along with the air storage tank volume.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
CAD Interval	Average CAD	Original Cycles	Cycles (NC) =total ct/(tu+tl)	Specific Capacity (SC)	Tank Volume (Vs)	Motor Rating	Upper Presure Limit	Lower Pressure Limit	ΔP	Unload Time (tu)	Shutdown Timer Setting	Zero Power Shutdown time	Unload Time (tu)	Load Time (tl)	Load Time (tl)	Total Cycle Time (CT)	Loaded Power Demand (Pload)	Unloaded Power Demand (Punload)	Estimated Power Consumption	Corrected Power Consumption
m3/min	m3/min			m3/min	m3	kW	bar	bar	bar	min	min	min	hrs	min	hrs	min	kW	kW	kWh	kWh
0.5 <= CAD < 1.0	0.94	7	1.4	8.260	10	45	7.5	6.5	1	10.61	5	5.61	0.18	1.37	0.0228	16.77	51.75	27.00	4.80	3.79
1.0 <= CAD < 1.5	1.25	145	29	8.260	10	45	7.5	6.5	1	8.03	5	3.03	0.13	1.43	0.0238	274.12	51.75	27.00	100.91	79.61
1.5 <= CAD < 2.0	1.69	85	17	8.260	10	45	7.5	6.5	1	5.91	5	0.91	0.10	1.52	0.0254	126.42	51.75	27.00	60.57	47.79
2.0 <= CAD < 2.5	2.24	47	9.4	8.260	10	45	7.5	6.5	1	4.47	5	0.00	0.07	1.66	0.0277	57.64	51.75	27.00	32.37	25.54
2.5 <= CAD < 3.0	2.79	39	7.8	8.260	10	45	7.5	6.5	1	3.59	5	0.00	0.06	1.83	0.0304	42.25	51.75	27.00	24.89	19.64
3.0 <= CAD < 3.5	3.22	23	4.6	8.260	10	45	7.5	6.5	1	3.11	5	0.00	0.05	1.98	0.0331	23.42	51.75	27.00	14.30	11.28
3.5 <= CAD < 4.0	3.75	20	4	8.260	10	45	7.5	6.5	1	2.67	5	0.00	0.04	2.22	0.0369	19.54	51.75	27.00	12.45	9.82
4.0 <= CAD < 4.5	4.20	23	4.6	8.260	10	45	7.5	6.5	1	2.38	5	0.00	0.04	2.46	0.0411	22.28	51.75	27.00	14.70	11.60
4.5 <= CAD < 5.0	4.80	30	6	8.260	10	45	7.5	6.5	1	2.08	5	0.00	0.03	2.89	0.0482	29.85	51.75	27.00	20.59	16.25
5.0 <= CAD < 5.5	5.26	35	7	8.260	10	45	7.5	6.5	1	1.90	5	0.00	0.03	3.33	0.0555	36.62	51.75	27.00	26.10	20.59
5.5 <= CAD < 6.0	5.73	10	2	8.260	10	45	7.5	6.5	1	1.75	5	0.00	0.03	3.95	0.0658	11.38	51.75	27.00	8.38	6.61
6.0 <= CAD < 6.5	6.09	3	0.6	8.260	10	45	7.5	6.5	1	1.64	5	0.00	0.03	4.61	0.0769	3.75	51.75	27.00	2.83	2.23
																		Total	322.89	254.74

Table 4. 10 - Optimization model results for Vs and CS as per manufacturer Source: Author

Chapter 4.5.5 - Comparative Analysis of Results

As can be seen in table 4.11, changing only the air storage tank to 10 m^3 can result in annual energy consumption, CO_2 emissions and energy cost savings of 16%. Changing the compressor to another FSD compressor with a specific capacity of 8.26 m^3/min can result in annual energy consumption, CO_2 emissions and energy cost savings of 24%.

<table>
<tr><th></th><th>Baseline</th><th colspan="2">Change of Air Storage Tank Only</th><th colspan="2">Change of Compressor and Air Storage Tank</th></tr>
<tr><td>Compressor Specific Capacity (m³/min)</td><td>10.153</td><td colspan="2">10.153</td><td colspan="2">8.26</td></tr>
<tr><td>Air Storage Tank Volume (m³)</td><td>2.00</td><td colspan="2">10.00</td><td colspan="2">10.00</td></tr>
<tr><td>Shift Energy Consumption (kWh)</td><td>334.57</td><td colspan="2">282.53</td><td colspan="2">254.74</td></tr>
<tr><td>Annual Energy Consumption (kWh)</td><td>122118.05</td><td colspan="2">103123.45</td><td colspan="2">92980.10</td></tr>
<tr><td>Annual Energy Cost (Euros)</td><td>37856.60</td><td colspan="2">31968.27</td><td colspan="2">28823.83</td></tr>
<tr><td>Annual CO₂ Emissions (kg-CO₂)</td><td>54953.12</td><td colspan="2">46405.55</td><td colspan="2">41841.05</td></tr>
<tr><td>Annual Energy Consumption Saving (kWh)</td><td>/</td><td rowspan="3">16%</td><td>18994.60</td><td rowspan="3">24%</td><td>29137.95</td></tr>
<tr><td>Annual Energy Cost Saving (Euros)</td><td>/</td><td>5888.33</td><td>29137.95</td></tr>
<tr><td>Annual CO₂ Emissions Saving (kg-CO₂)</td><td>/</td><td>8547.57</td><td>13112.08</td></tr>
</table>

Table 4.11 – Comparison of optimization results against the baseline figures Source: Author

Chapter 4.6 - Summary

As can be seen from the results, substantial energy savings, CO_2 emissions reductions, and energy costs savings can be made by performing data collection, data analysing and optimizing. This allows decisions to be made on factual information, rather than on costly trial and error decisions.

It must be noted that this optimization was only done on two scenarios, one considering only the air storage tank volume and the other considering FSD compressor specific capacity along with the associated air storage tank volume. Further energy consumption reductions can still be made by considering a single variable speed drive (VSD) compressor, or 2 compressors working together with one operating as the base-load compressor and the other as a trim compressor. However, the model used will need to significantly adjusted to take into consideration the variation in power demand in relation to the CAD.

Improving energy efficiency of the compressed air system should not stop at the optimizing the compressor and air storage tank. As system approach, addressing both the supply and demand side, should be followed to maximize energy efficiency. Every component within the system needs to be assessed, short comings identified, and measures put in place to correct them. Other proven measures which also need to considered includes pressure drop reduction, identifying and repairing air leaks and ensuring compressed air is only used where and when necessary. Additionally, heat recovery on compressors can contribute substantially to reducing overall energy consumption.

Continuous performance monitoring of the compressed air system, supplemented by an effective planned maintenance system, is important to ensure the system operates at its optimal level at all times and to allow early detection of potential problems which can negatively impact performance and efficiency. Proper training needs to be conducted to ensure the human element side is addressed. Improper system uses and wasteful compressed air use contributes significantly to CAS energy consumption.

The case study highlights how energy performance within a shipyard can be improved with a focus on a single significant energy user. However, sub components of the proposed holistic framework cannot be viewed in isolation as it remains part of the overall system which is highly integrated. Maintaining a system view is essential to ensure that actions taken in one pillar does not negatively affect the other.

Additionally, identification of possible energy performance improvements measures needs to be incorporated into the energy management action plans to avoid valuable effort, time and savings potential going to waste or being forgotten about as a result of busy operating schedules. This will ensure these items remains on record, requiring proper planning, implementation, follow up and review by management, as per PDCA cycle.

Considering the case study, the practical process to be followed will be similar as per below:

1. Setting the objective: Reduce energy consumption form the CAS.

2. Setting the target: Reduce energy consumption by 15% by 2022, based on the 2019 baseline

3. Compiling an energy action plan which may include actions as per table 4.11:

Action #	Required Action	Person Responsible	Target Date	Status	Remarks
1	Perform energy audit on compressed air system	W. Mem			
2	Establish energy consumption baseline for CAS	W. Mem			

3	Identify energy performance improvement measures for CAS	W. Mem			
4	Perform cost –benefit analysis on energy performance improvement measures for CAS	W. Mu			
5	Select energy performance improvement measures to implement and get them approved	W. Mu			

Table 4. 11 – Action Plan Source: Author

4. Procuring and installing the parts of the system to achieve the energy performance improvement. Briefing all related departments on the system changes and training the relevant employees in relation to the changes affected, as may be required.
5. Continue monitoring the energy performance of the CA. and evaluating if it is performing as envisaged.
6. Review conducted by management on the CAS performance results and new goals for continual improvement is decided upon.

Chapter 5 – Conclusion and Future Research

Shipyards operate within a demanding and complex setting. They are faced with multiple and intricate challenges, which needs to be overcome to ensure the shipyards sustainability. However, it is not only the sustainability of the shipyard that is of concern, but also that of our planet. Thus shipyards also need to operate in an environmentally conscious manner. Climate change, driven by rising GHG emissions into the atmosphere is a major international concern because of its global damaging impacts.

Emissions of GHGs into the atmosphere, specifically CO_2, from the context of this dissertation can be drastically reduced from shipyard operations through appropriate energy management practices. It was found that approaches to reduce energy consumption and associated GHG emissions from shipyard activities are available, albeit limited and from single perspectives. Thus, to provide a complete overview these approaches needed to be brought together. Therefore, a holistic framework for shipyard energy management was developed and proposed. The developed holistic framework for shipyard energy management comprises of 7 pillars, namely 1) renewable energy employment, 2) compliance, 3) production facilities and technology, 4) process improvement, 5) integrated hull, outfitting and painting process (IHOP), 6) project management and 7) shipyard layout. When addressing energy performance improvement within shipyards, the interrelation between all pillars within the holistic framework needs to considered at all times. Especially in relation to how planned actions can either benefit, negatively impact or supplement the other energy management pillars. The case study of a significant energy user, the air compressor in the case, within the Production facilities and Technology pillar shows how optimization models can be used to facilitate a rational decision making decisions process. The interrelation with the Compliance pillar is evident through the use of logged data from an energy audit on the significant energy user. This is further emphasized by the objective setting, targets setting, action plan compilation, monitoring and verification required to ensure an effective PDCA cycle.

Level of implementation of the holistic framework will vary from yard to yard depending on their position within the market and available resources. However, energy management and energy performance improvement within a shipyard will not function if there is no commitment from top management, providing the framework, resources and an enabling environment. Additionally, there should be an energy manager supported by his energy management team to ensure that the shipyard energy management plan is implemented properly and that set objectives and targets are achieved. They should be the link between the top management, the energy management plan and all employees and must ensure focus is maintained. Energy management and consciousness should be instilled within every employee within the shipyard for the system to operate effectively.

Figure 5.1 is representative of a summary to this dissertation.

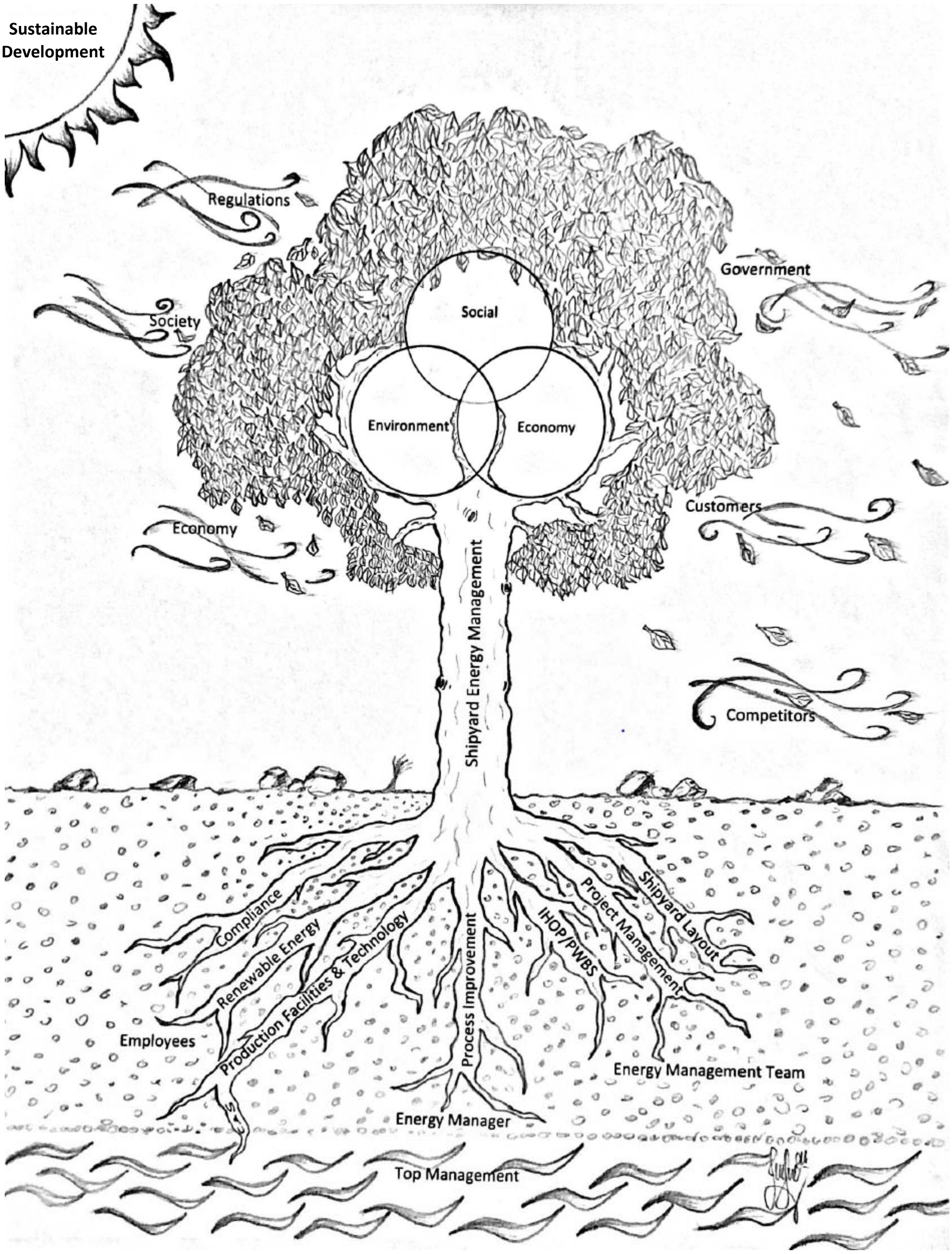

Figure 5. 1 – Dissertation Summary Source: Author

The roots represent the 7 pillars supporting energy management within shipyards, portrayed by the trunk of the tree. The trunk in turn provides strength and rigidity to the shipyard represented by the crown of the tree. The soil represents the solidity to the system provided by all the employees, the energy manager and his team. The water represents top management, providing the essential and enabling resources. The wind represents all the external forces the shipyard has to content with for continued survival and prosperity. These external forces become stronger and more demanding over time thus continual development and improvement is required at all times. The sun is a natural resource and represents sustainable development. Without the sun, water, soil, air, roots and trunk there will be no crown to the tree causing it to wither away over time. Thus only together can all these components ensure the sustainability of the shipyard and the environment.

Thus, concentrating on the proposed and developed holistic framework, which incorporates the above mentioned components, will ensure that continual energy performance improvement, reduced GHG emissions, lean and efficient shipyard operations, improved societal acceptance, a competitive edge, reduced energy costs through reduced and efficient energy consumption and beneficial infrastructure investments is achieved. The developed framework can be easily applied to any shipyard with appropriate tailoring in relation to the needs of the subject shipyard.

Further work and recommendations

The model developed for the optimization of the specific capacity of a FSD compressor and associated air storage tank volume was not further expanded to include multiple compressors, including the use of variable VSD compressors. Thus this should be considered for future work.

The focus of the case study was on a single significant energy user, which in future work needs to be expanded to all significant energy users within a shipyard. Ideally a standardized and detailed assessment should be performed at multiple shipyards' leading to a comparative analysis to establish a true representative list of all the significant energy users. A study on how shipyards go about improving energy performance and identifying best practices along with common mistakes and misperceptions will also beneficial.

Finally, it needs to be established to what extend shipyards actually operate within the holistic energy management framework and identify concepts that can be introduced or improved upon.

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Appendices

Appendix 1 – Data Logged Information

Time Interval	Cycle #	a	b	c	d	e	f		g	h	i	j
		Load Time (sec)	Power Demand in Load Mode (kW)	Unload Time (Sec)	Power Demand in Unload Mode (kW)	Cycle Time (Sec)	Cycle Time (Min)		Load Factor	CAP/cycle (m3)	CAD rate/cycle (m3/min)	CAD rate/cycle (m3/sec)
						e=a+c	f=e/60		LF%=Ltime/(Ltime+Ultime)	CAP=SPC*PI*Tload(min) CAP=SPC*b*(a/60)	CAD=CAP/Cycle Time (min) CAD=h/f	CAD=i/60
08:35-0900	1	12	63.91	13	35.47	25	0.42		48.00%	2.04	4.89	0.08
08:35-0900	2	15	63.91	12	35.47	27	0.45		55.56%	2.55	5.66	0.09
08:35-0900	3	13	63.91	35	35.47	48	0.80		27.08%	2.21	2.76	0.05
08:35-0900	4	10	63.91	49	35.47	59	0.98		16.95%	1.70	1.73	0.03
08:35-0900	5	9	63.91	59	35.47	68	1.13		13.24%	1.53	1.35	0.02
08:35-0900	6	11	63.91	65	35.47	76	1.27		14.47%	1.87	1.48	0.02
08:35-0900	7	11	63.91	56	35.47	67	1.12		16.42%	1.87	1.67	0.03
08:35-0900	8	12	63.91	42	35.47	54	0.90		22.22%	2.04	2.27	0.04
08:35-0900	9	11	63.91	74	35.47	85	1.42		12.94%	1.87	1.32	0.02
08:35-0900	10	10	63.91	48	35.47	58	0.97		17.24%	1.70	1.76	0.03
08:35-0900	11	13	63.91	66	35.47	79	1.32		16.46%	2.21	1.68	0.03
08:35-0900	12	11	63.91	72	35.47	83	1.38		13.25%	1.87	1.35	0.02
08:35-0900	13	12	63.91	62	35.47	74	1.23		16.22%	2.04	1.65	0.03
08:35-0900	14	12	63.91	59	35.47	71	1.18		16.90%	2.04	1.72	0.03
08:35-0900	15	11	63.91	61	35.47	72	1.20		15.28%	1.87	1.56	0.03
08:35-0900	16	11	63.91	61	35.47	72	1.20		15.28%	1.87	1.56	0.03
08:35-0900	17	12	63.91	73	35.47	85	1.42		14.12%	2.04	1.44	0.02
08:35-0900	18	11	63.91	73	35.47	84	1.40		13.10%	1.87	1.33	0.02
08:35-0900	19	12	63.91	38	35.47	50	0.83		24.00%	2.04	2.45	0.04
09:00-09:30	20	10	63.63	39	35.79	49	0.82		20.41%	1.69	2.07	0.03
09:00-09:30	21	16	63.63	48	35.79	64	1.07		25.00%	2.71	2.54	0.04
09:00-09:30	22	16	63.63	15	35.79	31	0.52		51.61%	2.71	5.24	0.09
09:00-09:30	23	10	63.63	45	35.79	55	0.92		18.18%	1.69	1.85	0.03
09:00-09:30	24	11	63.63	63	35.79	74	1.23		14.86%	1.86	1.51	0.03
09:00-09:30	25	11	63.63	71	35.79	82	1.37		13.41%	1.86	1.36	0.02
09:00-09:30	26	11	63.63	72	35.79	83	1.38		13.25%	1.86	1.35	0.02
09:00-09:30	27	11	63.63	72	35.79	83	1.38		13.25%	1.86	1.35	0.02
09:00-09:30	28	10	63.63	67	35.79	77	1.28		12.99%	1.69	1.32	0.02
09:00-09:30	29	11	63.63	63	35.79	74	1.23		14.86%	1.86	1.51	0.03
09:00-09:30	30	10	63.63	86	35.79	96	1.60		10.42%	1.69	1.06	0.02
09:00-09:30	31	11	63.63	83	35.79	94	1.57		11.70%	1.86	1.19	0.02
09:00-09:30	32	11	63.63	43	35.79	54	0.90		20.37%	1.86	2.07	0.03
09:00-09:30	33	12	63.63	67	35.79	79	1.32		15.19%	2.03	1.54	0.03
09:00-09:30	34	11	63.63	53	35.79	64	1.07		17.19%	1.86	1.74	0.03
09:00-09:30	35	12	63.63	40	35.79	52	0.87		23.08%	2.03	2.34	0.04
09:00-09:30	36	11	63.63	62	35.79	73	1.22		15.07%	1.86	1.53	0.03
09:00-09:30	37	11	63.63	72	35.79	83	1.38		13.25%	1.86	1.35	0.02
09:00-09:30	38	11	63.63	76	35.79	87	1.45		12.64%	1.86	1.28	0.02
09:00-09:30	39	11	63.63	75	35.79	86	1.43		12.79%	1.86	1.30	0.02
09:00-09:30	40	11	63.63	124	35.79	135	2.25		8.15%	1.86	0.83	0.01
09:00-09:30	41	11	63.63	75	35.79	86	1.43		12.79%	1.86	1.30	0.02
09:00-09:30	42	12	63.63	73	35.79	85	1.42		14.12%	2.03	1.43	0.02
09:00-09:30	43	11	63.63	43	35.79	54	0.90		20.37%	1.86	2.07	0.03
09:00-09:30	44	15	63.63	46	35.79	61	1.02		24.59%	2.54	2.50	0.04
09:30-10:00	45	11	63.96	26	35.47	37	0.62		29.73%	1.87	3.03	0.05
09:30-10:00	46	11	63.96	52	35.47	63	1.05		17.46%	1.87	1.78	0.03
09:30-10:00	47	16	63.96	15	35.47	31	0.52		51.61%	2.72	5.27	0.09
09:30-10:00	48	16	63.96	15	35.47	31	0.52		51.61%	2.72	5.27	0.09
09:30-10:00	49	15	63.96	24	35.47	39	0.65		38.46%	2.55	3.92	0.07

09:30-10:00	50	16	63.96	17	35.47	33	0.55		48.48%	2.72	4.95	0.08
09:30-10:00	51	11	63.96	19	35.47	30	0.50		36.67%	1.87	3.74	0.06
09:30-10:00	52	16	63.96	27	35.47	43	0.72		37.21%	2.72	3.80	0.06
09:30-10:00	53	14	63.96	15	35.47	29	0.48		48.28%	2.38	4.92	0.08
09:30-10:00	54	18	63.96	24	35.47	42	0.70		42.86%	3.06	4.37	0.07
09:30-10:00	55	16	63.96	15	35.47	31	0.52		51.61%	2.72	5.27	0.09
09:30-10:00	56	15	63.96	21	35.47	36	0.60		41.67%	2.55	4.25	0.07
09:30-10:00	57	16	63.96	14	35.47	30	0.50		53.33%	2.72	5.44	0.09
09:30-10:00	58	15	63.96	22	35.47	37	0.62		40.54%	2.55	4.14	0.07
09:30-10:00	59	16	63.96	14	35.47	30	0.50		53.33%	2.72	5.44	0.09
09:30-10:00	60	17	63.96	21	35.47	38	0.63		44.74%	2.89	4.56	0.08
09:30-10:00	61	18	63.96	13	35.47	31	0.52		58.06%	3.06	5.92	0.10
09:30-10:00	62	16	63.96	21	35.47	37	0.62		43.24%	2.72	4.41	0.07
09:30-10:00	63	16	63.96	15	35.47	31	0.52		51.61%	2.72	5.27	0.09
09:30-10:00	64	13	63.96	20	35.47	33	0.55		39.39%	2.21	4.02	0.07
09:30-10:00	65	16	63.96	15	35.47	31	0.52		51.61%	2.72	5.27	0.09
09:30-10:00	66	13	63.96	19	35.47	32	0.53		40.63%	2.21	4.14	0.07
09:30-10:00	67	17	63.96	17	35.47	34	0.57		50.00%	2.89	5.10	0.09
09:30-10:00	68	11	63.96	55	35.47	66	1.10		16.67%	1.87	1.70	0.03
09:30-10:00	69	10	63.96	63	35.47	73	1.22		13.70%	1.70	1.40	0.02
09:30-10:00	70	11	63.96	59	35.47	70	1.17		15.71%	1.87	1.60	0.03
09:30-10:00	71	11	63.96	67	35.47	78	1.30		14.10%	1.87	1.44	0.02
09:30-10:00	72	11	63.96	58	35.47	69	1.15		15.94%	1.87	1.63	0.03
09:30-10:00	73	11	63.96	62	35.47	73	1.22		15.07%	1.87	1.54	0.03
09:30-10:00	74	11	63.96	63	35.47	74	1.23		14.86%	1.87	1.52	0.03
09:30-10:00	75	11	63.96	58	35.47	69	1.15		15.94%	1.87	1.63	0.03
09:30-10:00	76	11	63.96	62	35.47	73	1.22		15.07%	1.87	1.54	0.03
09:30-10:00	77	11	63.96	63	35.47	74	1.23		14.86%	1.87	1.52	0.03
09:30-10:00	78	11	63.96	59	35.47	70	1.17		15.71%	1.87	1.60	0.03
09:30-10:00	79	11	63.96	59	35.47	70	1.17		15.71%	1.87	1.60	0.03
09:30-10:00	80	11	63.96	65	35.47	76	1.27		14.47%	1.87	1.48	0.02
09:30-10:00	81	10	63.96	64	35.47	74	1.23		13.51%	1.70	1.38	0.02
09:30-10:00	82	11	63.96	65	35.47	76	1.27		14.47%	1.87	1.48	0.02
09:30-10:00	83	11	63.96	29	35.47	40	0.67		27.50%	1.87	2.81	0.05
09:30-10:00	84	11	63.96	23	35.47	34	0.57		32.35%	1.87	3.30	0.06
09:30-10:00	85	12	63.96	71	35.47	83	1.38		14.46%	2.04	1.47	0.02
10:00-10:30	86	11	63.57	67	35.87	78	1.30		14.10%	1.86	1.43	0.02
10:00-10:30	87	11	63.57	56	35.87	67	1.12		16.42%	1.86	1.66	0.03
10:00-10:30	88	11	63.57	64	35.87	75	1.25		14.67%	1.86	1.49	0.02
10:00-10:30	89	12	63.57	56	35.87	68	1.13		17.65%	2.03	1.79	0.03
10:00-10:30	90	12	63.57	31	35.87	43	0.72		27.91%	2.03	2.83	0.05
10:00-10:30	91	11	63.57	60	35.87	71	1.18		15.49%	1.86	1.57	0.03
10:00-10:30	92	11	63.57	67	35.87	78	1.30		14.10%	1.86	1.43	0.02
10:00-10:30	93	11	63.57	71	35.87	82	1.37		13.41%	1.86	1.36	0.02
10:00-10:30	94	11	63.57	66	35.87	77	1.28		14.29%	1.86	1.45	0.02
10:00-10:30	95	11	63.57	68	35.87	79	1.32		13.92%	1.86	1.41	0.02
10:00-10:30	96	10	63.57	67	35.87	77	1.28		12.99%	1.69	1.32	0.02
10:00-10:30	97	10	63.57	69	35.87	79	1.32		12.66%	1.69	1.28	0.02
10:00-10:30	98	11	63.57	69	35.87	80	1.33		13.75%	1.86	1.39	0.02
10:00-10:30	99	11	63.57	65	35.87	76	1.27		14.47%	1.86	1.47	0.02
10:00-10:30	100	11	63.57	70	35.87	81	1.35		13.58%	1.86	1.38	0.02
10:00-10:30	101	11	63.57	63	35.87	74	1.23		14.86%	1.86	1.51	0.03
10:00-10:30	102	11	63.57	70	35.87	81	1.35		13.58%	1.86	1.38	0.02
10:00-10:30	103	12	63.57	62	35.87	74	1.23		16.22%	2.03	1.64	0.03
10:00-10:30	104	10	63.57	33	35.87	43	0.72		23.26%	1.69	2.36	0.04
10:00-10:30	105	11	63.57	39	35.87	50	0.83		22.00%	1.86	2.23	0.04
10:00-10:30	106	11	63.57	66	35.87	77	1.28		14.29%	1.86	1.45	0.02

10:00-10:30	107	11	63.57	45	35.87	56	0.93		19.64%	1.86	1.99	0.03
10:00-10:30	108	12	63.57	38	35.87	50	0.83		24.00%	2.03	2.43	0.04
10:00-10:30	109	16	63.57	51	35.87	67	1.12		23.88%	2.70	2.42	0.04
10:00-10:30	110	18	63.57	46	35.87	64	1.07		28.13%	3.04	2.85	0.05
10:00-10:30	111	11	63.57	49	35.87	60	1.00		18.33%	1.86	1.86	0.03
10:00-10:30	112	11	63.57	60	35.87	71	1.18		15.49%	1.86	1.57	0.03
10:30-11:00	113	11	63.57	73	35.87	84	1.40		13.10%	1.86	1.33	0.02
10:30-11:00	114	11	63.57	65	35.87	76	1.27		14.47%	1.86	1.47	0.02
10:30-11:00	115	11	63.57	60	35.87	71	1.18		15.49%	1.86	1.57	0.03
10:30-11:00	116	11	63.57	60	35.87	71	1.18		15.49%	1.86	1.57	0.03
10:30-11:00	117	11	63.57	55	35.87	66	1.10		16.67%	1.86	1.69	0.03
10:30-11:00	118	11	63.57	68	35.87	79	1.32		13.92%	1.86	1.41	0.02
10:30-11:00	119	12	63.57	54	35.87	66	1.10		18.18%	2.03	1.84	0.03
10:30-11:00	120	12	63.57	62	35.87	74	1.23		16.22%	2.03	1.64	0.03
10:30-11:00	121	11	63.57	61	35.87	72	1.20		15.28%	1.86	1.55	0.03
10:30-11:00	122	11	63.57	61	35.87	72	1.20		15.28%	1.86	1.55	0.03
10:30-11:00	123	11	63.57	66	35.87	77	1.28		14.29%	1.86	1.45	0.02
10:30-11:00	124	10	63.57	63	35.87	73	1.22		13.70%	1.69	1.39	0.02
10:30-11:00	125	11	63.57	44	35.87	55	0.92		20.00%	1.86	2.03	0.03
10:30-11:00	126	11	63.57	56	35.87	67	1.12		16.42%	1.86	1.66	0.03
10:30-11:00	127	15	63.57	27	35.87	42	0.70		35.71%	2.53	3.62	0.06
10:30-11:00	128	15	63.57	43	35.87	58	0.97		25.86%	2.53	2.62	0.04
10:30-11:00	129	20	63.57	28	35.87	48	0.80		41.67%	3.38	4.22	0.07
10:30-11:00	130	11	63.57	27	35.87	38	0.63		28.95%	1.86	2.94	0.05
10:30-11:00	131	15	63.57	38	35.87	53	0.88		28.30%	2.53	2.87	0.05
10:30-11:00	132	16	63.57	39	35.87	55	0.92		29.09%	2.70	2.95	0.05
10:30-11:00	133	14	63.57	32	35.87	46	0.77		30.43%	2.37	3.09	0.05
11:00-11:30	134	17	63.98	14	35.64	31	0.52		54.84%	2.89	5.60	0.09
11:00-11:30	135	14	63.98	29	35.64	43	0.72		32.56%	2.38	3.32	0.06
11:00-11:30	136	11	63.98	57	35.64	68	1.13		16.18%	1.87	1.65	0.03
11:00-11:30	137	12	63.98	24	35.64	36	0.60		33.33%	2.04	3.40	0.06
11:00-11:30	138	11	63.98	53	35.64	64	1.07		17.19%	1.87	1.75	0.03
11:00-11:30	139	11	63.98	45	35.64	56	0.93		19.64%	1.87	2.00	0.03
11:00-11:30	140	16	63.98	15	35.64	31	0.52		51.61%	2.72	5.27	0.09
11:00-11:30	141	13	63.98	47	35.64	60	1.00		21.67%	2.21	2.21	0.04
11:00-11:30	142	12	63.98	59	35.64	71	1.18		16.90%	2.04	1.72	0.03
11:00-11:30	143	12	63.98	56	35.64	68	1.13		17.65%	2.04	1.80	0.03
11:00-11:30	144	11	63.98	53	35.64	64	1.07		17.19%	1.87	1.75	0.03
11:00-11:30	145	11	63.98	66	35.64	77	1.28		14.29%	1.87	1.46	0.02
11:00-11:30	146	11	63.98	67	35.64	78	1.30		14.10%	1.87	1.44	0.02
11:00-11:30	147	11	63.98	62	35.64	73	1.22		15.07%	1.87	1.54	0.03
11:00-11:30	148	12	63.98	67	35.64	79	1.32		15.19%	2.04	1.55	0.03
11:00-11:30	149	10	63.98	66	35.64	76	1.27		13.16%	1.70	1.34	0.02
11:00-11:30	150	11	63.98	67	35.64	78	1.30		14.10%	1.87	1.44	0.02
11:00-11:30	151	11	63.98	66	35.64	77	1.28		14.29%	1.87	1.46	0.02
11:00-11:30	152	11	63.98	65	35.64	76	1.27		14.47%	1.87	1.48	0.02
11:00-11:30	153	11	63.98	62	35.64	73	1.22		15.07%	1.87	1.54	0.03
11:00-11:30	154	11	63.98	70	35.64	81	1.35		13.58%	1.87	1.39	0.02
11:00-11:30	155	11	63.98	37	35.64	48	0.80		22.92%	1.87	2.34	0.04
11:00-11:30	156	12	63.98	28	35.64	40	0.67		30.00%	2.04	3.06	0.05
11:00-11:30	157	12	63.98	27	35.64	39	0.65		30.77%	2.04	3.14	0.05
11:00-11:30	158	12	63.98	27	35.64	39	0.65		30.77%	2.04	3.14	0.05
11:00-11:30	159	12	63.98	43	35.64	55	0.92		21.82%	2.04	2.23	0.04
11:00-11:30	160	11	63.98	41	35.64	52	0.87		21.15%	1.87	2.16	0.04
11:00-11:30	161	12	63.98	44	35.64	56	0.93		21.43%	2.04	2.19	0.04
11:00-11:30	162	12	63.98	16	35.64	28	0.47		42.86%	2.04	4.37	0.07
11:00-11:30	163	17	63.98	19	35.64	36	0.60		47.22%	2.89	4.82	0.08

11:00-11:30	164	11	63.98	50	35.64	61	1.02		18.03%	1.87	1.84	0.03
11:30-12:00	165	12	63.59	57	35.19	69	1.15		17.39%	2.03	1.76	0.03
11:30-12:00	166	11	63.59	60	35.19	71	1.18		15.49%	1.86	1.57	0.03
11:30-12:00	167	12	63.59	64	35.19	76	1.27		15.79%	2.03	1.60	0.03
11:30-12:00	168	11	63.59	68	35.19	79	1.32		13.92%	1.86	1.41	0.02
11:30-12:00	169	11	63.59	59	35.19	70	1.17		15.71%	1.86	1.59	0.03
11:30-12:00	170	12	63.59	68	35.19	80	1.33		15.00%	2.03	1.52	0.03
11:30-12:00	171	11	63.59	68	35.19	79	1.32		13.92%	1.86	1.41	0.02
11:30-12:00	172	11	63.59	54	35.19	65	1.08		16.92%	1.86	1.72	0.03
11:30-12:00	173	11	63.59	59	35.19	70	1.17		15.71%	1.86	1.59	0.03
11:30-12:00	174	11	63.59	68	35.19	79	1.32		13.92%	1.86	1.41	0.02
11:30-12:00	175	11	63.59	68	35.19	79	1.32		13.92%	1.86	1.41	0.02
11:30-12:00	176	11	63.59	85	35.19	96	1.60		11.46%	1.86	1.16	0.02
11:30-12:00	177	11	63.59	55	35.19	66	1.10		16.67%	1.86	1.69	0.03
11:30-12:00	178	13	63.59	30	35.19	43	0.72		30.23%	2.20	3.07	0.05
11:30-12:00	179	12	63.59	37	35.19	49	0.82		24.49%	2.03	2.48	0.04
11:30-12:00	180	12	63.59	75	35.19	87	1.45		13.79%	2.03	1.40	0.02
11:30-12:00	181	10	63.59	83	35.19	93	1.55		10.75%	1.69	1.09	0.02
11:30-12:00	182	11	63.59	82	35.19	93	1.55		11.83%	1.86	1.20	0.02
11:30-12:00	183	11	63.59	89	35.19	100	1.67		11.00%	1.86	1.12	0.02
11:30-12:00	184	12	63.59	43	35.19	55	0.92		21.82%	2.03	2.21	0.04
11:30-12:00	185	11	63.59	80	35.19	91	1.52		12.09%	1.86	1.23	0.02
11:30-12:00	186	11	63.59	87	35.19	98	1.63		11.22%	1.86	1.14	0.02
11:30-12:00	187	12	63.59	91	35.19	103	1.72		11.65%	2.03	1.18	0.02
12:00-12:30	188	11	63.53	91	35.18	102	1.70		10.78%	1.86	1.09	0.02
12:00-12:30	189	11	63.53	84	35.18	95	1.58		11.58%	1.86	1.17	0.02
12:00-12:30	190	12	63.53	72	35.18	84	1.40		14.29%	2.03	1.45	0.02
12:00-12:30	191	12	63.53	28	35.18	40	0.67		30.00%	2.03	3.04	0.05
12:00-12:30	192	12	63.53	30	35.18	42	0.70		28.57%	2.03	2.90	0.05
12:00-12:30	193	12	63.53	31	35.18	43	0.72		27.91%	2.03	2.83	0.05
12:00-12:30	194	12	63.53	31	35.18	43	0.72		27.91%	2.03	2.83	0.05
12:00-12:30	195	12	63.53	30	35.18	42	0.70		28.57%	2.03	2.90	0.05
12:00-12:30	196	10	63.53	68	35.18	78	1.30		12.82%	1.69	1.30	0.02
12:00-12:30	197	11	63.53	79	35.18	90	1.50		12.22%	1.86	1.24	0.02
12:00-12:30	198	11	63.53	75	35.18	86	1.43		12.79%	1.86	1.30	0.02
12:00-12:30	199	11	63.53	76	35.18	87	1.45		12.64%	1.86	1.28	0.02
12:00-12:30	200	10	63.53	72	35.18	82	1.37		12.20%	1.69	1.24	0.02
12:00-12:30	201	11	63.53	85	35.18	96	1.60		11.46%	1.86	1.16	0.02
12:00-12:30	202	11	63.53	89	35.18	100	1.67		11.00%	1.86	1.11	0.02
12:00-12:30	203	11	63.53	84	35.18	95	1.58		11.58%	1.86	1.17	0.02
12:00-12:30	204	11	63.53	90	35.18	101	1.68		10.89%	1.86	1.10	0.02
12:00-12:30	205	11	63.53	43	35.18	54	0.90		20.37%	1.86	2.06	0.03
12:00-12:30	206	11	63.53	48	35.18	59	0.98		18.64%	1.86	1.89	0.03
12:00-12:30	207	11	63.53	78	35.18	89	1.48		12.36%	1.86	1.25	0.02
12:00-12:30	208	11	63.53	95	35.18	106	1.77		10.38%	1.86	1.05	0.02
12:00-12:30	209	12	63.53	88	35.18	100	1.67		12.00%	2.03	1.22	0.02
12:00-12:30	210	10	63.53	75	35.18	85	1.42		11.76%	1.69	1.19	0.02
12:30-13:00	211	11	63.46	79	34.85	90	1.50		12.22%	1.86	1.24	0.02
12:30-13:00	212	11	63.46	98	34.85	109	1.82		10.09%	1.86	1.02	0.02
12:30-13:00	213	11	63.46	98	34.85	109	1.82		10.09%	1.86	1.02	0.02
12:30-13:00	214	10	63.46	101	34.85	111	1.85		9.01%	1.69	0.91	0.02
12:30-13:00	215	11	63.46	105	34.85	116	1.93		9.48%	1.86	0.96	0.02
12:30-13:00	216	11	63.46	100	34.85	111	1.85		9.91%	1.86	1.00	0.02
12:30-13:00	217	11	63.46	95	34.85	106	1.77		10.38%	1.86	1.05	0.02
12:30-13:00	218	11	63.46	96	34.85	107	1.78		10.28%	1.86	1.04	0.02
12:30-13:00	219	11	63.46	96	34.85	107	1.78		10.28%	1.86	1.04	0.02
12:30-13:00	220	11	63.46	97	34.85	108	1.80		10.19%	1.86	1.03	0.02

12:30-13:00	221	10	63.46	94	34.85	104	1.73		9.62%	1.69	0.97	0.02
12:30-13:00	222	11	63.46	97	34.85	108	1.80		10.19%	1.86	1.03	0.02
12:30-13:00	223	11	63.46	96	34.85	107	1.78		10.28%	1.86	1.04	0.02
12:30-13:00	224	11	63.46	94	34.85	105	1.75		10.48%	1.86	1.06	0.02
12:30-13:00	225	11	63.46	98	34.85	109	1.82		10.09%	1.86	1.02	0.02
12:30-13:00	226	11	63.46	94	34.85	105	1.75		10.48%	1.86	1.06	0.02
12:30-13:00	227	11	63.46	94	34.85	105	1.75		10.48%	1.86	1.06	0.02
13:00-13:30	228	11	63.13	99	36.58	110	1.83		10.00%	1.85	1.01	0.02
13:00-13:30	229	11	63.13	97	36.58	108	1.80		10.19%	1.85	1.03	0.02
13:00-13:30	230	11	63.13	93	36.58	104	1.73		10.58%	1.85	1.07	0.02
13:00-13:30	231	11	63.13	98	36.58	109	1.82		10.09%	1.85	1.02	0.02
13:00-13:30	232	11	63.13	91	36.58	102	1.70		10.78%	1.85	1.09	0.02
13:00-13:30	233	10	63.13	86	36.58	96	1.60		10.42%	1.68	1.05	0.02
13:00-13:30	234	11	63.13	76	36.58	87	1.45		12.64%	1.85	1.27	0.02
13:00-13:30	235	11	63.13	80	36.58	91	1.52		12.09%	1.85	1.22	0.02
13:00-13:30	236	12	63.13	58	36.58	70	1.17		17.14%	2.01	1.73	0.03
13:00-13:30	237	12	63.13	31	36.58	43	0.72		27.91%	2.01	2.81	0.05
13:00-13:30	238	13	63.13	30	36.58	43	0.72		30.23%	2.18	3.04	0.05
13:00-13:30	239	12	63.13	45	36.58	57	0.95		21.05%	2.01	2.12	0.04
13:00-13:30	240	12	63.13	40	36.58	52	0.87		23.08%	2.01	2.32	0.04
13:00-13:30	241	11	63.13	32	36.58	43	0.72		25.58%	1.85	2.58	0.04
13:00-13:30	242	10	63.13	60	36.58	70	1.17		14.29%	1.68	1.44	0.02
13:00-13:30	243	12	63.13	84	36.58	96	1.60		12.50%	2.01	1.26	0.02
13:00-13:30	244	14	63.13	23	36.58	37	0.62		37.84%	2.35	3.81	0.06
13:00-13:30	245	12	63.13	29	36.58	41	0.68		29.27%	2.01	2.95	0.05
13:00-13:30	246	19	63.13	21	36.58	40	0.67		47.50%	3.19	4.78	0.08
13:00-13:30	247	14	63.13	14	36.58	28	0.47		50.00%	2.35	5.03	0.08
13:00-13:30	248	18	63.13	25	36.58	43	0.72		41.86%	3.02	4.22	0.07
13:00-13:30	249	12	63.13	14	36.58	26	0.43		46.15%	2.01	4.65	0.08
13:00-13:30	250	16	63.13	27	36.58	43	0.72		37.21%	2.69	3.75	0.06
13:00-13:30	251	14	63.13	26	36.58	40	0.67		35.00%	2.35	3.52	0.06
13:00-13:30	252	12	63.13	41	36.58	53	0.88		22.64%	2.01	2.28	0.04
13:00-13:30	253	17	63.13	18	36.58	35	0.58		48.57%	2.85	4.89	0.08
13:00-13:30	254	16	63.13	26	36.58	42	0.70		38.10%	2.69	3.84	0.06
13:00-13:30	255	13	63.13	15	36.58	28	0.47		46.43%	2.18	4.68	0.08
13:00-13:30	256	11	63.13	26	36.58	37	0.62		29.73%	1.85	2.99	0.05
13:00-13:30	257	17	63.13	41	36.58	58	0.97		29.31%	2.85	2.95	0.05
13:30-14:00	258	14	64.08	15	36.05	29	0.48		48.28%	2.38	4.93	0.08
13:30-14:00	259	11	64.08	23	36.05	34	0.57		32.35%	1.87	3.31	0.06
13:30-14:00	260	16	64.08	40	36.05	56	0.93		28.57%	2.73	2.92	0.05
13:30-14:00	261	14	64.08	25	36.05	39	0.65		35.90%	2.38	3.67	0.06
13:30-14:00	262	13	64.08	42	36.05	55	0.92		23.64%	2.21	2.42	0.04
13:30-14:00	263	15	64.08	16	36.05	31	0.52		48.39%	2.56	4.95	0.08
13:30-14:00	264	17	64.08	22	36.05	39	0.65		43.59%	2.90	4.46	0.07
13:30-14:00	265	13	64.08	15	36.05	28	0.47		46.43%	2.21	4.75	0.08
13:30-14:00	266	17	64.08	19	36.05	36	0.60		47.22%	2.90	4.83	0.08
13:30-14:00	267	16	64.08	22	36.05	38	0.63		42.11%	2.73	4.30	0.07
13:30-14:00	268	11	64.08	39	36.05	50	0.83		22.00%	1.87	2.25	0.04
13:30-14:00	269	17	64.08	18	36.05	35	0.58		48.57%	2.90	4.96	0.08
13:30-14:00	270	13	64.08	15	36.05	28	0.47		46.43%	2.21	4.75	0.08
13:30-14:00	271	11	64.08	29	36.05	40	0.67		27.50%	1.87	2.81	0.05
13:30-14:00	272	17	64.08	44	36.05	61	1.02		27.87%	2.90	2.85	0.05
13:30-14:00	273	12	64.08	19	36.05	31	0.52		38.71%	2.04	3.96	0.07
13:30-14:00	274	13	64.08	20	36.05	33	0.55		39.39%	2.21	4.03	0.07
13:30-14:00	275	15	64.08	46	36.05	61	1.02		24.59%	2.56	2.51	0.04
13:30-14:00	276	13	64.08	46	36.05	59	0.98		22.03%	2.21	2.25	0.04
13:30-14:00	277	18	64.08	16	36.05	34	0.57		52.94%	3.07	5.41	0.09

13:30-14:00	278	15	64.08	25	36.05	40	0.67		37.50%	2.56	3.83	0.06
13:30-14:00	279	14	64.08	38	36.05	52	0.87		26.92%	2.38	2.75	0.05
13:30-14:00	280	14	64.08	15	36.05	29	0.48		48.28%	2.38	4.93	0.08
13:30-14:00	281	17	64.08	22	36.05	39	0.65		43.59%	2.90	4.46	0.07
13:30-14:00	282	16	64.08	14	36.05	30	0.50		53.33%	2.73	5.45	0.09
13:30-14:00	283	14	64.08	22	36.05	36	0.60		38.89%	2.38	3.97	0.07
13:30-14:00	284	18	64.08	26	36.05	44	0.73		40.91%	3.07	4.18	0.07
13:30-14:00	285	13	64.08	15	36.05	28	0.47		46.43%	2.21	4.75	0.08
13:30-14:00	286	17	64.08	20	36.05	37	0.62		45.95%	2.90	4.70	0.08
13:30-14:00	287	15	64.08	14	36.05	29	0.48		51.72%	2.56	5.29	0.09
13:30-14:00	288	22	64.08	15	36.05	37	0.62		59.46%	3.75	6.08	0.10
13:30-14:00	289	23	64.08	15	36.05	38	0.63		60.53%	3.92	6.19	0.10
13:30-14:00	290	17	64.08	12	36.05	29	0.48		58.62%	2.90	5.99	0.10
13:30-14:00	291	19	64.08	15	36.05	34	0.57		55.88%	3.24	5.71	0.10
13:30-14:00	292	13	64.08	15	36.05	28	0.47		46.43%	2.21	4.75	0.08
13:30-14:00	293	17	64.08	19	36.05	36	0.60		47.22%	2.90	4.83	0.08
13:30-14:00	294	12	64.08	15	36.05	27	0.45		44.44%	2.04	4.54	0.08
13:30-14:00	295	17	64.08	20	36.05	37	0.62		45.95%	2.90	4.70	0.08
13:30-14:00	296	22	64.08	16	36.05	38	0.63		57.89%	3.75	5.92	0.10
13:30-14:00	297	18	64.08	18	36.05	36	0.60		50.00%	3.07	5.11	0.09
13:30-14:00	298	12	64.08	21	36.05	33	0.55		36.36%	2.04	3.72	0.06
13:30-14:00	299	11	64.08	46	36.05	57	0.95		19.30%	1.87	1.97	0.03
13:30-14:00	300	12	64.08	48	36.05	60	1.00		20.00%	2.04	2.04	0.03
13:30-14:00	301	17	64.08	24	36.05	41	0.68		41.46%	2.90	4.24	0.07
13:30-14:00	302	20	64.08	14	36.05	34	0.57		58.82%	3.41	6.01	0.10
13:30-14:00	303	14	64.08	22	36.05	36	0.60		38.89%	2.38	3.97	0.07
14:00-14:30	304	11	64.08	39	35.12	50	0.83		22.00%	1.87	2.25	0.04
14:00-14:30	305	11	64.08	26	35.12	37	0.62		29.73%	1.87	3.04	0.05
14:00-14:30	306	17	64.08	16	35.12	33	0.55		51.52%	2.90	5.27	0.09
14:00-14:30	307	12	64.08	34	35.12	46	0.77		26.09%	2.04	2.67	0.04
14:00-14:30	308	14	64.08	41	35.12	55	0.92		25.45%	2.38	2.60	0.04
14:00-14:30	309	11	64.08	49	35.12	60	1.00		18.33%	1.87	1.87	0.03
14:00-14:30	310	12	64.08	21	35.12	33	0.55		36.36%	2.04	3.72	0.06
14:00-14:30	311	13	64.08	37	35.12	50	0.83		26.00%	2.21	2.66	0.04
14:00-14:30	312	17	64.08	17	35.12	34	0.57		50.00%	2.90	5.11	0.09
14:00-14:30	313	13	64.08	15	35.12	28	0.47		46.43%	2.21	4.75	0.08
14:00-14:30	314	12	64.08	31	35.12	43	0.72		27.91%	2.04	2.85	0.05
14:00-14:30	315	11	64.08	56	35.12	67	1.12		16.42%	1.87	1.68	0.03
14:00-14:30	316	17	64.08	24	35.12	41	0.68		41.46%	2.90	4.24	0.07
14:00-14:30	317	12	64.08	22	35.12	34	0.57		35.29%	2.04	3.61	0.06
14:00-14:30	318	13	64.08	47	35.12	60	1.00		21.67%	2.21	2.21	0.04
14:00-14:30	319	11	64.08	60	35.12	71	1.18		15.49%	1.87	1.58	0.03
14:00-14:30	320	17	64.08	42	35.12	59	0.98		28.81%	2.90	2.94	0.05
14:00-14:30	321	17	64.08	14	35.12	31	0.52		54.84%	2.90	5.60	0.09
14:00-14:30	322	11	64.08	46	35.12	57	0.95		19.30%	1.87	1.97	0.03
14:00-14:30	323	11	64.08	36	35.12	47	0.78		23.40%	1.87	2.39	0.04
14:00-14:30	324	15	64.08	53	35.12	68	1.13		22.06%	2.56	2.25	0.04
14:00-14:30	325	16	64.08	15	35.12	31	0.52		51.61%	2.73	5.28	0.09
14:00-14:30	326	12	64.08	25	35.12	37	0.62		32.43%	2.04	3.31	0.06
14:00-14:30	327	18	64.08	26	35.12	44	0.73		40.91%	3.07	4.18	0.07
14:00-14:30	328	18	64.08	14	35.12	32	0.53		56.25%	3.07	5.75	0.10
14:00-14:30	329	15	64.08	14	35.12	29	0.48		51.72%	2.56	5.29	0.09
14:00-14:30	330	19	64.08	20	35.12	39	0.65		48.72%	3.24	4.98	0.08
14:00-14:30	331	15	64.08	16	35.12	31	0.52		48.39%	2.56	4.95	0.08
14:00-14:30	332	13	64.08	14	35.12	27	0.45		48.15%	2.21	4.92	0.08
14:00-14:30	333	21	64.08	19	35.12	40	0.67		52.50%	3.58	5.37	0.09
14:00-14:30	334	15	64.08	13	35.12	28	0.47		53.57%	2.56	5.48	0.09

14:00-14:30	335	15	64.08	14	35.12	29	0.48		51.72%	2.56	5.29	0.09
14:00-14:30	336	20	64.08	17	35.12	37	0.62		54.05%	3.41	5.52	0.09
14:00-14:30	337	15	64.08	14	35.12	29	0.48		51.72%	2.56	5.29	0.09
14:00-14:30	338	12	64.08	25	35.12	37	0.62		32.43%	2.04	3.31	0.06
14:00-14:30	339	11	64.08	48	35.12	59	0.98		18.64%	1.87	1.91	0.03
14:00-14:30	340	12	64.08	40	35.12	52	0.87		23.08%	2.04	2.36	0.04
14:00-14:30	341	16	64.08	18	35.12	34	0.57		47.06%	2.73	4.81	0.08
14:00-14:30	342	15	64.08	15	35.12	30	0.50		50.00%	2.56	5.11	0.09
14:00-14:30	343	11	64.08	60	35.12	71	1.18		15.49%	1.87	1.58	0.03
14:00-14:30	344	10	64.08	80	35.12	90	1.50		11.11%	1.70	1.14	0.02
14:30-15:00	345	10	63.4	93	35.02	103	1.72		9.71%	1.69	0.98	0.02
14:30-15:00	346	12	63.4	85	35.02	97	1.62		12.37%	2.02	1.25	0.02
14:30-15:00	347	11	63.4	88	35.02	99	1.65		11.11%	1.85	1.12	0.02
14:30-15:00	348	10	63.4	77	35.02	87	1.45		11.49%	1.69	1.16	0.02
14:30-15:00	349	11	63.4	87	35.02	98	1.63		11.22%	1.85	1.14	0.02
14:30-15:00	350	11	63.4	91	35.02	102	1.70		10.78%	1.85	1.09	0.02
14:30-15:00	351	11	63.4	81	35.02	92	1.53		11.96%	1.85	1.21	0.02
14:30-15:00	352	10	63.4	96	35.02	106	1.77		9.43%	1.69	0.95	0.02
14:30-15:00	353	11	63.4	82	35.02	93	1.55		11.83%	1.85	1.20	0.02
14:30-15:00	354	11	63.4	92	35.02	103	1.72		10.68%	1.85	1.08	0.02
14:30-15:00	355	11	63.4	86	35.02	97	1.62		11.34%	1.85	1.15	0.02
14:30-15:00	356	11	63.4	86	35.02	97	1.62		11.34%	1.85	1.15	0.02
14:30-15:00	357	11	63.4	89	35.02	100	1.67		11.00%	1.85	1.11	0.02
14:30-15:00	358	11	63.4	79	35.02	90	1.50		12.22%	1.85	1.24	0.02
14:30-15:00	359	11	63.4	92	35.02	103	1.72		10.68%	1.85	1.08	0.02
14:30-15:00	360	11	63.4	48	35.02	59	0.98		18.64%	1.85	1.89	0.03
14:30-15:00	361	11	63.4	79	35.02	90	1.50		12.22%	1.85	1.24	0.02
14:30-15:00	362	11	63.4	64	35.02	75	1.25		14.67%	1.85	1.48	0.02
14:30-15:00	363	12	63.4	31	35.02	43	0.72		27.91%	2.02	2.82	0.05
14:30-15:00	364	12	63.4	31	35.02	43	0.72		27.91%	2.02	2.82	0.05
14:30-15:00	365	12	63.4	51	35.02	63	1.05		19.05%	2.02	1.93	0.03
15:00-15:30	366	11	63.2	83	35.02	94	1.57		11.70%	1.85	1.18	0.02
15:00-15:30	367	10	63.2	75	35.02	85	1.42		11.76%	1.68	1.19	0.02
15:00-15:30	368	11	63.2	39	35.02	50	0.83		22.00%	1.85	2.22	0.04
15:00-15:30	369	12	63.2	48	35.02	60	1.00		20.00%	2.02	2.02	0.03
15:00-15:30	370	11	63.2	95	35.02	106	1.77		10.38%	1.85	1.05	0.02
15:00-15:30	371	11	63.2	96	35.02	107	1.78		10.28%	1.85	1.04	0.02
15:00-15:30	372	11	63.2	95	35.02	106	1.77		10.38%	1.85	1.05	0.02
15:00-15:30	373	11	63.2	95	35.02	106	1.77		10.38%	1.85	1.05	0.02
15:00-15:30	374	11	63.2	99	35.02	110	1.83		10.00%	1.85	1.01	0.02
15:00-15:30	375	11	63.2	93	35.02	104	1.73		10.58%	1.85	1.07	0.02
15:00-15:30	376	11	63.2	97	35.02	108	1.80		10.19%	1.85	1.03	0.02
15:00-15:30	377	11	63.2	93	35.02	104	1.73		10.58%	1.85	1.07	0.02
15:00-15:30	378	10	63.2	92	35.02	102	1.70		9.80%	1.68	0.99	0.02
15:00-15:30	379	11	63.2	90	35.02	101	1.68		10.89%	1.85	1.10	0.02
15:00-15:30	380	11	63.2	83	35.02	94	1.57		11.70%	1.85	1.18	0.02
15:00-15:30	381	11	63.2	73	35.02	84	1.40		13.10%	1.85	1.32	0.02
15:00-15:30	382	11	63.2	84	35.02	95	1.58		11.58%	1.85	1.17	0.02
15:00-15:30	383	11	63.2	91	35.02	102	1.70		10.78%	1.85	1.09	0.02
15:00-15:30	384	11	63.2	71	35.02	82	1.37		13.41%	1.85	1.35	0.02
15:30-16:00	385	11	63.69	89	35.82	100	1.67		11.00%	1.86	1.12	0.02
15:30-16:00	386	11	63.69	88	35.82	99	1.65		11.11%	1.86	1.13	0.02
15:30-16:00	387	11	63.69	89	35.82	100	1.67		11.00%	1.86	1.12	0.02
15:30-16:00	388	11	63.69	70	35.82	81	1.35		13.58%	1.86	1.38	0.02
15:30-16:00	389	14	63.69	46	35.82	60	1.00		23.33%	2.37	2.37	0.04
15:30-16:00	390	15	63.69	16	35.82	31	0.52		48.39%	2.54	4.92	0.08
15:30-16:00	391	14	63.69	37	35.82	51	0.85		27.45%	2.37	2.79	0.05

15:30-16:00	392	10	63.69	42	35.82	52	0.87		19.23%	1.69	1.95	0.03
15:30-16:00	393	17	63.69	35	35.82	52	0.87		32.69%	2.88	3.32	0.06
15:30-16:00	394	14	63.69	21	35.82	35	0.58		40.00%	2.37	4.06	0.07
15:30-16:00	395	13	63.69	38	35.82	51	0.85		25.49%	2.20	2.59	0.04
15:30-16:00	396	15	63.69	23	35.82	38	0.63		39.47%	2.54	4.01	0.07
15:30-16:00	397	11	63.69	43	35.82	54	0.90		20.37%	1.86	2.07	0.03
15:30-16:00	398	16	63.69	15	35.82	31	0.52		51.61%	2.71	5.24	0.09
15:30-16:00	399	15	63.69	32	35.82	47	0.78		31.91%	2.54	3.24	0.05
15:30-16:00	400	11	63.69	46	35.82	57	0.95		19.30%	1.86	1.96	0.03
15:30-16:00	401	16	63.69	15	35.82	31	0.52		51.61%	2.71	5.24	0.09
15:30-16:00	402	15	63.69	27	35.82	42	0.70		35.71%	2.54	3.63	0.06
15:30-16:00	403	11	63.69	55	35.82	66	1.10		16.67%	1.86	1.69	0.03
15:30-16:00	404	16	63.69	16	35.82	32	0.53		50.00%	2.71	5.08	0.08
15:30-16:00	405	15	63.69	28	35.82	43	0.72		34.88%	2.54	3.54	0.06
15:30-16:00	406	11	63.69	55	35.82	66	1.10		16.67%	1.86	1.69	0.03
15:30-16:00	407	14	63.69	16	35.82	30	0.50		46.67%	2.37	4.74	0.08
15:30-16:00	408	15	63.69	43	35.82	58	0.97		25.86%	2.54	2.63	0.04
15:30-16:00	409	14	63.69	51	35.82	65	1.08		21.54%	2.37	2.19	0.04
15:30-16:00	410	11	63.69	26	35.82	37	0.62		29.73%	1.86	3.02	0.05
15:30-16:00	411	17	63.69	14	35.82	31	0.52		54.84%	2.88	5.57	0.09
15:30-16:00	412	14	63.69	45	35.82	59	0.98		23.73%	2.37	2.41	0.04
15:30-16:00	413	11	63.69	61	35.82	72	1.20		15.28%	1.86	1.55	0.03
15:30-16:00	414	11	63.69	27	35.82	38	0.63		28.95%	1.86	2.94	0.05
15:30-16:00	415	16	63.69	43	35.82	59	0.98		27.12%	2.71	2.75	0.05
15:30-16:00	416	11	63.69	27	35.82	38	0.63		28.95%	1.86	2.94	0.05
15:30-16:00	417	11	63.69	57	35.82	68	1.13		16.18%	1.86	1.64	0.03
15:30-16:00	418	15	63.69	30	35.82	45	0.75		33.33%	2.54	3.39	0.06
16:00-16:45	419	11	63.52	38	35.75	49	0.82		22.45%	1.86	2.27	0.04
16:00-16:45	420	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	421	14	63.52	39	35.75	53	0.88		26.42%	2.36	2.68	0.04
16:00-16:45	422	11	63.52	52	35.75	63	1.05		17.46%	1.86	1.77	0.03
16:00-16:45	423	16	63.52	14	35.75	30	0.50		53.33%	2.70	5.40	0.09
16:00-16:45	424	16	63.52	31	35.75	47	0.78		34.04%	2.70	3.45	0.06
16:00-16:45	425	12	63.52	39	35.75	51	0.85		23.53%	2.03	2.38	0.04
16:00-16:45	426	15	63.52	26	35.75	41	0.68		36.59%	2.53	3.71	0.06
16:00-16:45	427	14	63.52	17	35.75	31	0.52		45.16%	2.36	4.58	0.08
16:00-16:45	428	15	63.52	30	35.75	45	0.75		33.33%	2.53	3.38	0.06
16:00-16:45	429	12	63.52	44	35.75	56	0.93		21.43%	2.03	2.17	0.04
16:00-16:45	430	16	63.52	14	35.75	30	0.50		53.33%	2.70	5.40	0.09
16:00-16:45	431	15	63.52	21	35.75	36	0.60		41.67%	2.53	4.22	0.07
16:00-16:45	432	12	63.52	50	35.75	62	1.03		19.35%	2.03	1.96	0.03
16:00-16:45	433	15	63.52	15	35.75	30	0.50		50.00%	2.53	5.07	0.08
16:00-16:45	434	17	63.52	26	35.75	43	0.72		39.53%	2.87	4.01	0.07
16:00-16:45	435	11	63.52	41	35.75	52	0.87		21.15%	1.86	2.14	0.04
16:00-16:45	436	12	63.52	18	35.75	30	0.50		40.00%	2.03	4.05	0.07
16:00-16:45	437	20	63.52	30	35.75	50	0.83		40.00%	3.38	4.05	0.07
16:00-16:45	438	11	63.52	21	35.75	32	0.53		34.38%	1.86	3.48	0.06
16:00-16:45	439	17	63.52	46	35.75	63	1.05		26.98%	2.87	2.73	0.05
16:00-16:45	440	11	63.52	40	35.75	51	0.85		21.57%	1.86	2.19	0.04
16:00-16:45	441	11	63.52	60	35.75	71	1.18		15.49%	1.86	1.57	0.03
16:00-16:45	442	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	443	14	63.52	58	35.75	72	1.20		19.44%	2.36	1.97	0.03
16:00-16:45	444	11	63.52	20	35.75	31	0.52		35.48%	1.86	3.60	0.06
16:00-16:45	445	12	63.52	64	35.75	76	1.27		15.79%	2.03	1.60	0.03
16:00-16:45	446	11	63.52	39	35.75	50	0.83		22.00%	1.86	2.23	0.04
16:00-16:45	447	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	448	14	63.52	56	35.75	70	1.17		20.00%	2.36	2.03	0.03

16:00-16:45	449	11	63.52	45	35.75	56	0.93		19.64%	1.86	1.99	0.03
16:00-16:45	450	13	63.52	66	35.75	79	1.32		16.46%	2.20	1.67	0.03
16:00-16:45	451	11	63.52	72	35.75	83	1.38		13.25%	1.86	1.34	0.02
16:00-16:45	452	11	63.52	39	35.75	50	0.83		22.00%	1.86	2.23	0.04
16:00-16:45	453	12	63.52	73	35.75	85	1.42		14.12%	2.03	1.43	0.02
16:00-16:45	454	11	63.52	74	35.75	85	1.42		12.94%	1.86	1.31	0.02
16:00-16:45	455	11	63.52	35	35.75	46	0.77		23.91%	1.86	2.42	0.04
16:00-16:45	456	17	63.52	17	35.75	34	0.57		50.00%	2.87	5.07	0.08
16:00-16:45	457	11	63.52	73	35.75	84	1.40		13.10%	1.86	1.33	0.02
16:00-16:45	458	11	63.52	66	35.75	77	1.28		14.29%	1.86	1.45	0.02
16:00-16:45	459	13	63.52	73	35.75	86	1.43		15.12%	2.20	1.53	0.03
16:00-16:45	460	11	63.52	45	35.75	56	0.93		19.64%	1.86	1.99	0.03
16:00-16:45	461	16	63.52	15	35.75	31	0.52		51.61%	2.70	5.23	0.09
16:00-16:45	462	16	63.52	36	35.75	52	0.87		30.77%	2.70	3.12	0.05
16:00-16:45	463	11	63.52	57	35.75	68	1.13		16.18%	1.86	1.64	0.03
16:00-16:45	464	11	63.52	69	35.75	80	1.33		13.75%	1.86	1.39	0.02
16:00-16:45	465	11	63.52	76	35.75	87	1.45		12.64%	1.86	1.28	0.02
16:00-16:45	466	12	63.52	83	35.75	95	1.58		12.63%	2.03	1.28	0.02
16:00-16:45	467	11	63.52	78	35.75	89	1.48		12.36%	1.86	1.25	0.02
	Totals	5904		23301		29205	486.75					
	Average	12.64	63.69	49.90	35.60	62.54	1.04		20.22%	2.14	2.56	0.04