Factors and market trends impacting the efficiency of compressor systems

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Aufgabenstellung

Eröffnungsprotokoll

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Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Leoben, March 2, 2017

(Benedikt Brezina)

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Kurzfassung

Da immer mehr Unternehmen zu einer effizienteren Nutzung von Energie und Ressourcen übergehen ist der Verbrauch von elektrischer Energie ein wichtiger Faktor. Kompressoren sind die unsichtbaren Arbeitspferde der modernen Gesellschaft und sind in fast allen Facetten des Lebens vorzufinden. Sei es beim Komprimieren von Gasen, zum Heizen und Kühlen sowie in vielen anderen Herstellungsprozessen kommen Kompressoren zum Einsatz. Im Allgemeinen ist Kompressor - Technologie nicht besonders effizient im Hinblick auf die Energienutzung. Diese Ineffizienz birgt eine riesige Menge an Energieeinsparungspotential, die durch Verbesserungen erreicht werden kann.

Diese Arbeit zeigt die Arbeitsprinzipien der am häufigsten verwendeten Verdichter - Typen in der Druckluft und Kältetechnik - Industrie und zeigt die möglichen Einflussfaktoren, die in Bezug auf die mechanische Konstruktion, Schmierung und Verbesserung von betrieblichen Abläufen zu Energieeinsparungen beitragen können.

Typische Marktforschungsinstrumente werden untersucht und auf ihre Anwendbarkeit in einer Kompressor Marktstudie bewertet. Auf der Grundlage dieser Auswahl von Werkzeugen wird eine Marktstudie in den jeweiligen Nischenmärkten durchgeführt um einen Ist – Zustand der Kompressor – Industrie zu gewinnen.

Basierend auf den erhaltenen Informationen sowohl in qualitativer als auch quantitativer Form werden Lebenszykluskostenmodelle für verschiedene Verdichter – Systeme erstellt. Diese Modelle werden in ein Marketing – Software – Tool integriert, die es Kunden sowie dem Verkaufspersonal des Unternehmens ermöglicht, potentielle Kosteneinsparungsmaßnahmen für verschiedene Kompressor – Systeme zu bestimmen.

Schlussendlich wird ein umfassender Überblick über zukünftige Technologien und Markttrends im Kompressor und Kältetechnik – Segment sowie die vielversprechendsten Wachstumsbereiche aus der Sicht eines Schmiermittelherstellers gegeben.

Abstract

As more and more companies are driving towards a more efficient use of energy and resources one big concern is the use of electricity. Compressors are the hidden work horses of modern civilizations and are found in almost all facets of life. Be it from pumping gases, heating, and refrigeration to various manufacturing purposes compressors can be found almost anywhere. In general compressor technology is not very efficient in terms of energy use. This inefficiency potentially bears a huge amount of energy saving that can be achieved.

This thesis shows the working principles of the most commonly used compressor types in the compressed air and refrigeration industries and shows the possible design factors that contribute to energy savings in terms of mechanical design, lubrication improvement and operational aspects.

Typical marketing research instruments are reviewed and evaluated for their applicability in a compressor market study. Based on this set of tools a market study in the relevant niche markets is performed to gain a current state of the compressor industry.

Based on the obtained information both in qualitative and quantitative terms live cycle cost models for different compressor systems are created. These models are integrated into a marketing software tool that allows customers and the sales personnel of the company to determine possible cost saving opportunities for a specified system.

Finally a comprehensive overview of future technology and market trends in the compressor and refrigeration industry is given with the most promising growth areas from the perspective of a lubricant manufacturing company.

Table of contents

List of figures

List of tables

Abbreviations

AAPOR	American Association of Opinion and Marketing Research
AC	air conditioning
AC	alternating current
AMA	American Marketing Association
B2B	business to business
B2C	business to consumer
BCR	benefit to cost ratio
CAPEX	capital expenditures
CAS	compressed air systems
COP	coefficient of performance
CPG	consumer packaged goods
DC	direct current
EE	energy efficiency
EEI	energy efficiency index
EER	energy efficiency ratio
ESOMAR	European Society for Opinion and Marketing Research
EU	European Union
FMCG	fast – moving consumer goods
GPP	Green Public Procurement
HSE	health safety environment
ICC	International Chamber of Commerce
LCA	life cycle analysis
LCC	life cycle cost
LCCA	life cycle cost analysis
LCP	life cycle profit
MEPS	minimum energy performance standard
MRA	Marketing Research Association
NPV	net present value
OEM	original equipment manufacturer
OPEX	operational expenditures
ORC	Organic Rankine Cycle
PBP	payback period
TCO	total cost of ownership
VSD	variable speed drive

1 Introduction

The global energy demand is constantly increasing and is predicted to do so for the foreseeable future. As developing countries are approaching the living standards of the Western world more and more complexity finds its way into these societies. With increased economic growth and technological sophistication the energy demand is expected to grow exponentially in such regions. As the world faces the upcoming challenges of climate change and the energy crisis as fossil fuels are phased out the demand and the significance of electrical energy will with no doubt increase over the coming decades.

The huge international effort to reduce CO_2 emissions and transition to green energy technologies is at an all-time high. One big factor in this transition is the reduction in energy consumption for the same work that is being received, hence the increase of energy efficiency.

Compressors and compressor systems are part of our everyday lives especially the more developed a society becomes the more compressors it seems are holding it up. From refrigeration systems that keep our food fresh and save to eat to air conditioning to provide us with more comfort. But also our infrastructure and industries rely heavily on compressors. Natural gas compressors supply the natural gas network and compressed air is used for pneumatic applications in a wide range of industries. The recent development of compressed air storage to store electricity generated by renewable energy sources that gained more and more popularity in the past years might become another key infrastructure technology that can profit enormously by increased energy efficiency.

From the fractional horsepower to the tens of thousands horsepower applications compressing gases is even today a fairly inefficient process. Over the lifetime of a compressor system the cost for the electricity usually makes up for the majority of the costs of the systems. The reduction of the energy consumption of such systems is in the interest of the environment and the users as they can often safe significant amounts of money by improving the efficiency of their compressor systems. A major challenge for such improvements it the unawareness of users about the cost savings potentials that can be achieved by investing in their compression systems. Such investments often show to have a reasonable good payback times.

In this thesis the most commonly used compressor types in compressed air and refrigeration applications are analyzed in terms of their energy efficiency gain potentials. But as many reports show when talking about efficiency in gas compression technology the systems have to be analyzed as a whole and taken in consideration. The most efficient compression unit won’t achieve anything if the rest of the system is lacking the proper attention for improvement. Therefore also all the important ancillary components are investigated to get a complete picture of all the influencing factors of efficiency and to further give recommendations on which factors to focus primarily. This thesis is written in partnership with one of the world’s leading lubricant manufactures specializing in lubricants for gas compression and refrigeration systems. Hence particular attention is given to efficiency factors that can be influenced by lubricant suppliers and to give an overview on what the compressor OEMs are doing to increase efficiency and what future technologies are likely to be introduced into the compressor market in the coming years.

The tools for a marketing study will be discussed and assessed for their applicability to do a market study on the compressor and refrigeration market. With the gained information from OEMs a lifecycle and total cost of ownership model is created for the common compressor systems. These models are finally integrated into the a marketing software tool that gives customers as well as sales staff the ability to determine the cost saving effects with different system configurations.

2 Compressors

The main purpose of compressors is to move gases from one place to another as well as increasing its pressure. Unlike pumps compressors work on a slightly different physical principle due to the compressibility of the working fluid which is explained in one of the subsequent chapters. In general compressors can be thought of machines that transform electrical energy or chemical energy (e.g. from diesel engines) into potential energy in the form of a compressed gas that can then perform work. Compressors although often hidden can be found almost anywhere in a modern society. Be it from fans and blowers to fridges and air conditioners to large industrial applications such as compressed air systems, cooling warehouses and natural gas compressors stations.

Over the last decades or even centuries a wide range of different types of compressors have been developed all with their unique strengths and weaknesses. Compressors are generally divided into two main groups, positive displacement compressors and dynamic compressors (Figure 1).

The positive displacement types works by means of a finite volume of gas that is reduced in size hence the pressure increases and as the discharge pressure is reached the compressed gas is released into the outlet line and the cycle is repeated. Dynamic compressors on the other hand exist in axial and radial form and increase the velocity of the compressed gas. The flow of the gas is restricted which converts the high kinetic energy of the gas to a higher static pressure. Unlike positive displacement compressors dynamic compressors are designed for a constant pressure instead of a constant flow rate[1]. A rule of thumb for compressor selection is to select dynamic compressors for base load supply and positive displacement compressors for times of peak demand. Usually a combination of both is used in order to optimize systems for energy efficiency.

This thesis' focus lies on the factors that influence energy efficiency in compressor systems in applications such as compressed air and industrial refrigeration. The types of compressors used for such applications are mostly confined to following four types:

- Reciprocating
- Screw
- Vane
- Scroll

More specifically today the majority of sold displacement compressor products for industrial applications are comprised to a large extent of reciprocating and screw compressors on which the particular attention is given in the following chapters.

[1] Arfalk, E., (Retrieved: 30.05.2016)

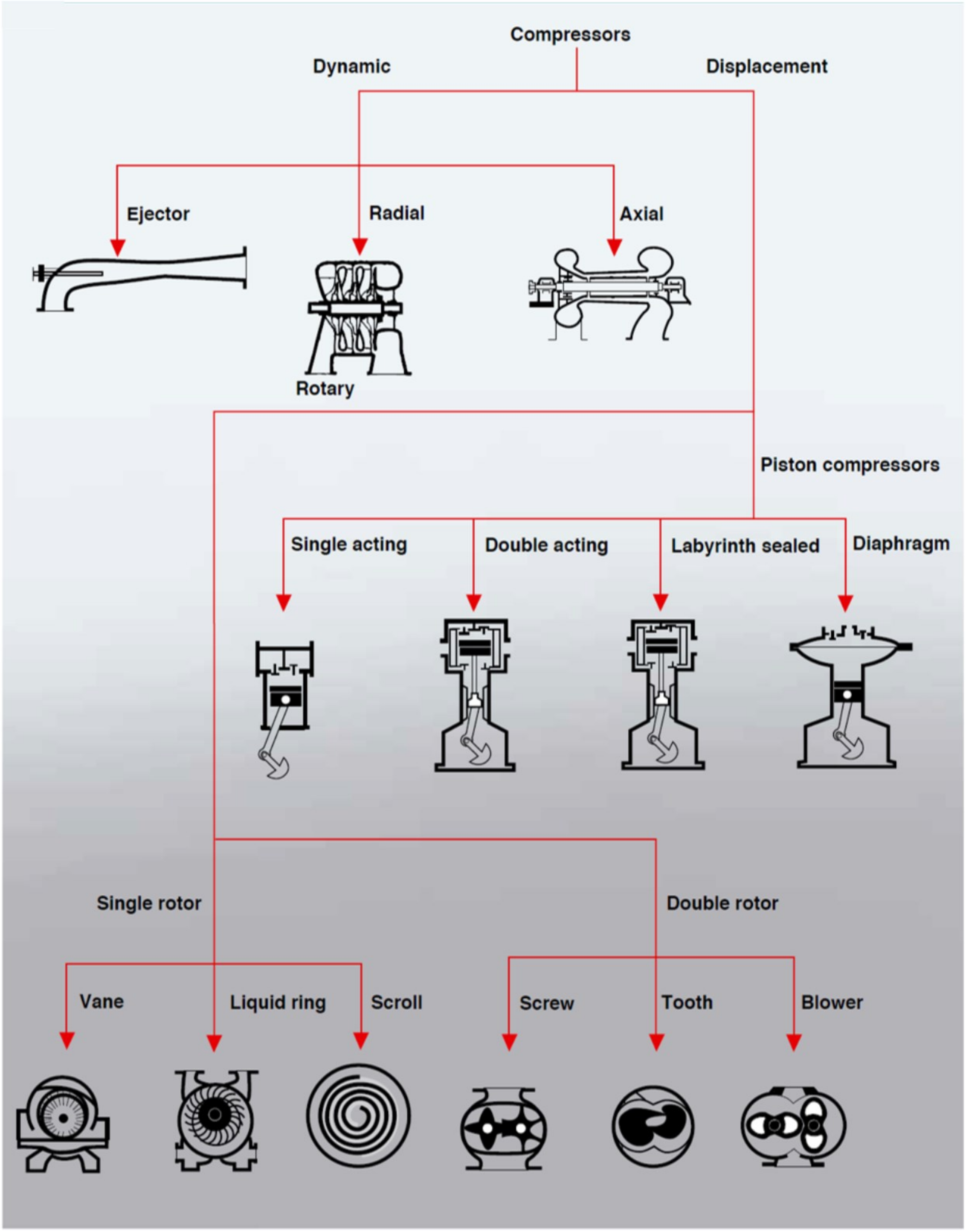

Figure 1: Overview of different compressor types[2]

[2] Atlas Copco (2010), p. 23

2.1 Compressor theory

When compressing a gas it is crucial to be able to predict the state of the compressed gas at every step in the system in order to make effective engineering design decisions. In the past many different equations of state have been developed of which many are very specialized and only work under specific conditions. When working with compressed gas it is important to know what range of pressure and temperature conditions to expect in order to choose the most suitable gas law for the application.

The simplest equation of state is the ideal gas law. This equation suits best for air under atmospheric conditions hence it is most accurate when the temperature is much higher than the critical temperature and the pressure is much lower than the critical pressure[3].

$$pV = nRT \qquad (1)$$

$p \dots pressure\ of\ gas$
$V \dots volume\ of\ gas$
$n \dots amount\ of\ substance$
$R \dots ideal\ gas\ constant$
$T \dots\ temperature\ of\ the\ gas$

To predict the properties of a real gas more accurately, the ideal gas law is often modified with an empirical compressibility factor Z. This value is a function of pressure and temperature of the respective gas and changes accordingly. The close the compressed has comes to a phase change the more significant is the introduction of the compressibility factor due to the deviation of the ideal gas behavior. Hence the modified ideal gas law becomes:

$$pV = ZnRT \qquad (2)$$

$Z \dots compressibility\ factor$

This equation is only accurate if Z is known well. It can be estimated reasonably accurate by the law of corresponding states which states that the value of Z as a function of reduced pressure and temperature is approximately the same for all gases. To predict Z with an equation rather than charts many different cubic equations of state are available, one of the simplest ones is the Relich Kwong equation. Other equations of state that are commonly used to predict compressor performance include the Soave Redlich Kwong, Peng Robinson, Benedict Webb Rubin, Han Starling, Lee-Kesler and API method equations.

[3] Bloch, H. (2006), p. 1.3

2.1.1 Changes of state

When working with compressed gases the basic working principles of thermodynamic changes of state are essential. The changes of a gas takes place in one or more of its properties which are pressure (p), volume (V) or temperature (T). The changes can be described with a PVT diagram which is a three dimensional diagram in these three properties. Usually these diagrams are simplified as projections in one of the three planes.

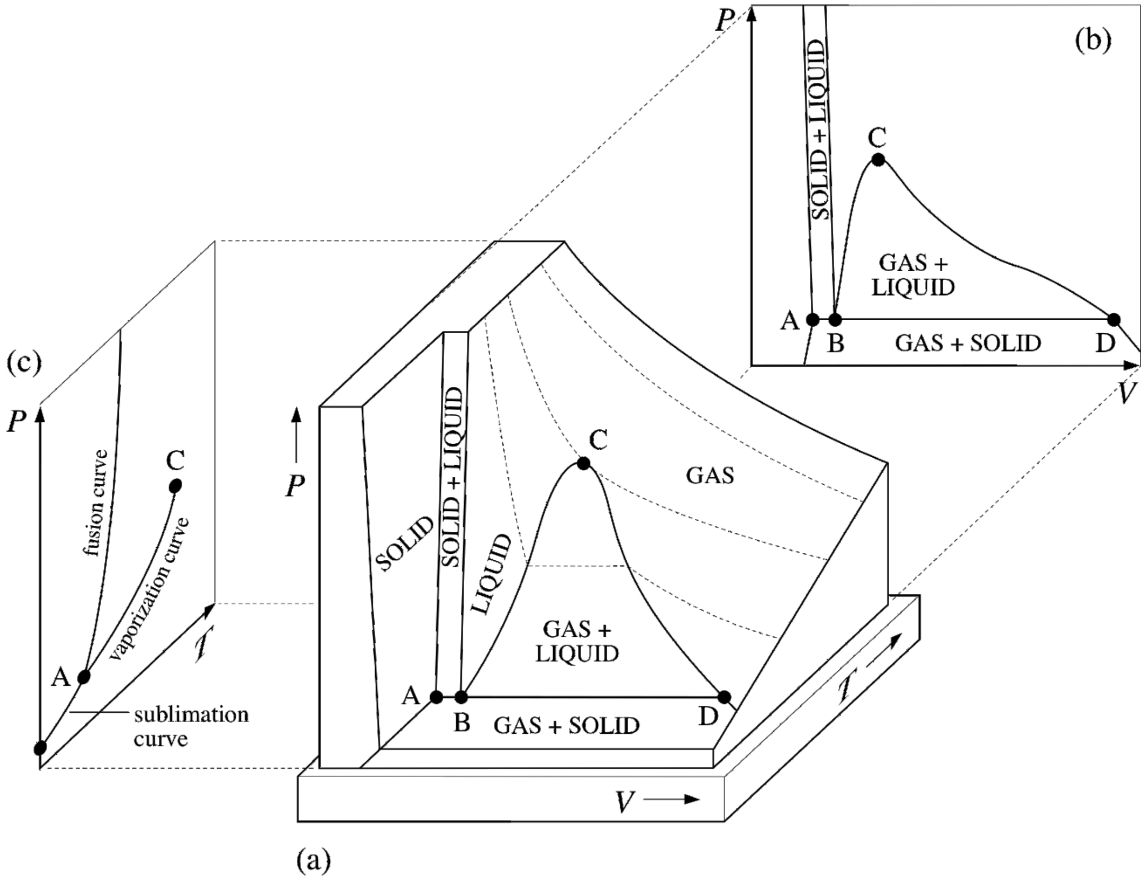

Figure 2: PVT surface of a typical substance with two projections in the PV (b) and PT (c) plane[4]

Five different changes in state can be considered:

- Isochoric (constant volume)
- Isobaric (constant pressure)
- Isthermal (constant temperature)
- Isentropic (without heat exchange with environment)
- Polytropic (complete heat exchange with environment)

[4] Robinson, G. (Retrieved: 29.08.2016)

2.1.2 Definitions of efficiency

When talking about energy efficiency it is necessary to clearly define which type of efficiency one refers to. Often the term efficiency is used interchangeably for all the different types of efficiency within the compressor industry although they are often based on completely different assumptions.
The often falsely used terms of different efficiencies makes it difficult to compare systems and can mislead unaware customers and engineers. The most commonly used terms of efficiency are the isentropic/adiabatic, volumetric and overall system efficiency[5]. The following chapters will explain them in more detail.

Isentropic efficiency

An isentropic change of state is defined as one that does not exchange heat with its surroundings. In reality changes of state are not exclusively just one type, usually it is in between these extreme cases. In gas compression it can be assumed that the compressed gas is not exchanging heat with its surroundings due to the usual high speed of compression which in reality does not allow sufficient heat - transfer in such short amounts of time.

When a compressor undergoes a steady flow process it consumes power. The isentropic efficiency of a compressor is defined as the ratio of the work input to the isentropic process to the work input to the actual process between the same input and exit pressures.

$$\eta_c = \frac{Isentropic\ Compressor\ Work}{Actual\ Compressor\ Work} = \frac{W_s}{W_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad (3)$$

$h_1 \ldots enthalpy\ at\ the\ entrance\ state$

$h_{2a} \ldots enthalpy\ at\ the\ exit\ state\ for\ the\ actual\ process$

$h_{2s} \ldots enthalpy\ at\ the\ exit\ state\ for\ the\ isentropic\ process$

Figure 3 shows the difference of these two processes. When the work is determined by the energy balance of the compressor and the kinetic and potential energies associated with a gas flowing through the compressor are negligible compared to the entropy change of the gas the energy balance can be reduced to the enthalpy terms hence the isentropic efficiency becomes a ratio of enthalpy changes as shown in the formula above.

Typically well designed compressors have isentropic or adiabatic efficiencies between 75 and 85 percent[6].

[5] Ueno, K. et al. (2003), pp. 3–8
[6] YJ Resources (2009), p. 2

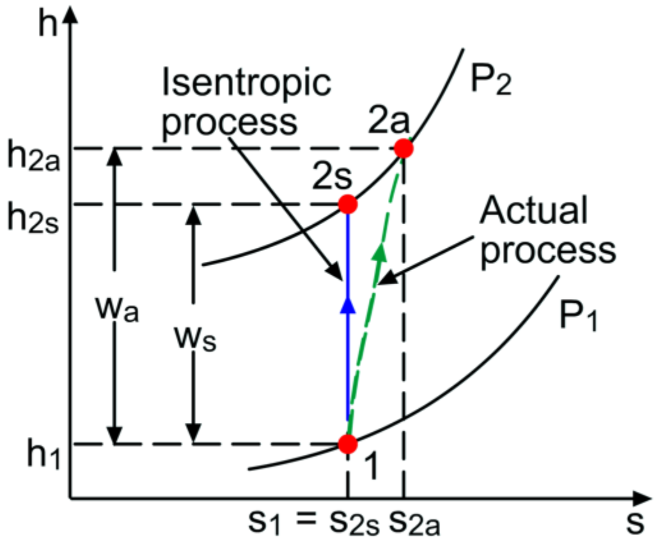

Figure 3: h – s diagram showing the difference between the ideal isentropic process and the actual process(h … enthalpy, s … entropy)[7]

Volumetric efficiency

The volumetric efficiency is heavily used with internal combustion engines but can also be applied to positive displacement compressors. The volumetric efficiency defines the ratio of the discharge mass – flowrate measured at the compressor outlet to the theoretical swept volume flow – rate.

$$\eta_V = \frac{\dot{m}}{\dot{m}_S} \qquad (4)$$

The mass flow – rate at the compressor discharge is usually measured experimentally. It is recommended to measure it directly and not derive it from volume flow – rate and density. The experimental determination of the volumetric efficiency is recommended because it also incorporates the imperfections of involved valves, wall friction and other friction losses.

[7] Huang, M.; Gramoll, K. (Retrieved: 09.09.2016)

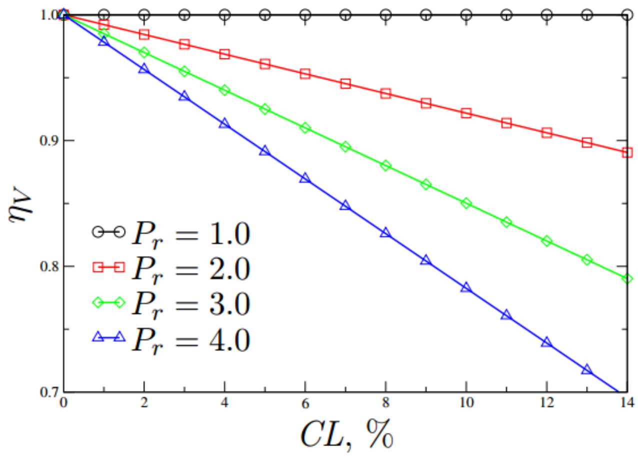

Figure 4: Volumetric efficiency as a function of clearance (polytropic index n = 1.2)[8]

When the volumetric efficiency is expressed as a function of Clearance (CL) and compression ratio (PR) it becomes obvious that the efficiency declines relatively fast with higher compression ratios and increasing clearance.

$$\eta_V = 1 - CL\left(P_R^{1/n} - 1\right) \qquad (5)$$

Overall system efficiency

The type of efficiency end users are likely the most focused on is the overall system efficiency. As most compressor systems in industrial environments are often a complex network of several compressors, pipework, controllers, motors and other auxiliary equipment the overall system efficiency is influenced by all components and gives a statement of the total cost the system is causing.

This efficiency is derived by the series product of several component efficiencies hence of all discussed efficiency definitions this one will have the lowest value.

$$\eta_{sys} = \eta_{ad} \cdot \eta_{motor} \cdot \eta_{controller} \cdot \eta_{auxiliary} \cdot \ldots \qquad (6)$$

[8] Ueno, K. et al. (2003), p. 6

2.2 Types of compressors

2.2.1 Reciprocating compressors

Reciprocating compressors work by compressing gas in a cylindrical chamber. One or more pistons are mounted on a crankshaft and moved back and forth within a compression cycle (Figure 5). The working principle is similar to a gasoline or diesel engine without the fuel injection and ignition. However the flow of energy is in reverse order. Instead of energy being transferred from the expansion of the gas in the cylinder energy from the crank shaft is transferred to the gas by compressing it increasing its pressure and temperature simultaneously.

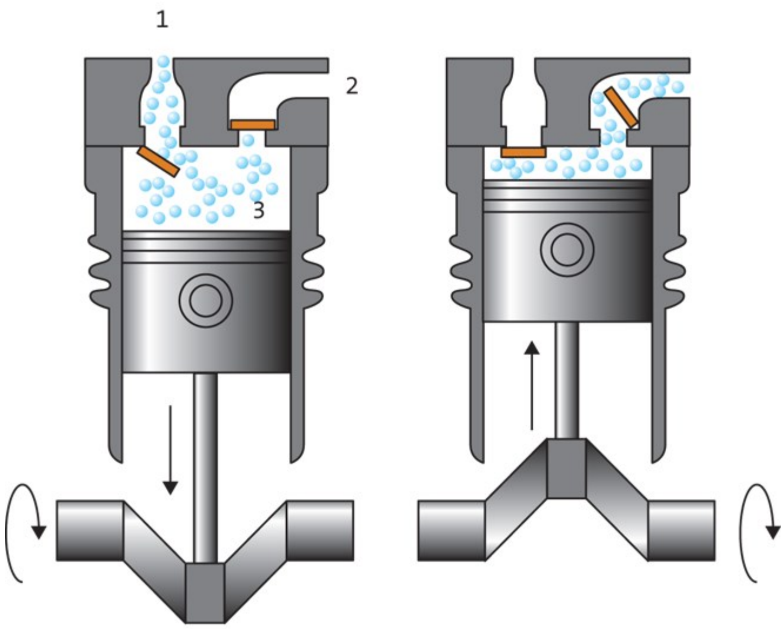

Figure 5: Schematic of a reciprocating compressor, (1) gas inlet, (2) high pressure outlet, (3) compression chamber[9]

Reciprocating compressors are the oldest type of compressor available and over the years different variations have been developed. Aside from the single acting type depicted in the figure above also double acting types are available. There exit oil – lubricated and oil – free variations each with their own set of advantages and disadvantages. Double acting compressors are usually more often used in big compressors. They utilize the negative stroke of the piston as well. Depending on the size and the required volume throughput compressors can consist of a single, double or multistage setup with several compression cylinders all attached to the same crankshaft. Smaller single acting compressors are usually in a vertical or V – shape configuration[10]. Bigger models for example for industrial air or natural gas compression are usually in an L or horizontal configuration. The lubrication works either as a splash lubrication or pressured lubrication.

[9] Frischmann, M. (Retrieved: 28.05.2016)
[10] Atlas Copco (2010), p. 32

As these kinds of compressors are very popular and widespread the available sizes are ranging from fractional horsepower compressors in the consumer sector such as fridges and freezers to natural gas compressors of up to 55,000 HP[11] (examples: Figure 6 to Figure 8).

Figure 6: Enclosed fractional horsepower reciprocating compressor for small consumer applications like fridges and freezers (1/4 HP)[12]

Figure 7: Small industrial air compressor (~25 HP)[13]

[11] GE Oil&Gas (Retrieved: 01.06.2016)
[12] Kulthorn Ldt. (Retrieved: 01.06.2016)
[13] AAPL Ldt. (Retrieved: 01.06.2016)

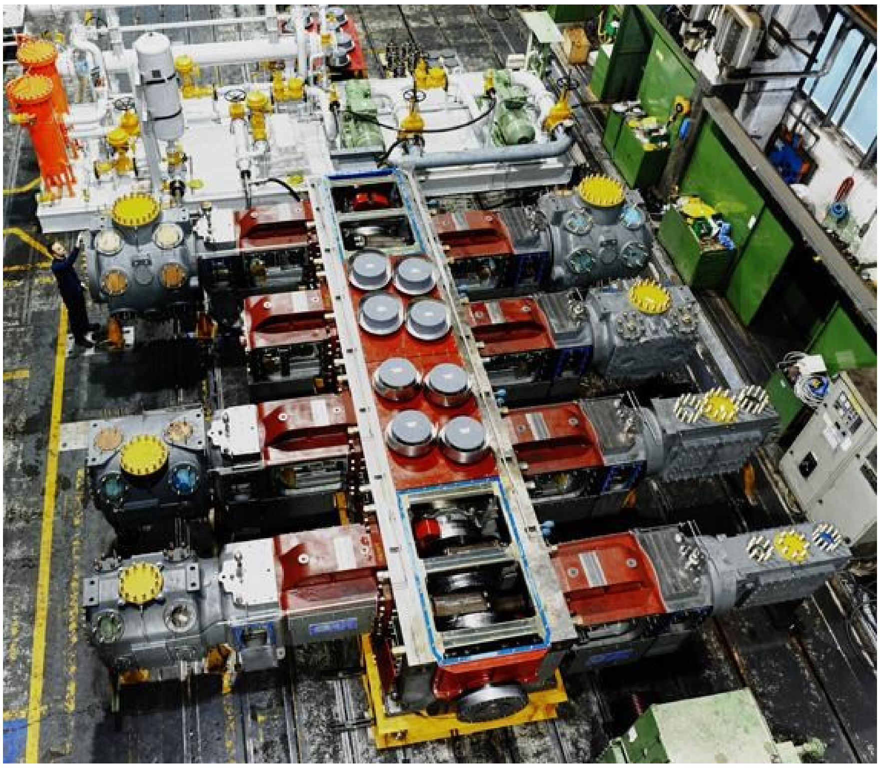

Figure 8: Large, eight cylinder, double acting natural gas compressor (~50,000 HP)[14]

The illustration in Figure 9 shows the relationship between volume and pressure in a piston compressor. The concept of volumetric efficiency explained in the previous chapter can be understood most easily by the working principle of a piston compressor with clearance at each end of the stroke.

Unlike rotary compressors such as the screw compressor the flow of pressurized gas in not continuous in a piston compressor. Reciprocating compressors use automatic spring loaded valves that open only when the proper differential pressure exists across the valve. The discharge valve opens when the chamber pressure is slightly above the discharge pressure. The same principle applies to the suction valve where it opens when the pressure in the cylinder is slightly lower than in the suction line. Both valves act as one way check valves and only allow flow in one direction.

[14] GE Oil&Gas (Retrieved: 01.06.2016)

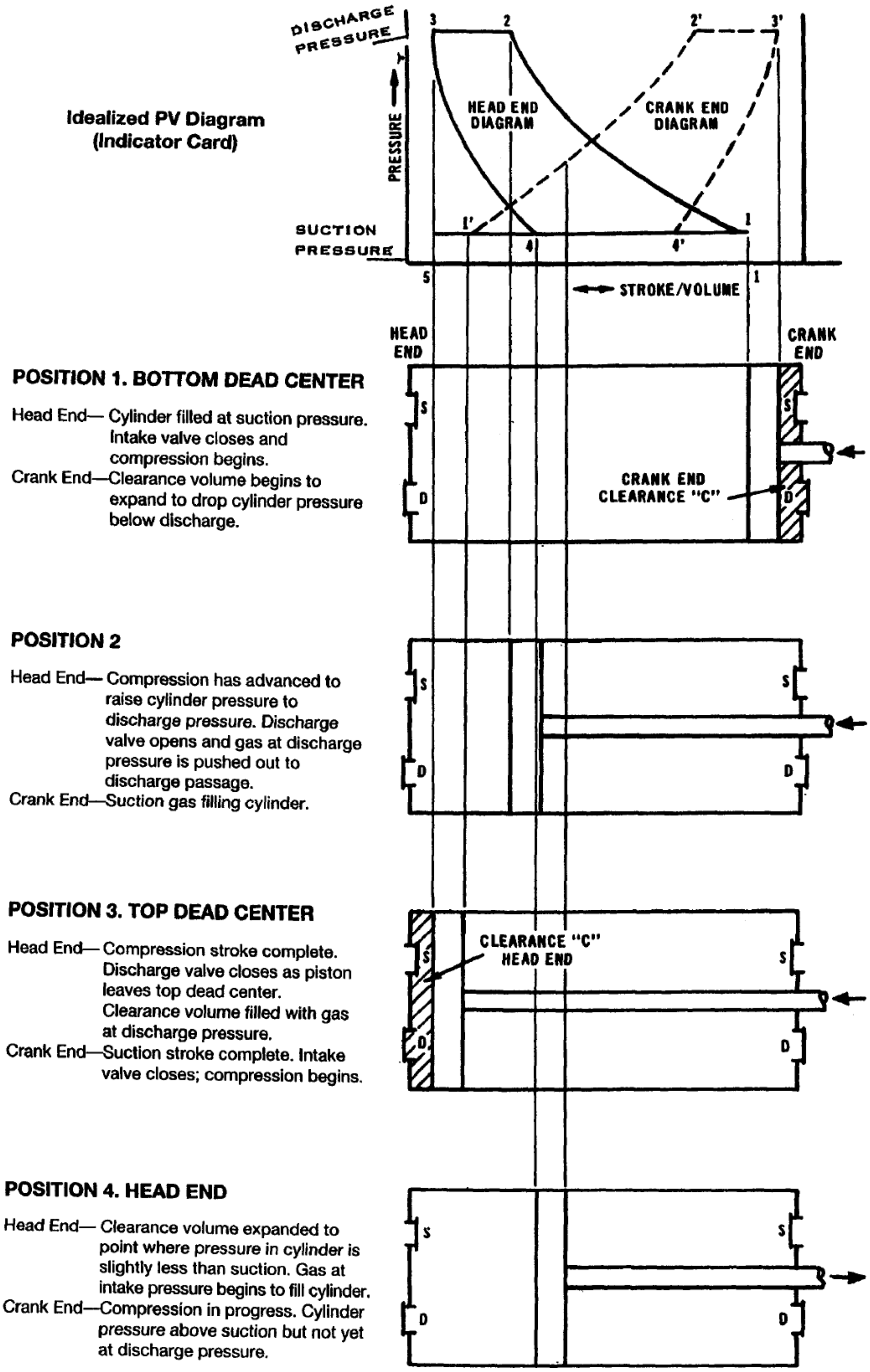

Figure 9: Illustration of the ideal single stage, double acting compression cycle[15]

[15] Bloch, H.; Hoefner, J. (1996), p. 33

2.2.2 Screw compressors

Screw compressors are another type of positive displacement compressors. They usually consist of two asymmetric rotors. Figure 11 shows an opened screw compressor with the suction and discharge sides marked. As low pressure gas enters the suction side it is forced to the discharge side through the moving cavities between the rotors. As the gas moves towards the discharge side the cavities become progressively smaller thereby compressing the.

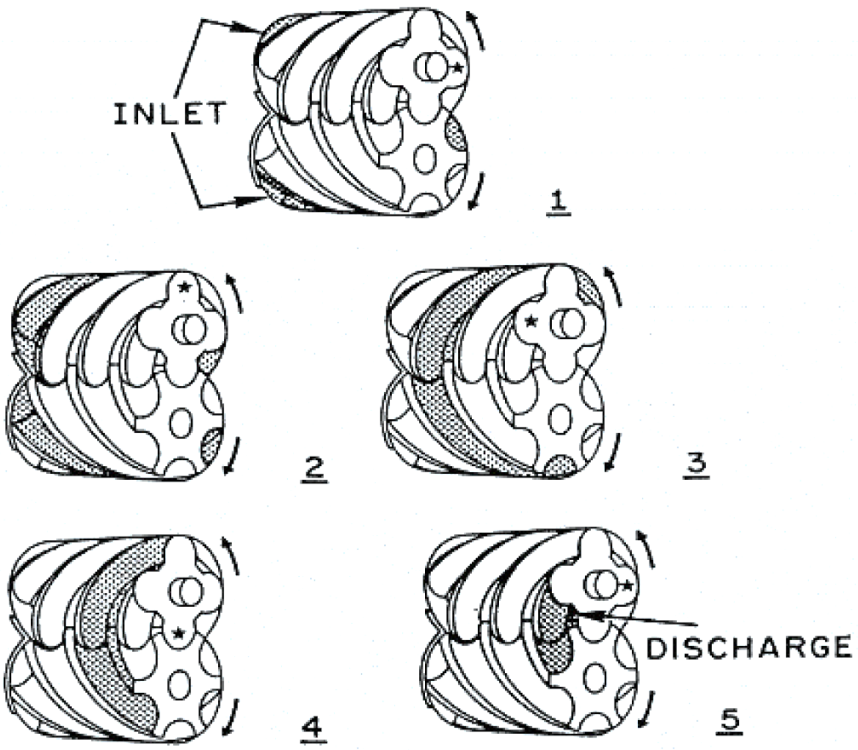

Figure 10: The principal of compression in a double helical screw compressor[16]

Screw compressors come in oil flooded and oil free versions. Depending on the requirements of the compressed gas a suitable compressor type is chosen. In applications such as food, medical or semiconductors usually oil free compressors have to be chosen because the residual lubricant carry-over (usually oil based) is not desired even after cleaning of the compressed gas. Due to the missing lubricant film however, lubricant free compressors have lower maximum discharge pressures. To achieve higher pressures lubricant free a multi-stage compression is necessary. Although typical oil free compressors have no oil in the compression chamber the bearings still need to be lubricated hence they have to be sealed off and lubricated separately. Ideally the rotors don't have a metal to metal contact during operation. This is ensured by precise manufacturing and timing gears which synchronize the rotations. Models without timing gears cannot be oil free compressors as the metal to metal contact of the rotors would destroy the compressor, they can only work as oil flooded compressors.

[16] Bloch, H. (2006), p. 23; Maschinenfabrik Aerzen

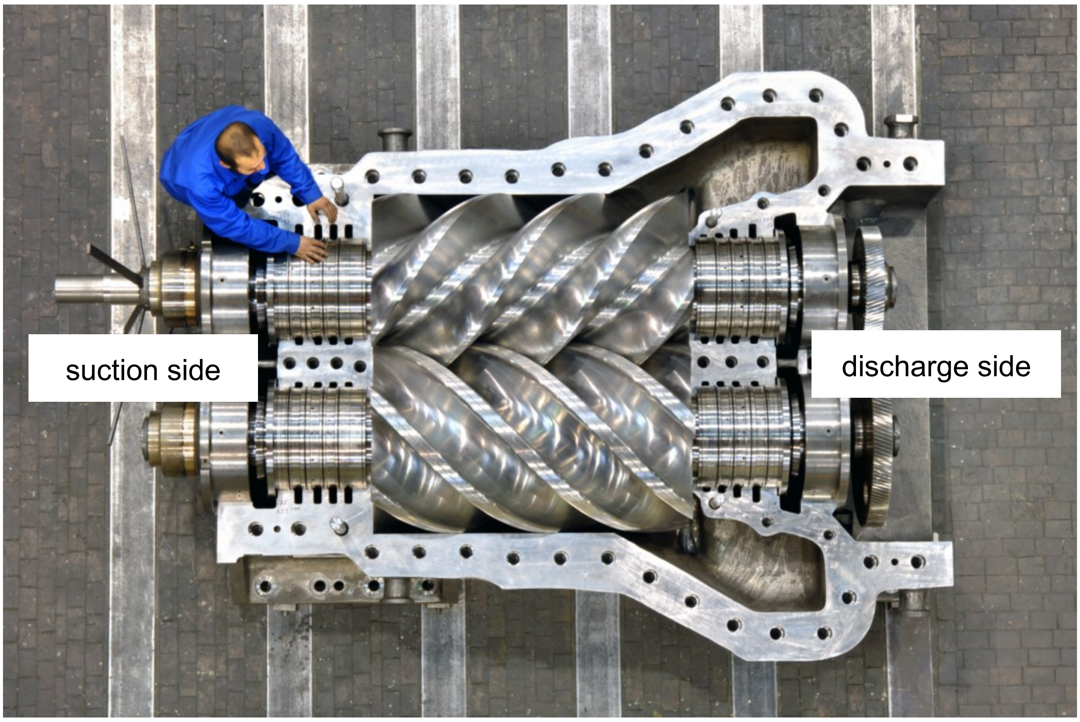

Figure 11: Top view of a large opened screw compressor for process gas[17]

In lubricated variants the lubricant serves three major purposes:

- Seal the internal clearances and therefore allow for greater compression ratios and higher volumetric efficiency. The sealing function splits up into rotor/rotor and rotor/housing clearances. More accurate machining processes and lubrication sealing prevent compressed gas to leak back towards the lower pressure side of the compressor. Generally the leakage behavior in screw compressors is good, however only if the rotors run at the designed speed. The lower the operating speed the worse the leakage behavior becomes. A big part of screw compressor manufacturing is the fitting clearances between the rotors and the chamber. This requirement for high precision machining makes rotary screw compressors usually more expensive than other compressors. Figure 12 shows a cross-section of a screw compressor and reveals the many leakage paths between the rotors and housing.
- Cooling the gas during compression. This becomes especially important under continuous load and high flowrates as well as high compression ratios. The heat hence the “wasted” energy transferred to the lubricant during compression is the major source for potential heat recovery later on as around 72 to 76%[18] of power consumption ends up as heat in the lubricant.
- The third major reason to use a lubricant is to actually lubricate the moving parts of the compressor. Usually bigger heavy duty models of screw compressors have hydrodynamic thrust and radial bearings whereas lighter duty models have roller

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[17] MAN Turbomachinery (Retrieved: 08.07.2016)
[18] Ruppelt, E.; Bahr, M. (Retrieved: 27.08.2016); Almig (Retrieved: 27.08.2016)

bearings. The maintenance of a proper lubricant film thickness and lubricant cleanliness is essential for a long bearing life.

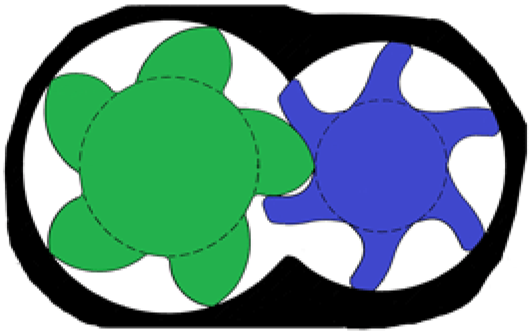

Figure 12: Cross-section view of the male and female helical screw rotors[19]

A more recent development is the utilization of water as a lubricant in screw compressors. These water flooded compressors have the advantage of the screw lubrication and cooling without the undesirable oil contamination in some applications. However this technology is in its relatively early stages and not applicable for all gases.

Generally the type and design of the bearings used in screw compressors are essential for a long service life. Ball and rolling element bearings susceptible to water and H_2S for example are mostly used in lighter duty air applications whereas journal bearings are usually used in heavy duty process gas applications due to their higher tolerance for water and H_2S as well as their practically unlimited service life. Ball and roller bearings are acceptable for lighter duty applications provided that oil cleanliness can be assured. In some applications it is possible to have a separate lubricant loop for the bearings.
Compared to reciprocating compressors screw compressors tend to be more stable during operation, hence they produce less vibrations and noise. This smoother operation also causes less maintenance work which lowers overall life-cycle costs.

In compressed air applications with a multi compressor setup screw compressors work most effectively as base load compressors with reciprocating compressors as peak load suppliers.

[19] Beld, C. (Retrieved: 24.08.2016)

Figure 13: Typical screw compressor package for compressed air enclosed for noise attenuation[20]

Screw compressors usually have high gas throughput rates that can range up to 60.000 acfm (100.000m^3/hour)[21]. The resulting heat from the compression process is usually cooled by a water-cooled rotor housing. Oil or water flooded types also have the ability to achieve much higher compression rations in one stage compared to reciprocating compressors due to the high amount of injected lubricant oil which serves additional cooling purposes during the compression[22]. This allows a high compression ratio without the penalty of extremely high discharge temperatures.

[20] Ingersol Rand (Retrieved: 08.07.2016)
[21] Bloch, H. (2006), p. 21
[22] Hanlon, P. (2001), p. 2.24

2.2.3 Vane compressors

Rotary vane compressors are a relatively old type of compressors. They work by means of an eccentrically placed cylinder in the rotary housing. This cylinder has slots where the sliding vanes are located. When this cylinder rotates the vanes in the cylinder are forced outwards by the centrifugal force. They slide along the inside wall of the rotary housing and create compression cavities that become progressively smaller during one turn of the cylinder until the cavity reaches the high pressure outlet and releases the compressed gas (Figure 14).

Unlike the figure below the rotating cylinder can also contain more than two vanes at different angles in order to reduce the volume of each compression cavity and minimize the differential pressure to the neighboring cavities (Figure 15).

Vane compressors can come in oil lubricated and oil free model. In oil lubricated systems the maintenance cost is usually higher due to the auxiliary equipment involved. In oil free systems the vanes have to be changed more often due to increased wear. The decision whether to use an oil lubricated or oil free system usually highly depends on the duty-cycle.

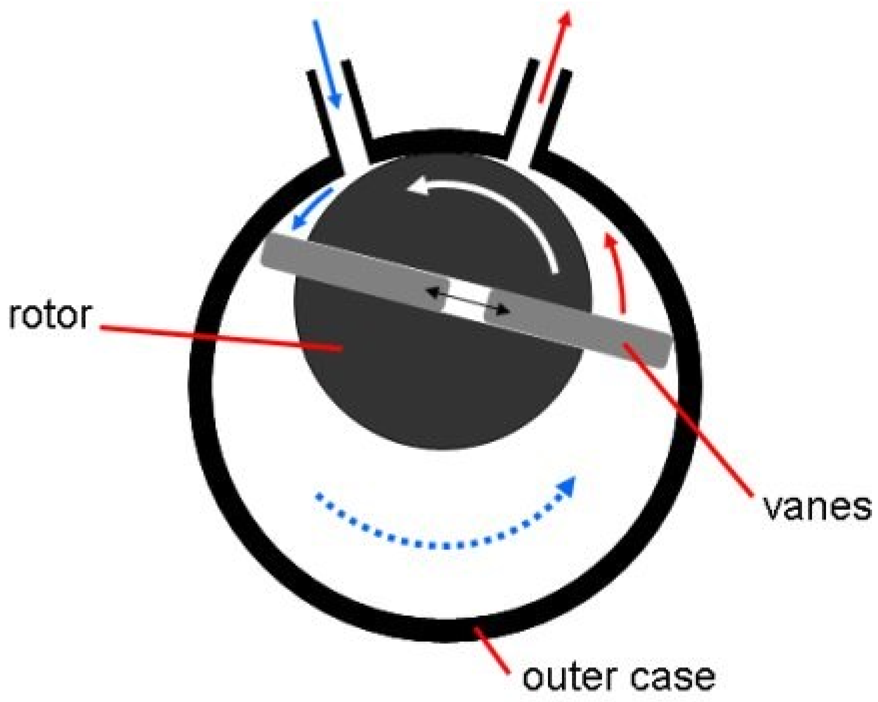

Figure 14: Principle of a rotary vane compressor with the vanes spring loaded against each other[23]

Although some manufactures claim that vane compressors have a longer life expectancy under continuous duty cycles and an easier maintenance vane compressors are usually seen as obsolete and often only the second choice after screw compressors.

[23] Dirac Delta Consultants Ltd (Retrieved: 08.09.2016)

Figure 15: Opened ammonia compressor incorporating eight vanes[24]

2.2.4 Scroll compressors

A scroll compressors consists of two interleaving scrolls. Usually one of them is fixed and the other one is moving in a circular fashion. This creates pockets that continuously move inwards to the outlet while decreasing their volume hence compressing the gas inside them.

The typical application of scroll compressors are in air conditioning and refrigeration applications for smaller consumer models. Often scroll compressors are used in air conditioning units in the automotive sector. Typically scroll compressors work more smoothly, quietly and reliably compared to traditional compressors making them ideal for lifetime sealed consumer products.

In terms of efficiency the scroll compressor is slightly more efficient than a comparable reciprocating unit due to the missing valve that would cost efficiency. The relatively small amount of moving parts makes them attractive for applications that cannot afford much maintenance interruption.

[24] Garden City Ammonia Program (Retrieved: 30.08.2016)

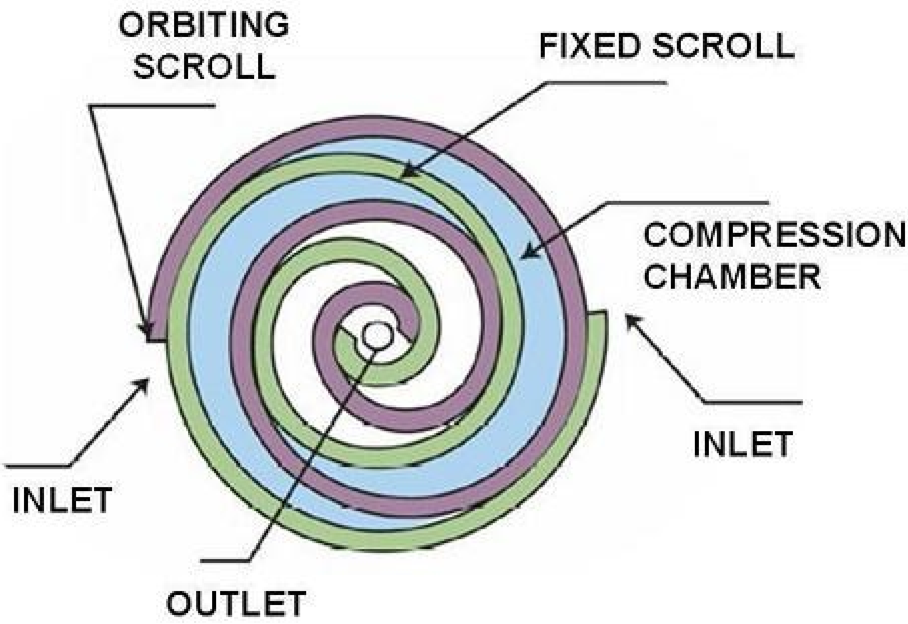

Figure 16: Key components and working principle of a scroll compressor[25]

Figure 17 shows an opened scroll compressors. Precise machining ensures small clearances that minimize leakage. The initial cost of scroll compressors is often higher than conventional compressors is however offset by the maintenance intensity of this compressor type. Often if a scroll compressor happens to be damaged it is too costly to repair hence most of them are sealed for life.

Figure 17: Details of the machined fixed and orbiting scrolls[26]

[25] Gentec Systems Corporation (Retrieved: 09.08.2016)
[26] Air Conditioner Professionals (Retrieved: 08.09.2016)

A typical construction of a small scroll compressor for refrigeration applications is shown in Figure 18. The sealed housing contains all the necessary components. Such compressors for consumer products are usually sealed for life and in case of a damage replaced as a whole.

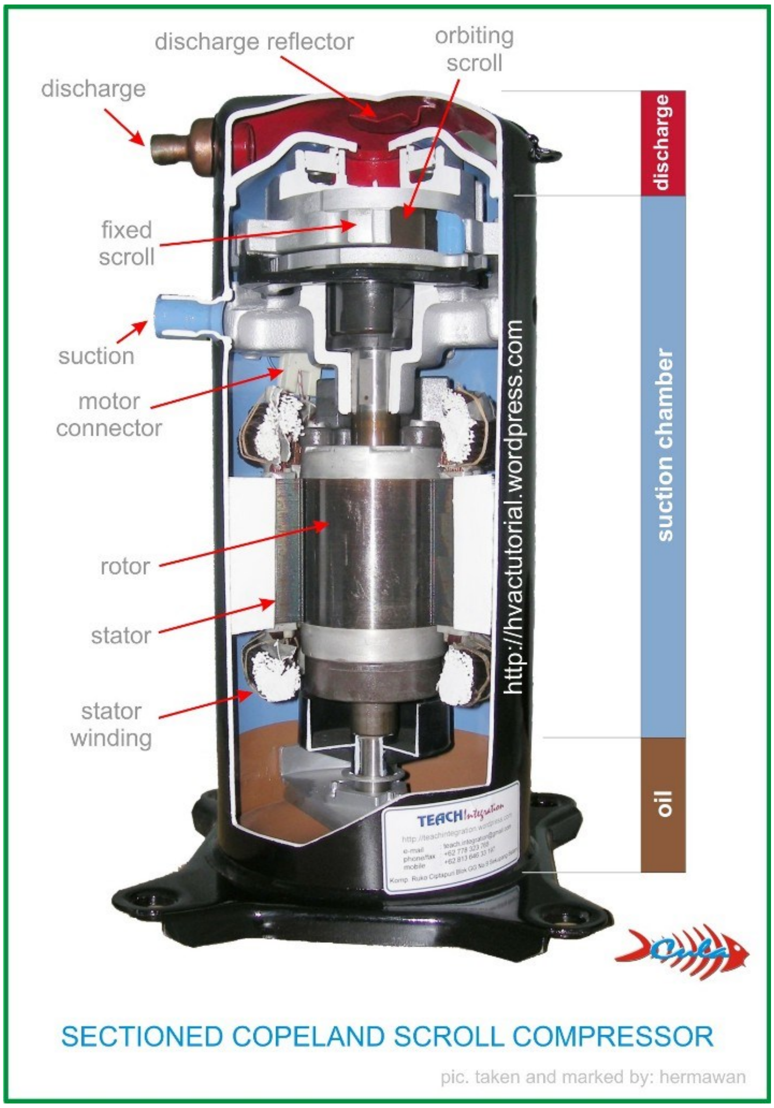

Figure 18: Sectioned view of a scroll compressor for refrigeration applications[27]

[27] Hermawan, A. (Retrieved: 08.09.2016)

2.3 Compressor selection

Depending on the application and size of the compressor system different types of compressors are suited best to operate most reliably and efficiently. When selecting a compressor type certain selection criteria have to be known and taken in consideration in order to optimize the system such as:

- Volume and mass flow rate of gas to be compressed
- Suction pressure
- Discharge pressure

Figure 19 shows an overview of the working envelopes of different compressor types that gives a first idea in the selection process what type might be suitable for the intended application.

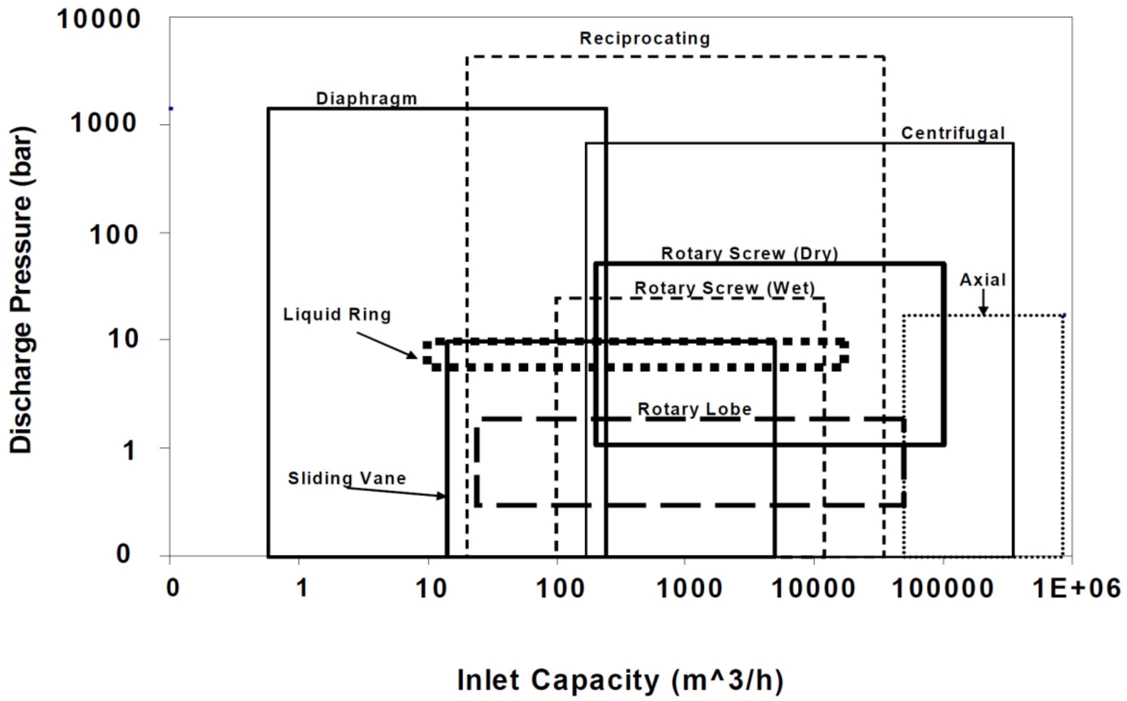

Figure 19: Typical operational envelopes of different compressor types[28]

Apart from these criteria above every compressor type has its own advantages and disadvantages to consider (Table 1). According to an article on compressor selection at the International Compressor Engineering Conference the final selection can be made based in the criteria of the four main groups (Table 2):

- Environmental
- Logistics
- Initial capital costs (CAPEX)
- Operating costs (OPEX)

[28] Process Industry Practices (2007), p. 10

Table 1: Advantages and disadvantages of different compressor types[29]

	Advantages	Disadvantages
Dynamic Compressors		
Centrifugal	• Wide operating range • High reliability and low maintenance	• Instability at reduced flow • Sensitive to changes in gas composition • Susceptible to rotor-dynamics problems
Axial	• High capacity for a given size and high efficiency • Heavy duty and low maintenance	• Low compression ratios • Limited turndown
Thermal/Jet	• No moving parts and low maintenance • High pressure ratio	• Very low efficiency • Narrow range of application
Positive Displacement Compressors		
Reciprocating (Piston)	• Wide pressure ratios • High efficiency	• Heavy foundations required due to unbalanced forces • Flow pulsation can cause vibration and structural problems • High maintenance compared to dynamic compressors
Screw	• Wide range of applications • Wet screw has high efficiency and high pressure ratio • Dry screw insensitive to changes in gas composition and can handle dirty gases	• Noisy • Wet screw not suitable for corrosive or dirty gases
Sliding Vane	• Simple in design • High single-stage pressure ratio	• Generally unsuitable for process gases • Low reliability
Scroll	• Almost 100% volumetric efficiency • Missing suction and discharge losses due to non-existing valves • Very quiet and low vibration • Small weight and footprint • Low gas pulsation	• No easy repair or maintenance due to hermetic sealing • Incremental capacity control problematic
Lobe	• Simple in design and construction • Low cost	• Limited operation range and pressure ratio • Capacity control limited to suction throttling
Liquid Ring	• High vacuum capability • High single-stage pressure ratio • High reliability	• Sealing liquid/process gas compatibility required • Sealing liquid separation equipment required • Limited suction pressure
Diaphragm	• Very high pressure • Available in special materials • No moving seals • Low flow	• Limited capacity range • Periodic replacement of diaphragms required • Flow pulsation problems

29 Carrier Corporation (2004), p. 14; Process Industry Practices (2007), p. 20

The following chapters will focus mainly on the capital and operational cost aspects of the selection process as they play a major role in compressor life cycle cost estimation.

Table 2: Overview of typical compressor selection criteria[30]

Typical Selection criteria			
Environmental	**Logistics**	**Initial capital costs (CAPEX)**	**Operating costs (OPEX)**
• Matching in appearance	• Suitability for future modification	• Foundation costs	• Plant life
• Noise	• Place of manufacturer	• Drive costs	• Service maintenance
• Allowable vibration	• Operator experience	• Equipment costs	• Power factor
• Gas tight (emission, fire hazard)	• Single/Multi - Source	• Installation costs	• Load variations
• oil free / water free	• Delivery		• Efficiency (optimum component matching)
			• Cost of spare parts

Efficiency itself is a part of the operational costs and has a huge impact on the total life cycle costs of a compressor system because energy costs account for the largest portion in the cost of a system over its lifetime.

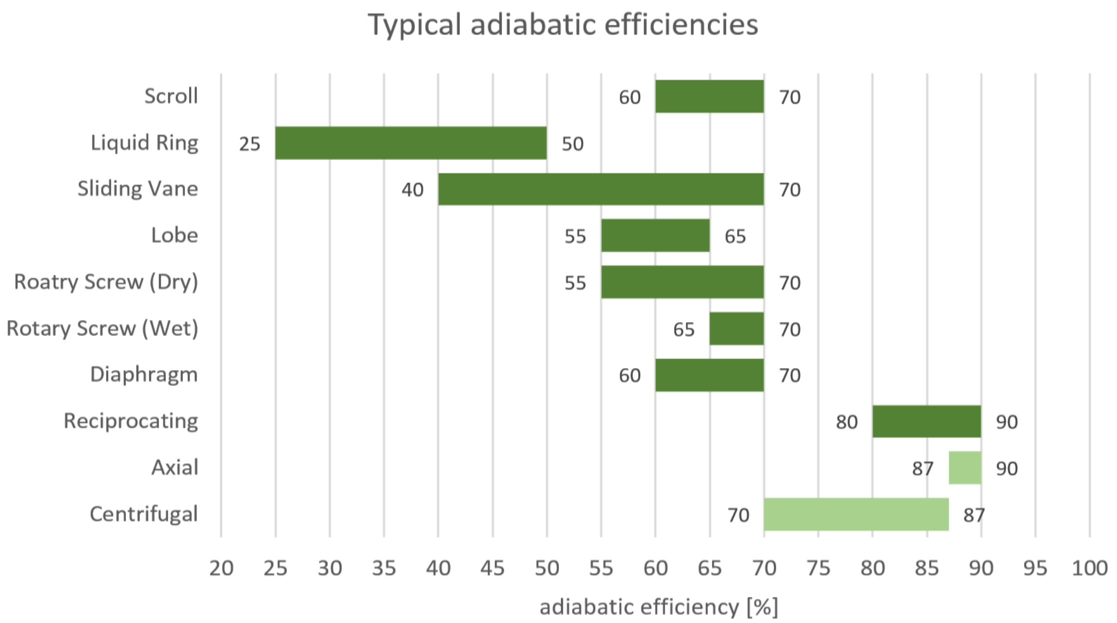

Figure 20: Typical efficiency ranges for different compressor types[31]

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[30] Modified from Khan, M. (1984), p. 625
[31] Carrier Corporation (2004), pp. 11–12; Process Industry Practices (2007), pp. 8–9; Campbell, J. (2014), p. 27

2.4 Single stage and multi stage compression

In compression systems design and planning sometimes it is more desirable and economical to use a multi stage compression system. During the gas compression process the compressed gas is increasing in temperature and resembles an isentropic process as the heat cannot be removed fast enough. Ideally an isothermal compression would be most efficient. In practice most commonly one, two or three staged compression is used as the gain in efficiency has a diminishing return with increasing numbers of stages. Temperatures of compressed gases without intercooling can become extremely hot which requires unnecessarily rugged components and is often undesired as the working gas will often be used at ambient temperatures. Additionally the high temperatures can cause additional safety hazards, especially if flammable compressor oils are involved in the process. In high pressure applications single stage compression can also decrease the volumetric efficiency in some compressor types. In screw compressors for example the high differential pressure can cause increased back leakage between the cavities. Typical advantages of staged compression are:

- The work done by the compressor is reduced, hence the total energy efficiency of the system increases. The energy savings can be significant in some cases.
- Prevention of mechanical problems as the temperature of the compressed gas is controlled and won’t reach extremes.
- Equipment susceptible to mechanical clogging and contamination such as valves remain in cleaner condition temperature and vaporization of lubrication oil becomes less of an issue.
- Generally staged systems allow to be built smaller and more balanced.
- Moisture buildup in the compressed gas can be handled more easily because it can be drained between each stage.
- The compression approaches an isothermal process as seen in Figure 21 and Figure 22.
- Lower compression ratios for each stages minimizes sealing problems for each compressor.
- Use of lighter moving parts reduce cost and make maintenance work easier.

The decision whether a single or a multi staged compression system is more appropriate for a specific application comes down to an engineering economics analysis including several factors such as space requirements, compression ratio, maintenance requirements and energy efficiency.

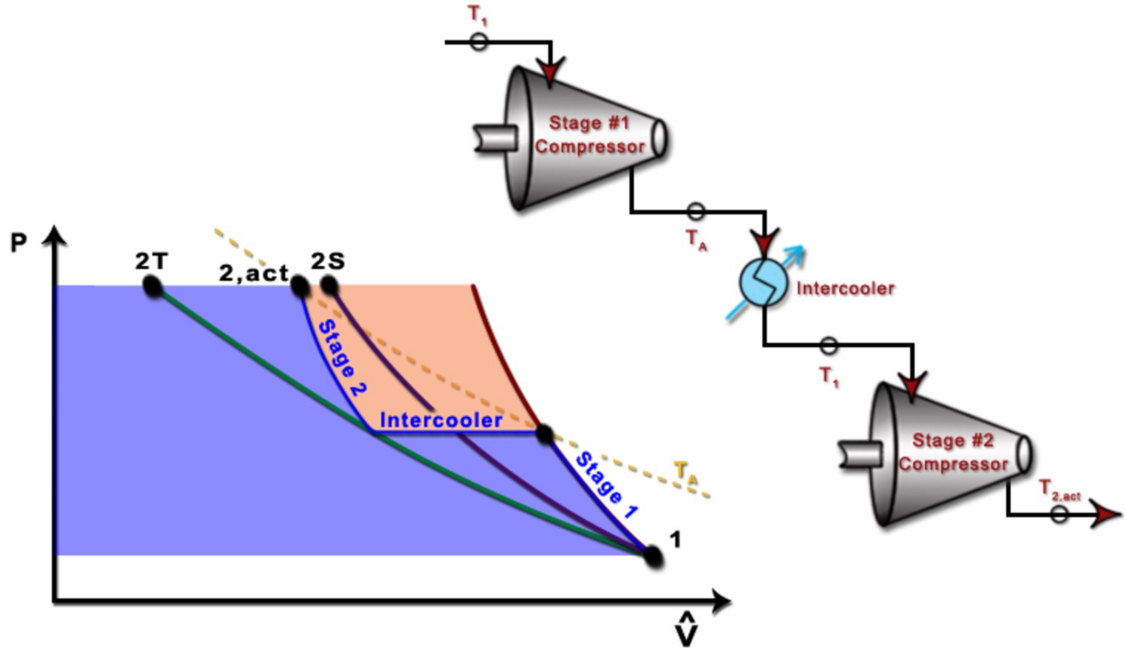

Figure 21: Principle of two stage compression[32]

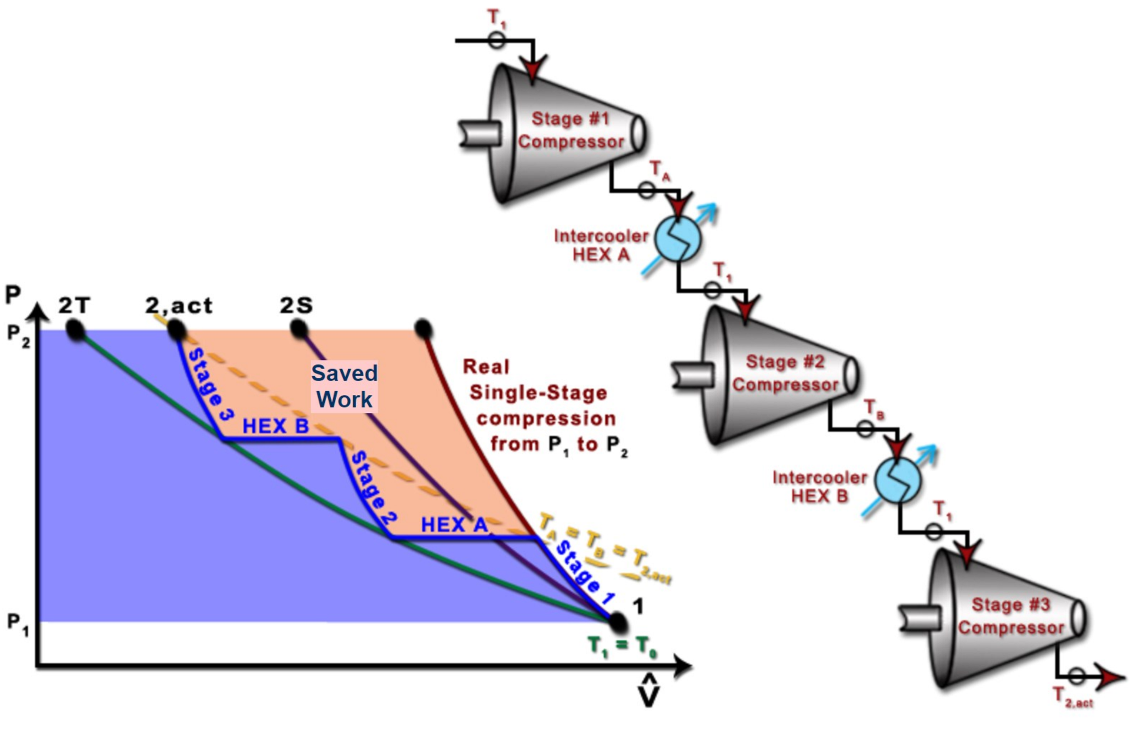

Figure 22: Principle of three stage compression[33]

[32] B-Cubed (Retrieved: 12.10.2016)
[33] B-Cubed (Retrieved: 12.10.2016)

3 Compressed air

The application of compressed air is widespread in many industries today. Often compressed air is called the fourth utility because it has become such an essential part of so many businesses[34]. Aside from the other three utilities water, gas and electricity which are usually provided by other companies the customer has complete control over the production of his compressed air supply. This can bring advantages but can also be a big source of wasted money if those systems are not designed properly or are not dimensioned correctly for the demand of the business.

The reason why compressed air is so popular as an energy source has several reasons:

- Compressed air is very versatile and can be stored in tanks where other sources of energy are absent or impractical.
- Compressed air can be used in areas with explosion or fire hazards.
- It can be used in extreme environments with high temperatures, vibrations and dust. This makes it an excellent candidate for applications such as in steel mills, foundries and mining.
- Pneumatic tools are usually lighter and easier to handle, maintain and repair than electrical counterparts.
- Pneumatic tools do not interfere in electromagnetically sensitive applications.
- Compressed air can be used in applications for medical and other applications that require a high degree of cleanliness.

When talking about energy efficiency of such a system the scope of the observation is very important. In many factories compressed air systems are constructed as a factory wide system with a complex distribution network and many different end-users. When looking at the overall system efficiency it becomes clear that individual compressor efficiency does not matter if other parts of the system are poorly designed or flawed in another way.

The overall goal should be to deliver the appropriate amount of air when it is needed to where it is needed in the right quality at the lowest cost per delivered volume. As compressed air tends to be the most expensive utility it is in many cases possible to reduce costs on the demand side and substitute compressed air power with cheaper alternatives or utilize it differently and thereby minimizing the required flowrate for the same outcome[35]. The cost saving potentials that can be achieved by reducing or eliminating unnecessary air consumption and artificial demand is shown in later chapters.

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[34] CEATI (2007), p. 22; Air Compressor Works (Retrieved: 27.06.2016)
[35] van Ormer, H. (2014), p. 15

3.1 Energy demand of compressed air systems

Despite their widespread use compressed air systems have huge energy savings potentials. Even today with the big emphasis on energy saving and climate change many systems have room for improvement. The inefficiency of compressed air systems not only arises from the inherent inefficiency of gas compression itself but often systems are not optimally designed or dimensioned incorrectly for the intended demand and usage profile.

The demand for electrical energy to power compressed air systems in industrialized nations is estimated to be around 10 % of the total electrical energy consumption and about 4,2 % global electrical energy consumption[36]. So when talking about energy savings potentials in compressed air it is important to remember that large amounts of energy can be saved due to the huge consumption of energy for this kind of technology. The more developed economies become the more the demand of compressed air increases as well. As the developing countries are quickly catching up to the developed world the demand for compressed air will likely increase as well in the coming decades.

3.2 Compressed air production

Compressed air systems are complex systems especially in industrial environments with many points of use and nonstop operation. Figure 23 shows a typical compressed air system in an industrial setting with the essential components marked.

When compressing gases the majority of the input energy is transferred into heat. A typical compression system has several heat sources where it is necessary to remove the excess heat by cooling the media. Aside from the electric motor and the gearbox which only produce a relatively small part of the overall heat the most heat occurs in the lubricant, the compressed air and the compressor housing. Therefore systems have oil coolers for the compressor oil, aftercoolers for the compressed air and for multistage systems additional intercoolers. In order to remove the heat from the compressor housing they can either be cooled by air cooled fins or by cooling water jackets with heat exchangers. In those coolers most of the energy of a compression system is wasted and hence they are excellent sources for energy/heat recovery to reuse the heat as process heat or the heat other parts of a building.

The compressed air is transported to the final point of use by the distribution system. It is a system of pipes and hoses that are typically set up as a ring system. The distribution system can be a source of huge losses if it is not properly maintained and leaking. The design of the piping also plays an important role in system efficiency. Small diameter pipes typically mean higher flow velocities hence higher friction and pressure losses. Unnecessary pipe bends and other auxiliary equipment can cause further pressure drops in the system.

Different air filters and pressure regulators are distributed throughout the system and enable the operator the set different air quality standards for specific points of use. Each

[36] Peltomaa, P. (2011), p. 7

filter and other device in the flow path cause additional pressure drop in the system and should be avoided if possible to save energy. The quality and maintenance of air filter is another important issue to maintain an efficient system as poorly maintained filters can cause large pressure drops. In lubricated systems the majority of the lubricating oil is separated out in the oil/air separator usually situated within the compressor package. The remaining oil can be filtered by oil filters in order to increase the air quality class.

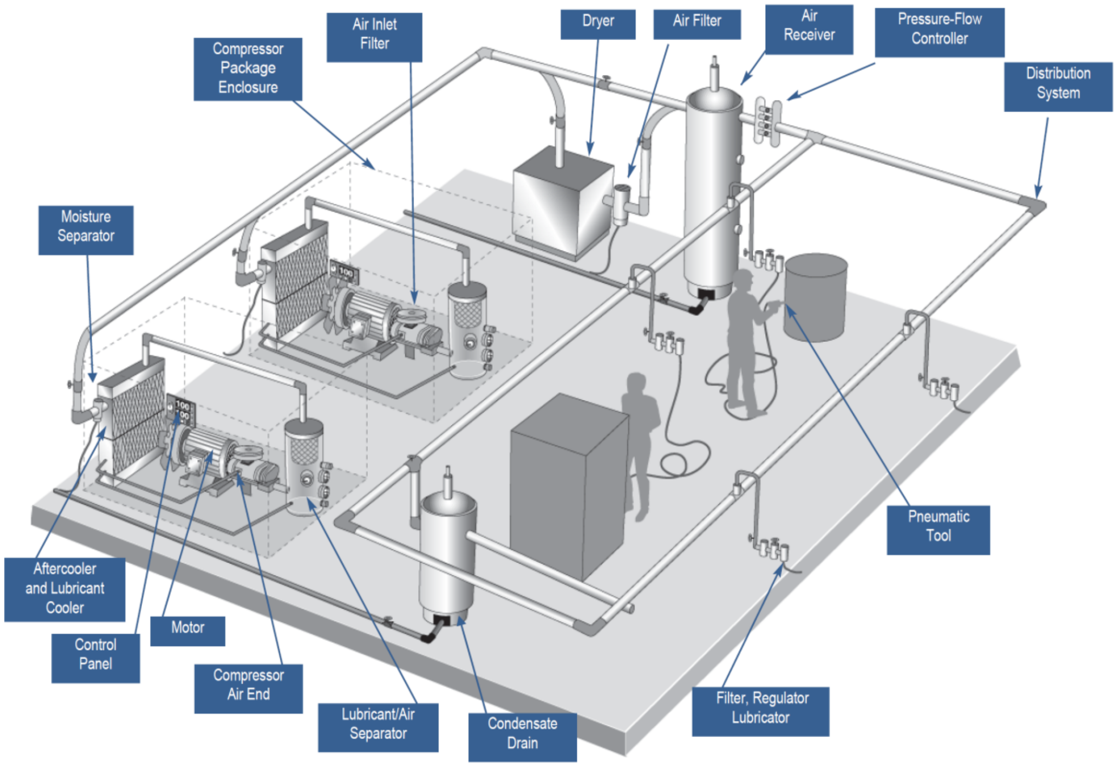

Figure 23: Components of a typical Industrial Compressed Air System[37]

Air receivers are tanks of air that act as a buffer between the compressor and the end users. It helps to minimize the rate of pressure change in the system and is especially useful in environments with intermittent demand peaks. For certain situations it might be more economical to have several smaller receivers in case the distribution network is large and the flow velocity in the pipe system would be too high on demand peaks.

When the air is cooled down after compression most of the moisture in the air condenses and is separated at the inter or aftercoolers. Keeping the air relatively dry is important to minimize potentially fatal corrosion at the point of use. Further drying of the air happens at dedicated air dryers. The most common dryer type is the refrigerant dryer. It consists of a cooling cycle to cool the incoming air below its dew point and heat it back up with warmer incoming are after the moisture is removed. Generally the reduction of saturated air by 20°F removes 50% of its moisture content. As long as dryers do not cool the air below water freezing point good moisture reduction can be achieved this way. Usually additional condensate drains are installed at the bottom of air receivers.

[37] Lawrence Berkeley National Laboratory; Resource Dynamics Corporation (2010), p. 43

3.3 Air quality

Depending on the applications of the end-users different qualities of air are required. The International Organization for Standardization published a norm that defines different air quality classes. The higher the class the greater the allowed amount of solid particles, water vapor and oil (Table 3). The standard allows to define a specific air purity for each of those components. For example an application might require the air to be very low in solid particles but less stringent on water and oil content. The produced air could be standardized to *ISO 8573-1:2010 Class 1.2.2*. The three digits ending this description are referring to the class of each contaminant. In some systems different air qualities might be required for different points of use in the factory. Applying higher quality filters only where they are really needed can thereby help to save costs and reduce maintenance efforts.

Table 3: Compressed air quality classification from ISO 8573-1:2010[38]

ISO8573-1:2010 CLASS	Solid Particulate				Water		Oil
	Maximum number of particles per m^3			Mass Concentration mg/m^3	Vapour Pressure Dewpoint	Liquid g/m^3	Total Oil (aerosol liquid and vapour)
	0.1 - 0.5 micron	0.5 - 1 micron	1 - 5 micron				mg/m^3
0	As specified by the equipment user or supplier and more stringent than Class 1						
1	≤ 20,000	≤ 400	≤ 10	-	≤ -70°C	-	0.01
2	≤ 400,000	≤ 6,000	≤ 100	-	≤ -40°C	-	0.1
3	-	≤ 90,000	≤ 1,000	-	≤ -20°C	-	1
4	-	-	≤ 10,000	-	≤ +3°C	-	5
5	-	-	≤ 100,000	-	≤ +7°C	-	-
6	-	-	-	≤ 5	≤ +10°C	-	-
7	-	-	-	5 - 10	-	≤ 0.5	-
8	-	-	-	-	-	0.5 - 5	-
9	-	-	-	-	-	5 - 10	-
X	-	-	-	> 10	-	> 10	> 10

Table 4 shows typical groups of air quality and applications in which they are commonly used. Especially in applications such as food, pharmaceuticals or medical and semiconductor production very high air quality standards are required. Therefore often class 0 air quality is advertised and used. Class 0 does not mean 0 contaminants, it is a written specified in an agreement between the user and manufacturer. However sometimes overlooked is the suction air quality which is not covered in compressor advertisements and requires additional air quality improvement measures.

Table 4: Typical applications for different air qualities[39]

Quality	Applications
Plant Air	Air tools, general plant air
Instrument air	Laboratories, paint spraying, powder coating, climate control
Process air	Food and pharmaceutical process air, electronics
Breathing air	Hospital air systems, diving tank refill stations, respirators for cleaning and/or grit blasting

[38] Parker Hannifin Ldt. (2010), p. 17
[39] Lawrence Berkeley National Laboratory; Resource Dynamics Corporation (2010), p. 8

4 Refrigeration

Similar to compressed air refrigeration applications are very widespread and are essential parts of modern life. As developing countries become more affluent the number of refrigerators, freezers and air conditioners in homes and in the industry is set to increase in the coming decades. This not only raises the standard of living in this parts of the world but can also dramatically reduce food and other temperature dependent waste. A study done by the University of Nottingham found that 44% (by weight) of global fruit and vegetable production is wasted due to limited or non-existent cooling chains[40]. The economic damage in India alone caused by food waste is estimated to be 5.5 billion USD annually. 20 percent of temperature sensitive healthcare products including vaccines arrive damaged or degraded which is also caused by insufficient availability of cooling warehouses and trucks[41]. About 15% of the global electricity is used to drive refrigeration and air conditioning systems[42]. As developing countries are mostly situated in warmer climates the proportion of electricity used for refrigeration and air conditioning is likely to exceed that of developed countries as they catch up with western standards due to lower refrigeration performance and demand in warmer environments. This high demand in electrical energy on a global scale shows how much energy can be saved if refrigeration systems are optimized for energy efficiency.

4.1 Principle of refrigeration

The principle of refrigeration was first introduced in a machine that can artificially produce "coldness" by the Scottish professor William Cullen in 1755. In the 20th century refrigeration technology became widespread and today can be found in every household.

In general refrigeration works by compressing a gas which is called the refrigerant. This refrigerant is chosen by its optimal thermophysical properties and HSE regulations for each specific application. In a refrigeration system energy is put into a system via a compressor. Typically multiple time the energy is removed from the system than was put into it by the compressor. The ratio to describe this efficiency of the cooling cycle is called the coefficient of performance .

$$COP = \frac{Cooling\ Duty}{Power\ Input} = \frac{Q}{P} \tag{7}$$

Q ...heat absorbed from cooling load

P ...power input to compressor

[40] Winkworth-Smith, C. et al. (2015), p. 12
[41] University of Birmingham (Retrieved: 24.11.2016)
[42] The International Institute of Refrigeration (2003), p. 21

The general idea of refrigeration is to use electrical energy to move heat energy from low temperature to a higher temperature. The temperature difference between the cold and the hot side are essential for the efficiency of the system. The higher the temperature difference or “temperature lift” becomes the more additional energy is needed to achieve that.

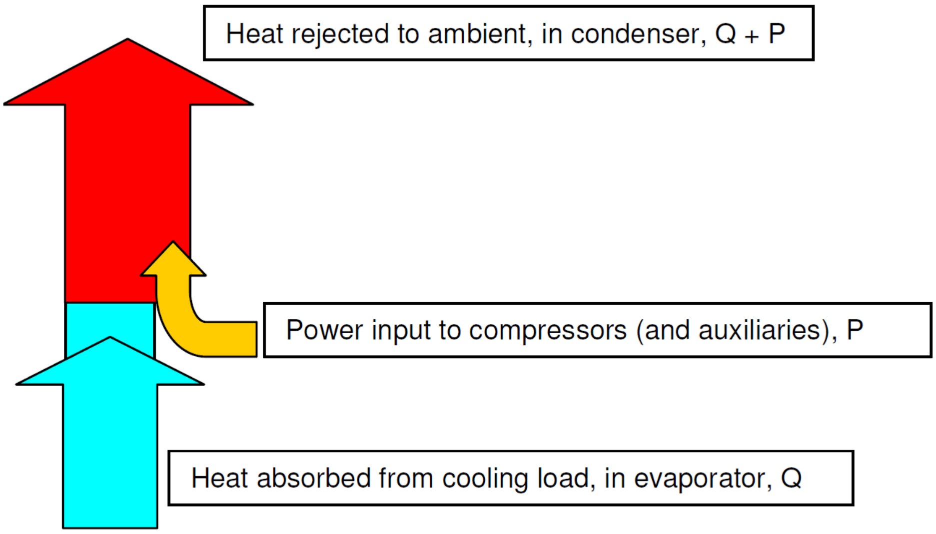

Figure 24: Principle of energy flows in refrigeration systems[43]

Hence the greatest energy savings can be achieved by not cooling down to low temperatures in the first place if it is not necessarily needed. The evaporating temperature of the refrigerant should be as high as possible and the condensing temperature as low as possible. Ambient temperatures and plant design are very important to ensure that the systems runs at highest possible COP for its environment. A rule of thumb is that for every 1°C increase in temperature lift additional 2 - 4% energy consumption of the system can be expected.

[43] The Food and Drink Federation (2007), p. 7

4.2 Refrigeration components

Similar to compressed air systems refrigeration systems consist of many components. The key components without no cooling cycle can work are the compressor, evaporator, expansion device and condenser (Figure 25).

In the compressor the refrigerant gas gets compressed and thereby increases in pressure and temperature. Depending on the size and the application of the system the compressor oil gets separated and recirculated after the high pressure outlet (industrial refrigeration) or gets fully circulated (fridge).

The hot and high pressured gas leaving the compressor moves into the condenser where the heat is removed and the refrigerant becomes liquid. The removal of the latent heat from the phase change is the reason the refrigerant is able to perform its cooling task later. In fridges the condenser is usually a refrigerant/air heat exchanger at the back of the fridge. In industrial or commercial applications it is typically a refrigerant/water heat exchanger and the cooling water is then cooled separately in cooling towers.

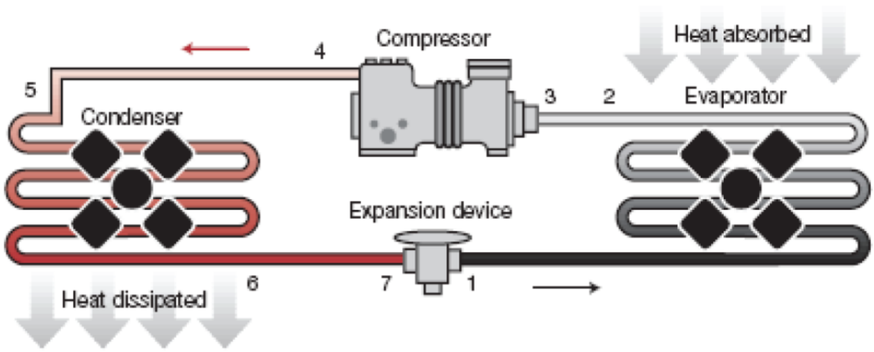

Figure 25: Simplified refrigeration cycle[44]

The expansion device maintains a pressure drop between the condenser and evaporator. Usually the expansion valve has a variable flow-restriction to control the rate of working fluid entering the evaporator.

In the evaporator the working fluid is absorbing heat due to the lowered pressure and boiling point. In order to assure optimal cooling the heat exchange efficiency of the evaporator is a key component. Too little (“starved”) or too much (“flooded”) refrigerant in the evaporator can lead to poor cooling performance and has to be considered when designing a system.

In addition to the electricity consumption of the compressor other components are usually found in refrigeration systems. Fans at the condenser and evaporator as well as refrigerant pumps and controller electronics add to the power consumption of the system and can in most cases be improved significantly to further increase system energy efficiency.

[44] CEATI International (2010), p. 25

5 Life cycle costing

When investing in big industrial machinery with a long service life it is a good practice to perform a Life cycle cost analysis (LCCA) beforehand. Such an analysis takes all the costs that accrue over the life of the system into consideration and allows to compare different investment choices according to their net present value (NPV).

The term “life cycle costing” was first mentioned in a report of the US Department of Defense to increase the effectiveness of government procurement[45]. It lead to a close relation on systems design in order to minimize downstream costs after purchasing decisions have already been made. Often TCO and LCC are used interchangeably although they are typically defined differently[46]:

> *“Total Cost of Ownership (TCO) refers to the sum of all costs incurred throughout the lifetime of owning or using an asset; they typically go beyond the original purchase price. TCO enables decision makers to look at asset procurement in a more strategic way (beyond the lowest bidder) and to level the playing field when choosing among competitive bids where the lowest priced bid may or may not be the least costly asset to procure.”*
>
> *“Life Cycle Costing (LCC) is a technique to establish the total cost of ownership. It is a structured approach that can assist management in the selection process. It can take into account any costs that the selection team feels are appropriate. Maintenance, asset disposal, training, cost of upgrades, energy consumption, resources used in manufacture and cost of duplicate service during installation are all examples of costs that could be included in an LCC analysis.”*

Making investment decisions based on the life cycle costs becomes especially important in compressor systems. A system may for example have low initial costs but a lower energy efficiency which leads to a much higher electricity cost portion over the system’s lifetime. When making an investment decision not only the lifecycle costs are important but also the achievable lifecycle profit (LCP). For the systems themselves other factors are relevant as well such as:

- production quality
- production safety
- subsequent investment requirement
- system maintenance
- environmental impact
- product quality
- downtime risk

[45] Dhillon, B. (2010), p. 42
[46] City of Fort Lauderdale et al. (2014), p. 3; Multnomah County (Retrieved: 16.10.2016)

When talking about life cycle costing it is necessary to know and understand the different perspectives of decision makers (Table 5). A product or systems life cycle can be seen from the perspective of a seller, a manufacturer and a customer. In this thesis special attention is given to the customer perspective as energy efficiency measures and purchasing decisions are important customer issues when trying to sell energy efficient compressor systems.

Table 5: Life cycle from different perspectives

Marketing perspective	Production perspective	Customer perspective
• Introduction	• Product conception	• Purchase
• Growth	• Design	• Operating
• Maturity	• Product and process development	• Support
• Decline	• Production	• Maintenance
	• Logistics	• Disposal

Including the disposal cost in life cycle costing calculations is an increasing trend in recent years especially in more developed regions as the legislative frameworks become tighter and it gets more difficult for customers and manufacturers to neglect social and environmental responsibilities.

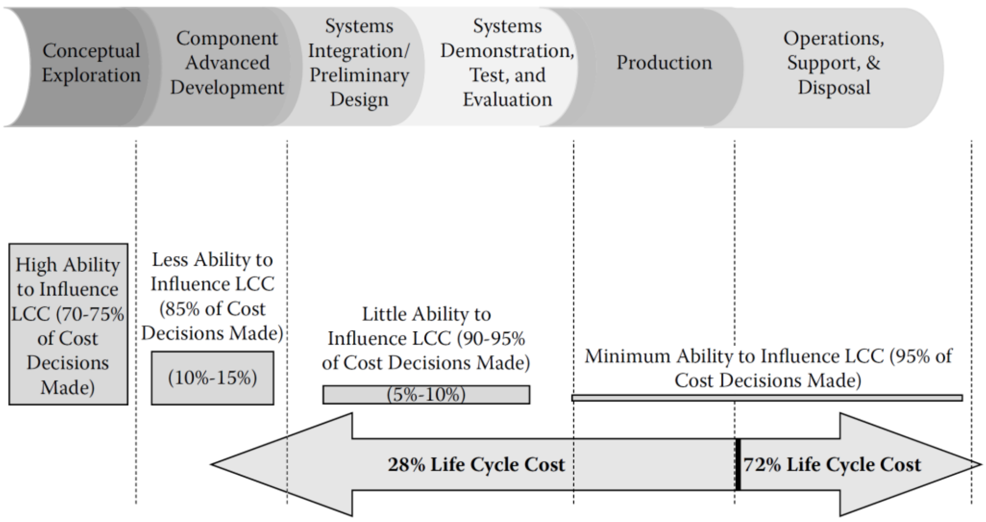

Figure 26: Costs incurred and committed during the systems life cycle acquisition process[47].

[47] Modified from Andrews, R. (2003), p. 13; Vail Farr, J. (2011), p. 28

In many cases when designing a system the majority of the costs occur at the operational stage of the life cycle. This can make it difficult to estimate potentially fatal investment decisions in the planning stage. Figure 26 and Figure 27 show when the majority of the costs are committed and incurred and how difficult it is in most cases to influence incurred cost in later stages if poor design decision have been made.

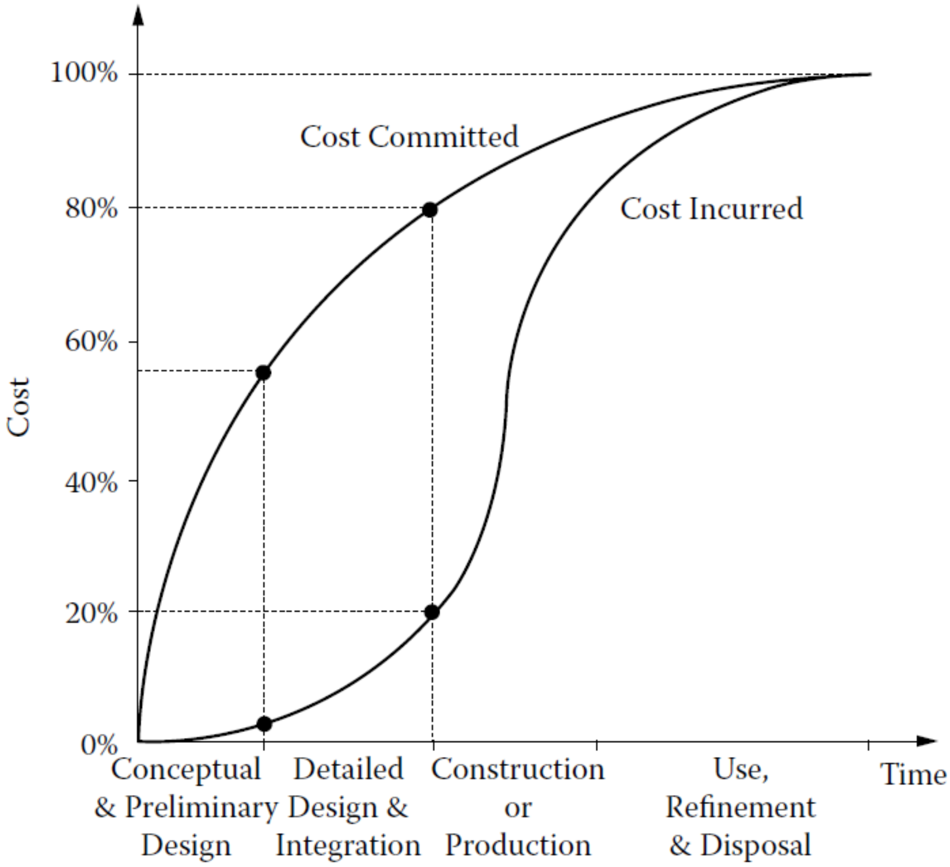

Figure 27: Typical function of costs committed versus incurred costs for the lifecycle of a project[48]

Life cycle costing serves three main purposes:

- It acts as a decision tool for the design and procurement of major open systems, infrastructure and so on. It was developed for this purpose in the first place. Especially systems that have potentially huge downstream costs which cannot estimated by the initial investment cost alone are able to be compared for investment decisions.
- LCC can overcome many shortcomings of traditional cost accounting and can give more valuable insight into the cost management of a system.
- As developed countries became more environmentally continues over the last years LCC reemerged as a design and engineering tool for environmental purposes.

[48] Vail Farr, J. (2011), p. 33

As mentioned before in order to achieve profitability of a system other factors aside the TCO are important in the decision making phase. Figure 28 shows a possible structure of additional parameters to determine the profitability namely the system effectiveness which consists of the technical effectiveness and the process efficiency with all their various sub-factors.

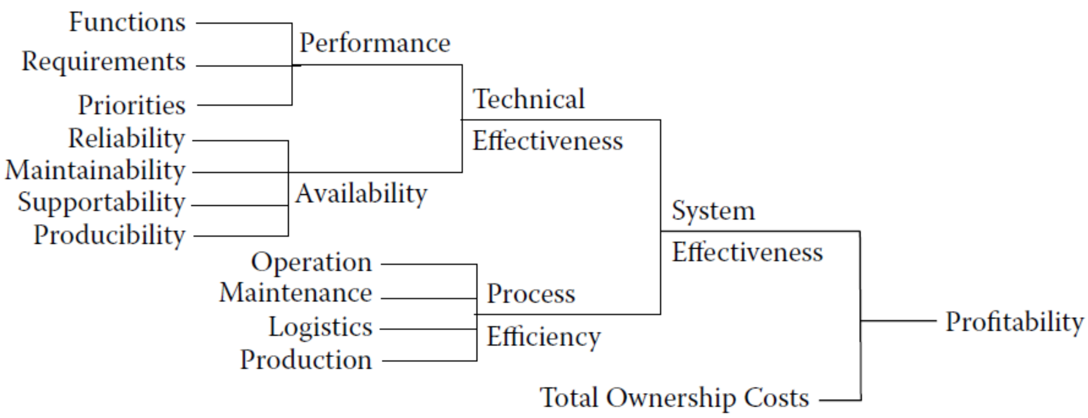

Figure 28: Components of operational effectiveness[49]

Many of the factors mentioned above as well as factors necessary to calculate the TCO are subject to a degree of risk and uncertainty. Especially for factors that have a large influence on the key cost drivers over long service lives it is important to minimize the risk and uncertainty or at least have a better understanding of the expected trends in the future.

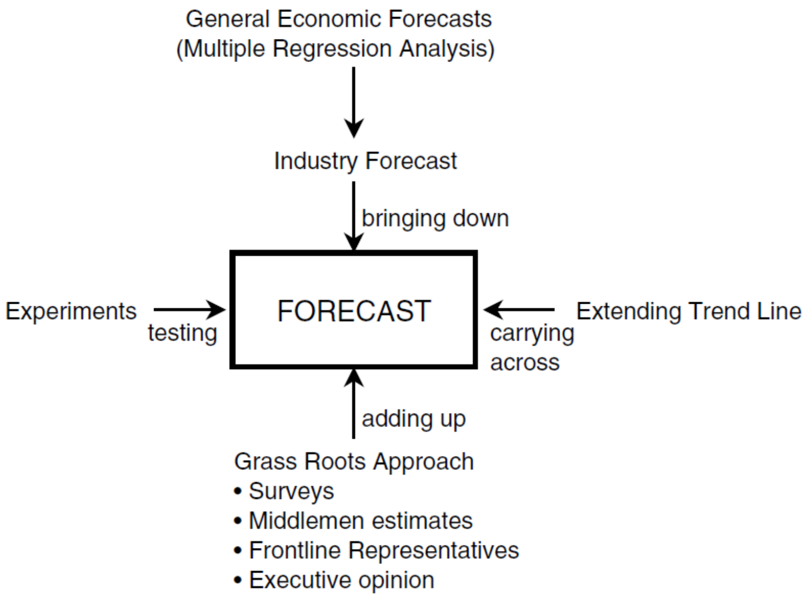

Figure 29: The four ways of forecasting[50]

[49] Modified from Stevens Institute of Technology (2008), p. 25; Vail Farr, J. (2011), p. 39
[50] Adapted from Allvine, F. (1996), p. 12; Emblemsvag, J. (2003), p. 47

A good life cycle cost estimation needs a reliable method of determining the future costs of a system and potential risk of cost provoking events to happen. The method to predict the future with a certain degree of accuracy is generally called forecasting which is regularly used in engineering and business day to day operations. Four ways of forecasting exist (Figure 29):

- Extending current trends is very common however it assumes that the future roughly follows today's trends and misses the potentially disrupting events such as new opportunities and threats.
- Another approach is conducting experiments and based on those results assumptions for the future are made.
- Industry forecasts give a general direction where the industry is headed but leaves the results in the hands of the forecast creators.
- The grass root approach collects information based on expert opinion in the form of interview or surveys. It is particularly useful to incorporate future innovations into the forecast. It is the most flexible approach and not relying on past information to make accurate predictions.

5.1 Types of cost models

Depending on the available resources and data different LCC models can be applied. Each has its specific advantages and disadvantages and comes with a different applicability depending on the state of the life cycle of a system. Data availability, time intensity and expected accuracy play a major role in choosing an appropriate LCC model (Figure 30).

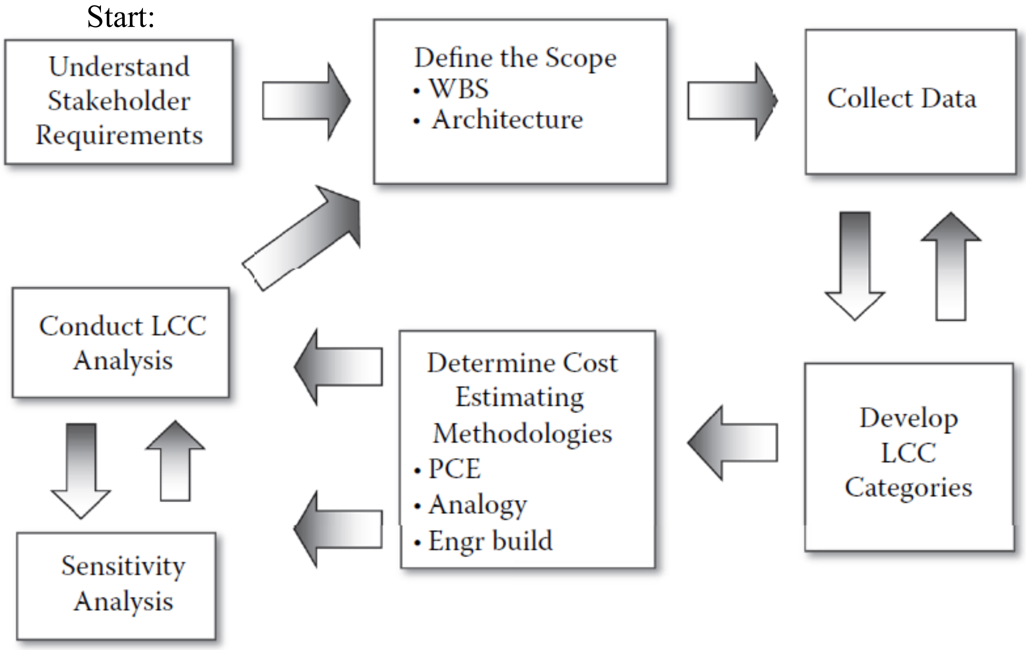

Figure 30: Process of developing an LCC model[51]

Four main types of cost methodologies are differentiated: analogy, parametric, engineering cost methods and cost accounting. Depending on the stage of the life cycle the shown modeling approaches have different applicability as shown in Figure 31. All shown models are part of a broadly defined framework called engineering economy.

Simulation based costing approaches such as parametric and analogy models are particularly useful for early stage costing whereas engineering cost models are more applicable mid-lifecycle and accounting methods in the later stages of a system's life cycle. Cost accounting is typically the most accurate costing methodology, the results and accuracy of early stage costing methods that are often based on complex statistical simulations hinge on some key factors such as assumptions made which require sufficient experience and historical data to work properly.

[51] Modified from Vail Farr, J. (2011), p. 32

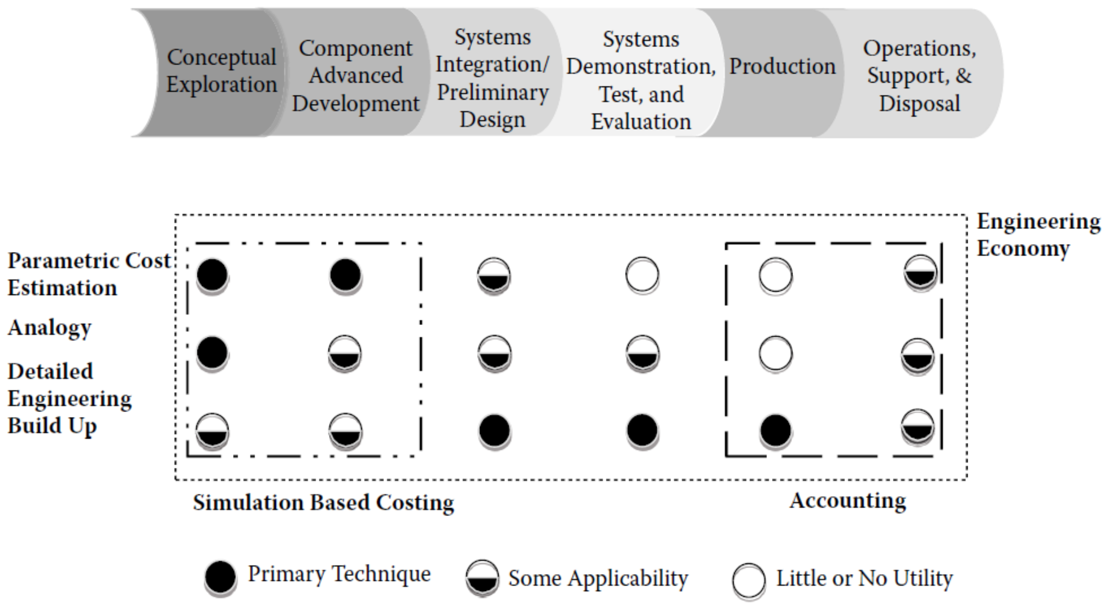

Figure 31: Methods, processes and tools used in costing complex systems[52]

5.1.1 Analogy models

Analogy costing is the most simple and crude approach to model a system. It takes historical costs from a similar system and fits them according to the dominant cost driver to the current system. Factors such as indirect labor or overhead costs cannot be derived from this method. This approach requires that sufficient and relevant historical data is available and the system in question has one dominant cost driver to base the analogy on. It has limited applicability due to its relative inaccuracy and the additional requirement that the analogous systems do not change significantly in terms of technology, size, operational characteristics and use patterns.

5.1.2 Parametric models

Another more advanced model is the parametric model. Costs of the whole system or components are described as linear or non-linear relationships between costs and product or process-related parameters. One major challenge is the determination of the relationship of the dependent and independent variables and their range of usefulness.

Three main differences exists between the parametric and the analogy model:

- Unlike the analogy model the parametric model does not require one main cost driver. It can use several parameters to determine the cost structure.
- Analogy models rely on linear relationships between costs and cost drivers whereas parametric models can incorporate non-linear regression models as well.

[52] Vail Farr, J. (2011), p. 85

- Whereas analogy models use analogies as driver parametric models use regression or response surface models such as linear, quadratic, multidimensional relationships. Hence sufficient measured data is required to develop accurate regressions.

Just like the analogy modeling approach this approach has its limitations and is most applicable to early stages of system life cycles. System optimizations based on parametric models are typically unsatisfactory due to the long implementation lag times and the changed optimums by the time the change is successfully implemented.

5.1.3 Engineering cost models

The New South Wales Government Asset Management Committee in describes the engineering cost methods as follows: “The Engineering Cost Method is used where there is detailed and accurate capital and operational cost data for the asset under study. It involves the direct estimation of a particular cost element by examining the asset component-by-component. It uses standard established cost factors (e.g. firm engineering and/or manufacturing estimates) to develop the cost of each element and its relationship to other elements (known as Cost Element Relationships—CER)”[53].

Engineering cost models offer a deeper insight into the cost structure than analogy or parametric models are however still unable to handle overhead costs which are becoming increasingly important as complexity in systems rises.

5.1.4 Cost accounting models

The most accurate method of cost modeling is the cost accounting method. It is commonly used in later stages of system life cycles and is typically grouped into three methods:

- Volume-based costing
- Unconventional costing
- Modern cost management

The main concept of volume-based costing is that the overhead costs are funneled to a single cost pool and then allocated to specific components of the systems according to a relevant cost driver such as units manufactured.

Unconventional costing methods include mostly methods that are quite different from most cost management methods or are not very popular such as the attribute based costing method or the feature costing method.

The most commonly used methods today are referred to as modern cost management systems which include ABC (Activity based costing), JIT (Just-in-Time costing), TC (Target costing) and SCM (Strategic cost management). The available literature on those costing methods is quite extensive, hence they are not discussed further in detail here as the costing model applied and discussed in later chapters is a combination of parametric and engineering cost modeling.

[53] Emblemsvag, J. (2003), p. 54

5.2 Life cycle costing specific to compressor systems

In compressed air and industrial refrigeration applications the operational expenditures over the life of the system is typically 8 to 10 times as much as the initial investment cost of the system. This shows the highly leveraged effect of energy efficiency and the important role it plays over the lifetime of such a system (Figure 32).

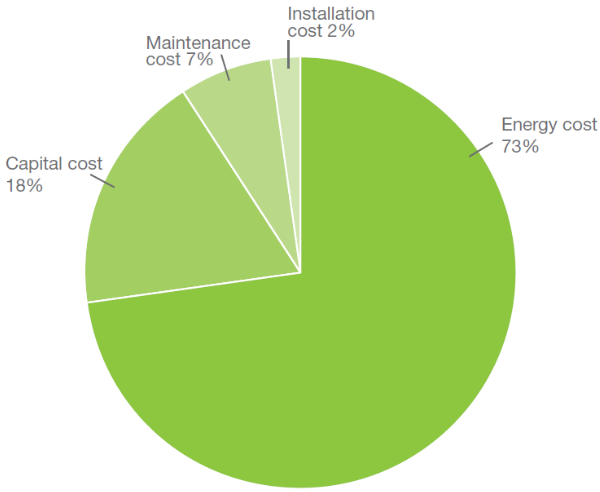

Figure 32: Typical lifetime ownership cost of a compressed air system[54]

LCC is often used to design and plan such systems and in many cases acts as an eye-opener to decision makers where the real costs of those systems actually occur. When decision makers are faced with different investment or overhaul options LCC can provide them the necessary information to make informed decisions in order to choose the most cost effective alternative with the limited data available. LCC for compressor systems have a lot in common with pumping systems as the majority of their life cycle costs stem from electricity costs, they are in widespread use and cornerstones for industrial activity.

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d \qquad (8)$$

LCC ... life cycle costs

C_{ic} ... initial costs, purchase price (compressor, system, pipes, etc.)

C_{in} ... installation and commissioning costs, training

C_e ... energy costs

C_o ... operating costs (e.g.: labor cost of system supervision)

C_m ... maintenance and repair costs

C_s ... down time costs (loss of production)

C_{env} ... environmental costs

C_d ... decommissioning/disposal costs

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54 Sustainability Victoria (2009), p. 6

Equation 8 shows what cost factors are primarily included in the LCC calculation of a compressor system[55]. Due to the large portion of the energy costs on the total costs the most effort should be put into accurate calculation of this cost portion.

When comparing different investment options it is necessary for the decision makers to have comparability between those options. Depending on the situation different profitability measures are used to compare investments as each has its limitations:

- Net present value (NPV) is the sum of all discounted cash flows over the lifetime of the investment. It gives an idea about the current worth of an investment in today's money. The applied discount rate that is used to calculated the NPV needs to be chosen carefully. It is also referred to as opportunity cost which is the rate of return the company can achieve elsewhere with similar risk.
- Benefit-cost ratio (BCR) is the ratio of the present value of the projected benefits to the project to the present value of the costs. If this ratio is greater than one the project is profitable however this number is not an absolute measure and does not capture the magnitude of the benefits and costs.
- Internal rate of return (IRR) is defined as the discount rate where the NPV becomes zero. This measure is widely used in making investment decisions due to its simplicity. However it has limited applicability in investments with long life cycles, irregular cash flows and changing discount rates.
- Return on Investment (ROI) is another very popular measure to compare investments. It is the ratio of the net income of an investment divided by the cost of the investment. Its downside is that time in not taken in consideration which can limit the comparability in some cases.
- Payback period (PBP) is the time required for the investment to earn the initial investment costs back. Especially in compressor system upgrades low payback periods are important in order to get investment approval.

Each investment has certain cash flows that are the basis for the calculation of its profitability. They are grouped in cash inflows and cash outflows. For projects regarding improved energy efficiency measures in compressor systems by upgrading parts of the systems the cash inflow from cost avoidance and savings is the key driver for the profitability of such an investment.

Typical cash ouflows:

- Procurement costs
- Operations and support
- Disposal costs
- Interest and repayment of borrowed funds
- Income tax

Typical cash inflows:

- Borrowed funds
- Revenue from cost avoidance or savings
- Salvage value

[55] Hydraulic Institute et al. (2001), p. 11

Figure 33 shows the graphical representation of the installed costs and the operating costs and how the above mentioned contributing input and output factors fit into this LCC calculation.

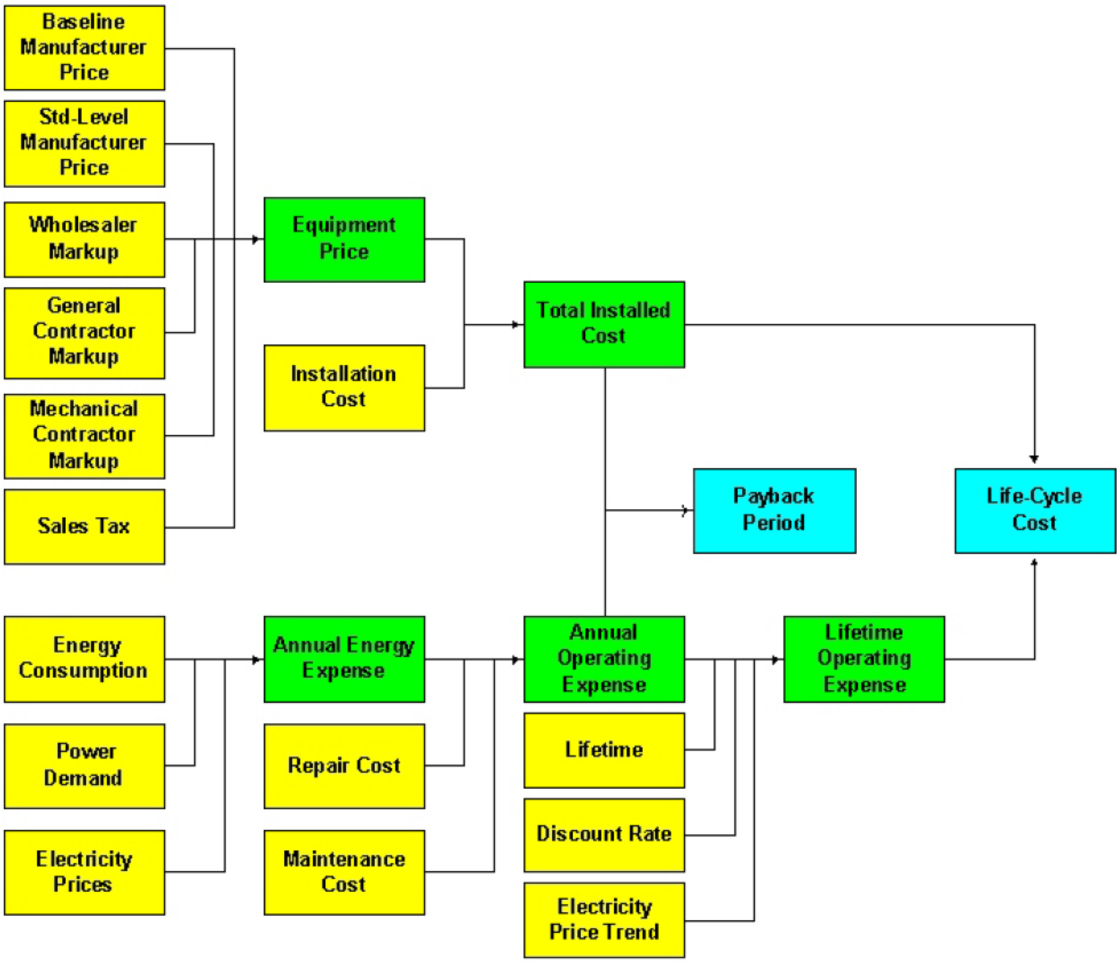

Figure 33: Typical inputs and flow of LCC and PBP calculation[56]

Based on the principles of LCCA a simplified web application was developed as a marketing tool in order to increase customer awareness for potentially significant cost savings and attractive investment opportunities. The detailed setup of the LCC model and application functionality will be explained in more detail in chapter 10 Life cycle cost calculator.

[56] Rosenquist, G. et al. (2004), p. 13

6 Energy efficiency regulations

Energy efficiency becomes more and more important in today's economies. In order for many businesses to stay competitive they try to minimize the waste of energy and inefficiency in their production facilities as much as possible. But also private households try to minimize their energy use which is often coupled with the environmental footprint.

In the past decades several energy efficiency labels, standards and directives have been developed to guide businesses and household consumers with their buying and investing decisions regarding energy usage. This chapter discusses some of the important proxies of that category and shows the possible applications in the field of compressor systems.

6.1 Efficiency labels and standards

To lower energy consumption and waste there are efficiency labels and standards that get used as tools to encourage these changes in consumer behavior. Both of these tools work complementary and aim to transform the market towards more energy efficient products. In order to define such standards and labels it is important that the term efficiency is clearly defined for each product category. For example the efficiency for refrigerators defined by the annual kWh consumption of electricity but the efficiency of a car is stated as the consumption of fuel, either liters per 100 kilometers (l/100 km) or miles per gallon (mpg).

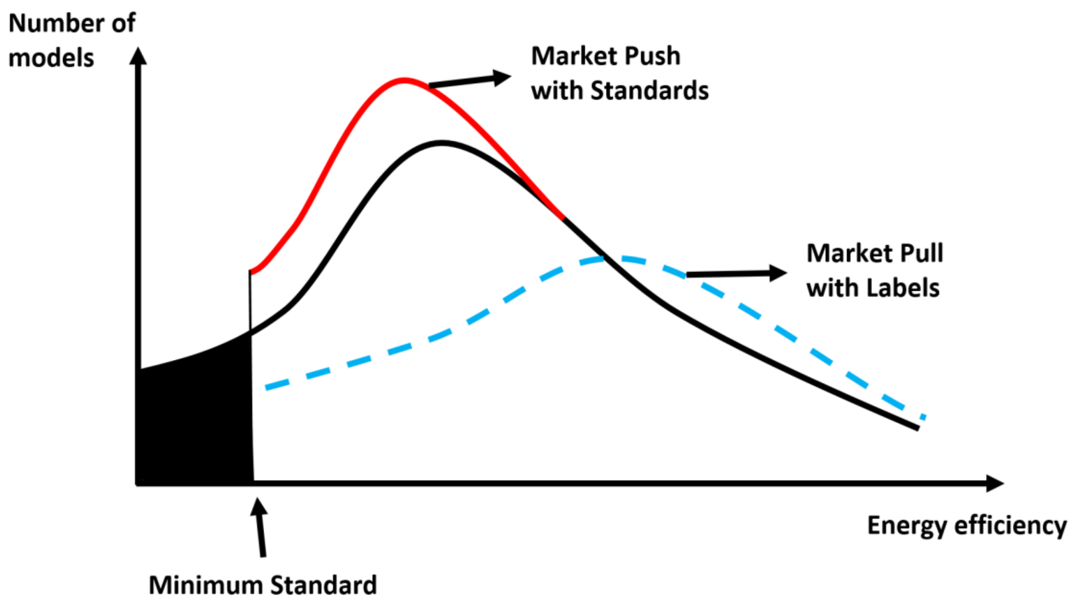

Figure 34: Depiction of how standards and labels both increase energy efficiency in the market[57]

[57] Modified from North American Energy Working Group (2013), p. 6

Standards work by pushing the market into the direction of more efficiency by cutting off the lower end hence the inefficient products by setting minimum values for orientation thereby moving the curve upwards (red).

Labels on the other hand pull the market towards efficiency by giving the customer the opportunity to be better informed at the time of purchase. In order for companies to stay competitive they have to offer products that carry these labels. For these labels to work properly clearly defined metrics and procedures have to be established that tell how the efficiency is measured and what the label ratings mean.

Standards and labels are tools that allow substantial changes in the market and have several advantages[58]:

- They have to potential to achieve large energy savings due to the widespread adaption.
- They are relatively cost effective.
- The changes have to be adapted by the manufacturing side instead of the much bigger consumer side.
- Equal treatment of all market participants.
- The achieved energy savings are relatively simple to quantify because of the available sales and efficiency improvement data by the manufacturers.

For many geographic regions and countries different standards and labels exist the most important ones for North America and the European Union are discussed in this chapter.

Figure 35: Energy efficiency labels and MEPS for residential refrigerators[59]

[58] North American Energy Working Group (2013), p. 7
[59] Morgado, D. (2014), p. 21; Enerdata Information Services (Retrieved: 17.07.2016)

Figure 35 and Figure 36 show the distribution of the existence of labels and efficiency standards by country for refrigerators and air conditioners. It can be noted that the introduction of efficiency labels for refrigerators is ahead of air conditioning units. This can likely be explained with the longer history of refrigerators and their longer existence in the marketplace.

Figure 36: Energy efficiency labels and MEPS for residential air conditioning[60]

Virtually all of the developed countries as well as emerging countries have adopted labels and minimum efficiency performance standards (MEPS) for refrigerators and air conditioners. Interesting to note is that no European country has introduced MEPS for air conditioners yet despite the huge emphasis on energy efficiency. This will likely change in the future as the effects of climate change become more and more prevalent in these countries and as more private households invest in air conditioning units.

6.1.1 Energy star

The Energy star is an international standard for energy efficient consumer products. It was created in 1992 by the Environmental Protection Agency in the United States of America[61]. To date most countries of the developed world have adopted the program. Many well – known consumer products carry the voluntary Energy Star logo and signal the potential buyer that this product consumes 20 – 30 percent less energy than required by federal standards.

[60] Morgado, D. (2014), p. 22; Enerdata Information Services (Retrieved: 17.07.2016)
[61] EPA's ENERGY STAR program (Retrieved: 07.07.2016)

Typical products that come with the Energy Star certification are:

- computer products and peripherals
- household appliances
- buildings
- heating and cooling systems
- servers
- factories

Historically the Energy Star certification started in the IT industry to promote more energy efficient computer systems but over the last years it spread out to many more areas of energy consumption including compressor and refrigeration systems.

Figure 37: Official Energy Star Logo[62]

6.1.2 EU energy label

Similar to the Energy Star label the European Union developed the EU energy label which shows the energy consumption of mostly white goods to customers. However compared to the Energy Star the customer gets more detailed information directly on the label. Figure 38 shows an example label for a refrigerator. The customer is informed about the general efficiency class with the color bar ranging from A to G and detailed information specific to the product such as average annual electricity consumption and noise levels. To accommodate even more efficient devices the range was later expanded with A+ to A+++. Inefficient products are mostly absent from the market and replaced with more efficient ones (Figure 39).

[62] EPA's ENERGY STAR program (Retrieved: 07.07.2016)

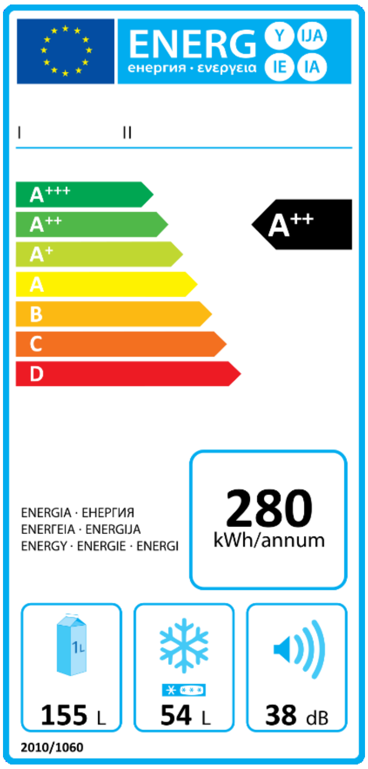

Figure 38: Example of an EU energy lab for a refrigerator[63]

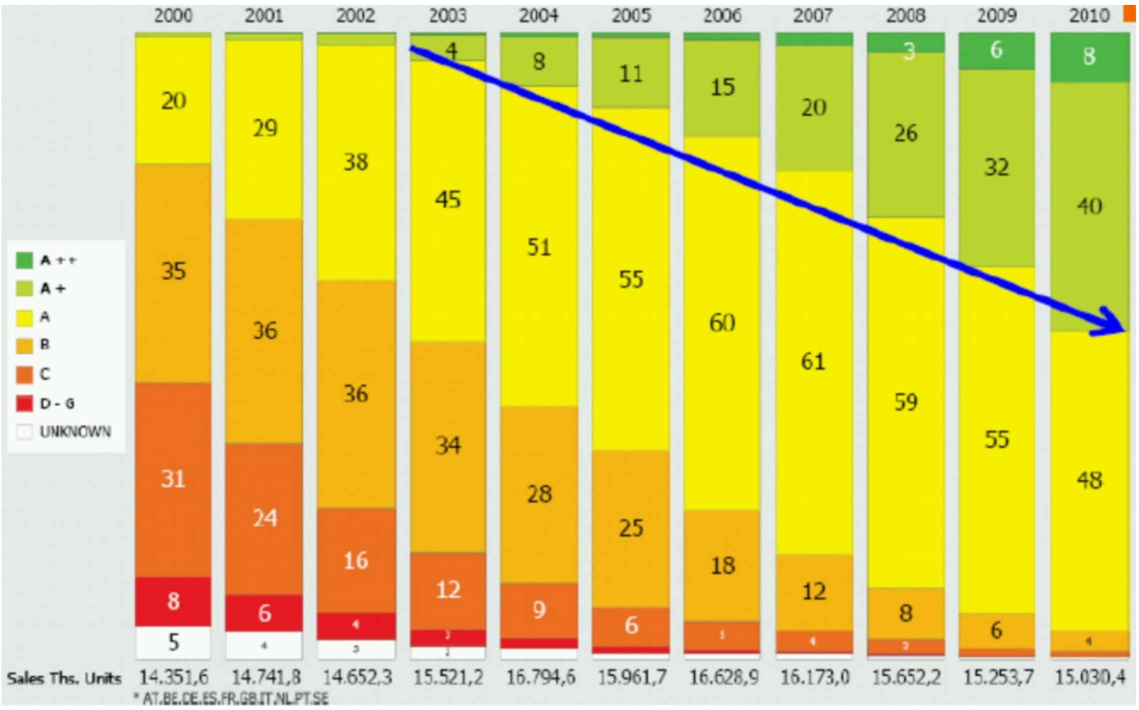

Figure 39: Impact of the EU energy label on cooling appliances market shares in ten major EU countries[64]

As seen below the rating criteria for each product are bound to parameters specific for the product. In case of a refrigerator it is rated by the energy efficiency index (EEI). The

[63] European Commission (Retrieved: 13.07.2016)
[64] Morgado, D. (2014), p. 25; Come On Labels project (Retrieved: 17.07.2016)

EEI gives an indication about the annual electricity consumption relative to the storage volume and the type of appliance[65].

Table 6: Energy efficiency rating criteria for refrigerators and freezers[66]

Refrigerating appliances, as EEI									
A+++	A++	A+	A	B	C	D	E	F	G
<22	<33	<42/44	<55	<75	<95	<110	<125	<150	>150

For the second category of appliances that are relevant for compressor systems, air conditioning units the rating is done either by energy efficiency ratio (EER) or coefficient of performance (COP) depending whether the unit works in cooling or heating mode. These ratings are valid for AC units with less than 12 kW of nameplate capacity. The scale has not yet extended for higher efficiencies although there already exist models in excess of EER and COP greater than 5.

Table 7: Energy efficiency rating criteria ACs in cooling applications[67]

Air conditioners, cooling EER in W/W						
A	B	C	D	E	F	G
>3.2	3.0–3.2	2.8–3.0	2.6–2.8	2.4–2.6	2.2–2.4	<2.2

Table 8: Energy efficiency rating criteria for ACs in heating applications[68]

Air conditioners, heating COP in W/W						
A	B	C	D	E	F	G
>3.6	3.4–3.6	3.2–3.4	3.0–3.2	2.8–3.0	2.6–2.8	2.4–2.6

In 2015 the European commission published a report that reviewed the effectiveness of the energy efficiency labels on the market in the EU[69]. The evaluation has shown that the usage of energy efficiency labels worked well in the last 20 years and that continued effort today is even more relevant. This effort is so effective that about half of the 20% energy savings target by 2020 is contributed by the legislative framework for energy – related products. The most recent extension of the labelling scale to the top efficiency of A+++ showed however less effectiveness for encouraging consumers to buy the products on the higher end of the efficiency scale hence a future change in the scale is likely.

[65] European Commission (Retrieved: 13.07.2016)
[66] European Commission (Retrieved: 13.07.2016)
[67] European Commission (Retrieved: 13.07.2016)
[68] European Commission (Retrieved: 13.07.2016)
[69] European Commission (2015), p. 18

This report claims that the energy efficiency policies which include the Ecodesign and Energy guide labels are effective and bring benefits to businesses and the society. The benefit to cost ratio (BCR) is estimated at 3.8 (other environmental policies usually have an average BCR of 3).

BCR is an indicator for projects of proposals to describe its benefits as a ratio in monetary terms. It is calculated by the benefit in terms of money divided by the cost. When the BCR is greater than one benefits outweigh the costs and the investment, project or proposal is considered to be good.

6.1.3 Energy Guide label

Similar to the EU energy label the energy guide label exists on the United States. It was introduced in 1975.

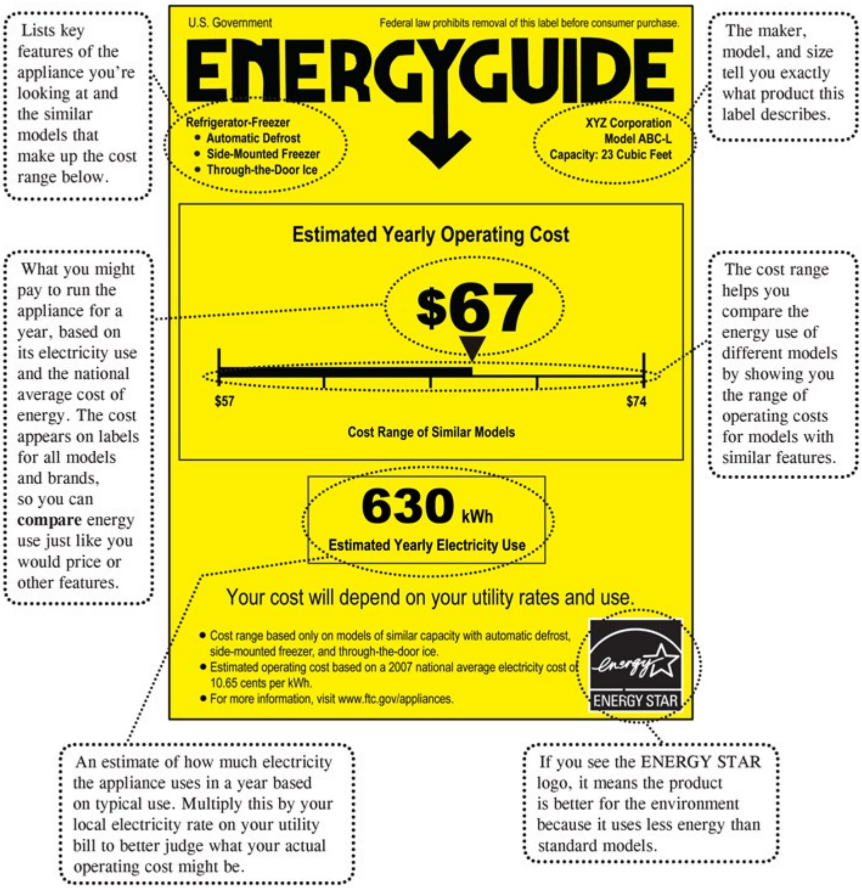

Figure 40: Example of an Energy guide label for a refrigerator / freezer[70]

Unlike the Energy star this label is mandatory and gives the consumer an overview of the product life cycle cost and efficiency. It generally applies for the same products the EU energy label does.

[70] The Federal Trade Commission (Retrieved: 21.07.2016)

6.1.4 EU Ecodesign label

Among the EU legislative framework to reduce energy consumption and the environmental footprint of products the Ecodesign directive was established to improve product sustainability at the design stage. The main goals are the reduction of water consumption, material, pollution, energy, waste and increase the recyclability. The range of products that fall under this regulation is split up into 10 categories:

- Air conditioning and related products
- Heating systems (electric and combustion)
- Food – preparation equipment
- Industrial furnaces and ovens
- Machine tools
- Network and data processing equipment
- Refrigeration equipment
- Audio and imaging equipment
- Transformers
- Water consuming equipment

The combination of the different legislative tools is driving the economy towards more energy efficiency (Figure 41).

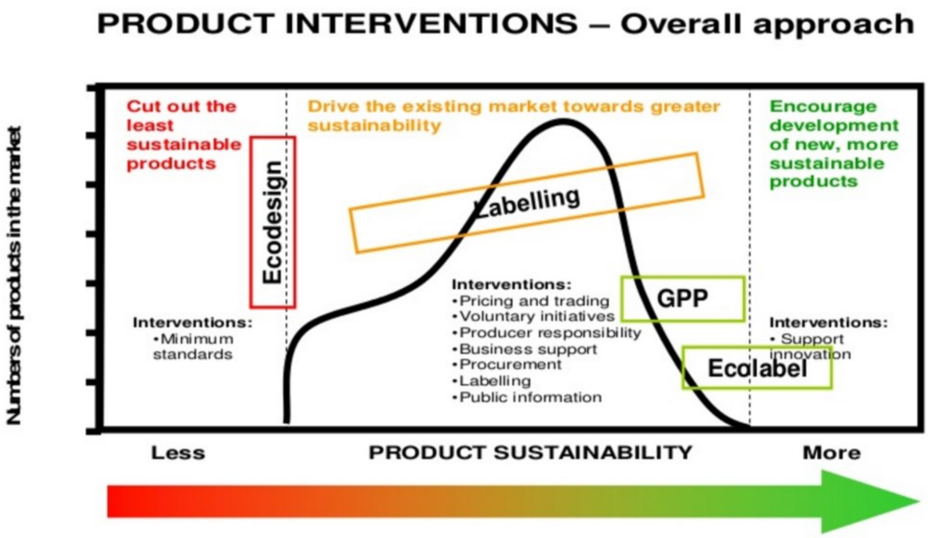

Figure 41: Impact of regulations on the sustainability and efficiency of products[71]

[71] Karolina D'Cunha (2015), p. 13

6.2 EU energy efficiency directive

In 2012 the European Union introduced the EU energy efficiency directive in order to reach the target of reducing the energy consumption of the EU by 20 percent by the year 2020 compared to its 1990 consumption. The member countries were obligated to transpose the new directive into national law until June 5th 2014. These newly implemented national laws are designed to:

- increase energy efficiency in the countries
- increase security of energy supply and prevention of future fuel poverty
- increase the share of renewable energy in the system
- decrease the amount of emitted CO_2
- create positive impulses for the economy
- create new jobs in the new “energy efficiency” sector

The goal is to annually save 1,5% of energy which should result in an total energy saving of at least 10,5% by the year 2020. The newly formed laws apply mainly to utility companies and to businesses. Depending in their size they have to undergo a mandatory energy audit on a regular basis by accredited energy auditors.

Not complying with the new savings targets or reaching them too late obligates the companies to pay financial penalties that vary depending on the company size. These penalties encourage the companies to invest in new energy saving technologies as they can be financially significant as well as damaging the company’s reputation.

Table 9 shows typical barriers why energy efficiency measures are so slowly implemented if they are not encouraged by legislative frameworks. Many of the stated points also apply to the compressed air and refrigeration systems where even today big savings potentials are still untapped. These untapped savings potentials are in general easily fixable system configurations that can be used to ensure the required energy savings are reached in the coming years as compressed air systems for example still account for 10 to 20% of the electricity consumption of a factory.

Table 9: Overview of the main energy savings barriers and effects[72]

	Barrier	Effect	Remedial policy tools
Visibility	EE is not measured	EE is invisible and ignored	Test procedures/measurement protocols/efficiency metrics
	EE is not visible to end users & service procurers	EE is invisible and ignored	Ratings/labels/disclosure/benchmarking/audits/real-time measurement and reporting
Priority	Low awareness of the value proposition among service procurers	EE is undervalued	Awareness-raising and communication efforts
	Energy expenditure is a low priority	EE is bundled-in with more important capital decision factors	Regulation, mechanisms to decouple EE actions from other concerns
Economy	Split incentives	EE is undervalued	Regulation, mechanisms to create EE financing incentives for those not paying all or any of the energy bill
	Scarce investment capital or competing capital needs	Underinvestment in EE	Stimulation of capital supply for EE investments, incubation and support of new EE business and financing models, incentives
	Energy consumption and supply subsidies	Unfavorable market conditions for EE	Removal of subsidies
	Unfavorable perception and treatment risk	EE project financing cost is inflated, energy price risk underestimated	Mechanisms to underwrite EE project risk, raise awareness of energy volatility risk, inform/train financial profession
Capacity	Limited know-how on implementing energy-saving measures	EE implementation is constrained	Capacity-building programs
	Limited government resources to support implementation	Barriers addressed more slowly	
Fragmentation	EE is more difficult to implement collectively	Energy consumption is split among many diverse end uses and users	Targeted regulations and other EE enhancement policies and measures
	Separation of energy supply and demand business models	Energy supply favored over energy service	Favorable regulatory frameworks that reward energy service provision over supply
	Fragmented and under-developed supply chains	Availability of EE is limited and it is more difficult to implement	Market transformation programs

[72] Waide, P. (2015), p. 25

7 Market research

Marketing research or market research is a field of study where the main purpose is the acquisition of data from the market. The market in this case is either the customer or the competitor. As an organization today in such a highly interconnected world and market-place the competitive advantage often comes from the essential bit of information that the competition does not possess at a given time.

In the literature market research and marketing research are often mentioned in the same sentence however are defined differently by many people. The main idea however is the gaining of knowledge and information which helps the organization for further business decisions.

The American Marketing Association defines marketing research as:

“The function that links the consumer, customer, and public to the marketer through information - information used to identify and define marketing opportunities and problems; generate, refine, and evaluate marketing actions; monitor marketing performance; and improve understanding of marketing as a process. Marketing research specifies the information required to address these issues, designs the method for collecting information, manages and implements the data collection process, analyses the results, and communicates the findings and their implications.”[73]

On the other hand ESOMAR (essential organization for encouraging, advancing and elevating market research) defines it slightly different:

“Market research, which includes social and opinion research, is the systematic gathering and interpretation of information about individuals or organizations using the statistical and analytical methods and techniques of the applied sciences to gain insight or support decision making. The identity of respondents will not be revealed to the user of the information without explicit consent and no sales approach will be made to them as a direct result of their having provided information.”[74]

Both definitions above show how differently, although partly overlapping, the meaning of marketing research can be perceived.

Market research is usually a relatively slow process that can take months to be finished and to generate meaningful data for informed business decisions. Hence the approach the base an organization’s decision making on market research data is only applicable on a more strategical medium to long term timeframe. For day to day decisions where often time fast reaction is critical for operations this approach is less suited or often times impossible to do especially if the necessary infrastructure is not already in place and well integrated in the organization.

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[73] American Marketing Association (Retrieved: 16.06.2016); Sarstedt, M.; Mooi, E. , p. 3
[74] ESOMAR (2007); Sarstedt, M.; Mooi, E. , p. 3

The sources of the market data that companies can obtain are different. An overview of typical providers of such data is shown below. Depending on the size of an organization the information gathering process can vary substantially. Usually bigger organizations have specialized departments of a group of people responsible for market research. The scale and complexity of an organizations' market research infrastructure depends also on the very needs of market data itself for the company.

Big companies which are heavily based on business to customer relations may more usually maintain an internal department of market research which constantly produces relevant data for the upper management to act on. Smaller businesses more relying towards business to business (B2B) interaction may only have one person working on such a research problem when needed or buy external services from specialized service providers.

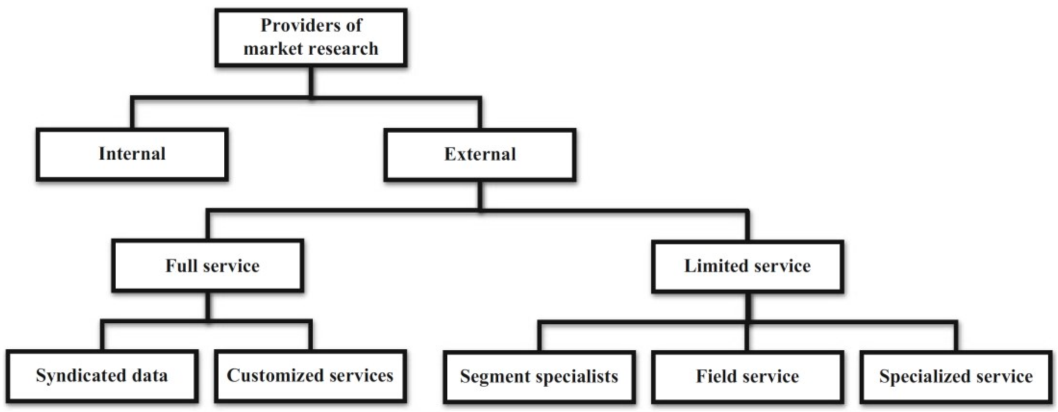

Figure 42: Overview of typical providers of market research data[75]

For the purpose of the market study in this thesis the cooperating company decided to utilized the services of an external provider, which in this case is the author of this thesis. The company mainly acts in a B2B environment where the customers are original equipment manufacturers (OEM) of compressor and refrigeration systems. The actual number of potential information sources is therefore relatively small when the main players in the compressor and refrigeration market are considered which are playing a stronger role in technological developments regarding energy efficiency compared to the smaller OEMs.

In B2B market research the requirements and processes differ from the research done in business to customer (B2C) studies. The tools and the main differences that are applicable in such a case are discussed in the following chapters. The main goal of the information gathering process is to find out what the key players in the market are currently doing and what they plan to introduce into the market in the coming years in terms of energy saving, recovery and efficiency measures. Hence the whole gathering process is mainly revolving around a qualitative market research processes which are discussed into more detail in the next chapters.

[75] Sarstedt, M.; Mooi, E. , p. 5

7.1 Types of market research

Generally the market research field is divided into two main categories, business to consumer and business to business research. B2B research focuses on the research on other businesses and is usually smaller in scale than a comparable B2C study. Probably the easiest and most obvious way to distinguish those two types is as Andrea McIntosh described B2B research, "The common element is the fact that our respondents are buying the goods or services we research, not with their own money but with the money of companies or organizations for whom they work"[76].

B2C or consumer research focuses mainly on fast - moving consumer goods (FMCG) and consumer packaged goods (CPG). With the advent of the internet and growing access for people to information and all different kind of goods and services B2B and B2C are often overlapping and research in that environment done together as their difference becomes blurry. An example for this situation could be the market for high end 'business' products that also appeal to 'advanced' consumers.

In classical B2C research the respondents represent more of a homogeneous crowd than in B2B research. In B2B research it is essential to not just interview the person on the top of the organization but also the main influencers. The range of respondents in B2B should be much more diverse the get an optimal unbiased view on a certain research question or problem.

7.2 Differences between B2C and B2B research

Although as mentioned above the boundary between B2C and B2B can sometimes become blurred for this study it is clear that the focus lies completely on B2B research as the customers entirely consist of compressor and refrigeration system OEMs. Nevertheless will this chapter point out the major distinctions between research studies done on other businesses and on consumers. In general the most important ones are[77]:

- requires different skillset
- respondents
- samples and sample sizes
- content
- geographical spread of respondents
- research methods employed
- Pareto principal
- complexity of decision making processes

[76] McNeil, R. (2005), p. 3
[77] McNeil, R. (2005), p. 10 ff; B2B International (Retrieved: 19.06.2016)

The ability to conduct B2B market studies requires a different skillset by the person or organization performing the study. Due to the relative small number of samples that are usually available the interviewer has to treat every contact with great care. The range of different respondents requires from the interviewers to be able to build rapport with many different kinds of people, from time pressured senior executives to engineers to workers. The information the interviewer wants to extract for such studies can often be highly technical and go into great detail. Hence it is essential for the interviewer to be or become an expert in this topic too. For this thesis it is therefore necessary to have a good understanding about the different compressor types, compressor and refrigeration systems as well as the major energy efficiency measures that companies already apply today before the questionnaires are conducted.

The range of interviewed people can vary more than in a B2C study. However for the study presented in this thesis the intended information is of a higher level engineering nature. Naturally this key design factors can only be answered adequately by engineers and executives. The main problem posed with such a study is that the respondents gain no immediate benefit from it and are usually hard to get a hold of. Often the intended respondents are people higher up in the hierarchy of an organization and responsible for more significant business decisions. Such people are often guarded by ‘gate keepers’ such as secretaries or personal assistants which might be an additional challenge for the researcher especially if there are no business contacts established so far. For very specialized questions there might only be very few key individuals in a company who can give satisfactory answers and they might be difficult to identify.

When making a market study in a certain industry or segment of an industry there might only be few respondents worldwide and they are usually geographically far apart. Although this presents a lesser problem in todays interconnected world where questionnaires can be held via telephone, video chat or email it might in some cases still be challenging and costly to conduct such a study with personal interviews.

In many business situations only a small fraction of customers makes up for the majority of sales. That are usually the bigger players in the business who naturally have a higher demand for products due to larger sales on their side. To account for that essential weighting in the study special care has to be given to key accounts with personal interviews ideally were the already established personal connections to people inside this companies are utilized. For the rest of the respondents consisting of less important smaller market participants the study is usually continued with less laborious online surveys.

As mentioned above the sample size that can be expected in B2B studies is usually substantially smaller than in B2C studies. This leads to the problem that in some cases only a handful of respondents are available worldwide and that every chance has to be taken to interview people in person if possible. Often one in depth personal interview can add tremendous value to the study. If there are tight timely or budgetary constraints on a research study this can lead to sub optimal outcomes. Often key companies are on different continents and far apart. Additionally this can make frequent study repeats difficult and the use of quantitative research models unpractical or impossible.

The often highly technical and detailed nature of B2B studies requires far more flexibility by the research when interviewing respondents. The results from such a study are much more of a qualitative nature than the mostly repeating process in a B2C study. They are a combination of the answers from often several people in a company who are taking part in a complex decision making process and can contribute their insight from their point of view. On some occasions the researcher is faced with the fact that the respondents are not necessarily willing to lay open some detailed data that can cost them the leading edge in a certain field. Hence the research has to be prepared to be flexible in their interviewing process and get as much information as necessary for the study without violating the ethical standards of marketing research which would likely lead to harmed personal connections for future studies.

The methodologies used in conventional B2C studies are often very specific and focus just on one single research methodology. Providers of such studies are often specialized in just one or few niche methodologies. In B2B research on the other hand the applied methodologies can vary throughout the study and change as needed depending in the scope of the study. Therefore the researcher or the research provider has to be proficient in a number of methodologies that have to be applied consecutively. For example a study could start with a strategic workshop followed by in depth interviews and focus groups, after that a large scale online survey with in depth interviewing of key accounts at the end.

7.3 The ethics of market research

The ethical standards in market research play an important role in all facets of this process. Although the B2B segment of market research is small compared to B2C the ethical standards mostly apply for both[78]. The most important points of the ethical standards and specifically the peculiarities of B2B ethics are shown in this chapter.

Worldwide there exist several associations for marketing and opinion research such as the European Society of Opinion and Marketing Research (ESOMAR), Marketing Research Association (MRA), American Marketing Association (AMA) and American Association of Opinion and Marketing Research (AAPOR). Each of these associations publishes their code of conduct or ethics and usually updates them regularly. In this chapter the codes of the ESOMAR and MRA are discussed into more detail[79]. However in general these codes are similar in most parts.

[78] McNeil, R. (2005), p. 242 ff

[79] ESOMAR (2007); MRA, (Retrieved: 22.06.2016)

The ICC/ESOMAR published a guideline named “international code on market and social research” and in this guideline they state the purpose of these codes to be a framework for self – regulation that should be applied internationally to fulfil following objectives[80]:

- the definition of ethical rules the researcher should follow throughout his work
- it should enhance the public’s confidence in market research and increase awareness of the rights and safeguards they are entitled to under this code
- emphasizing the need for special attention when research is done on children or young people
- protecting the freedom of researchers to seek, receive and publish information
- make sure that government and intergovernmental legislation or regulation in any form is not necessary

When taking a look at the purpose of these codes of conduct, it becomes obvious that a great part is only relevant for B2C research. B2B research is only a fraction of the field of market research and has therefore not a separate code of conduct and ethics. Below are shown the ten principles of the code of conduct published by the MRS[81]:

1. Researchers shall ensure that participation in their activities is based on voluntary informed consent.
2. Researchers shall be straightforward and honest in all their professional and business relationships.
3. Researchers shall be transparent as to the subject and purpose of data collection.
4. Researchers shall respect the confidentiality of information collected in their professional activities.
5. Researchers shall respect the rights and well-being of all individuals.
6. Researchers shall ensure that participants are not harmed or adversely affected by their professional activities.
7. Researchers shall balance the needs of individuals, clients, and their professional activities.
8. Researchers shall exercise independent professional judgement in the design, conduct and reporting of their professional activities.
9. Researchers shall ensure that their professional activities are conducted by persons with appropriate training, qualifications and experience.
10. Researchers shall protect the reputation and integrity of the profession.

[80] ESOMAR (2007), p. 4
[81] The Market Research Society (2014), p. 3

In comparison is shown below the eight points published by ICC/ESOMAR[82]. Although they differ in some points a general similarity can be recognized:

1. Market researchers shall conform to all relevant national and international laws.
2. Market researchers shall behave ethically and shall not do anything which might damage the reputation of market research.
3. Market researchers shall take special care when carrying out research among children and young people.
4. Respondents' cooperation is voluntary and must be based on adequate, and not misleading, information about the general purpose and nature of the project when their agreement to participate is being obtained and all such statements shall be honored.
5. The rights of respondents as private individuals shall be respected by market researchers and they shall not be harmed or adversely affected as the direct result of cooperating in a market research project.
6. Market researchers shall never allow personal data they collect in a market research project to be used for any purpose other than market research.
7. Market researchers shall ensure that projects and activities are designed, carried out, reported and documented accurately, transparently and objectively.
8. Market researchers shall conform to the accepted principles of fair competition.

When the points of the market research principles are compared several key similarities become obvious which seem to be really emphasized by market research professionals. These key principles also apply widely to B2B research and mainly revolve around the protection and confidentiality of respondents and their offered data, the transparency of the researcher and the maintenance of professional working methods and behavior by the researcher.

In the past and even still today shady sales methods that disguise as market research, so-called 'sugging', and unregulated researchers have brought a bad reputation to this profession which remains in the heads of many people. Therefore it is crucial for professional researchers to uphold these published principles to gain the trust of the researched subjects.

When a researcher interacts with a respondent it is his duty to respect the rights of the respondents and not to break any privacy or data protection laws that may be present in the country of research. Furthermore in B2B studies the pool of respondents is usually fairly small and the trust of each responded has to be kept intact in order to ensure support for future studies and business interactions.

[82] ESOMAR (2007), p. 4

7.4 The market research process

When doing a market research study, no matter which kind, the steps should be carefully planned in order to maintain an overview of the potentially huge amounts of data and to adhere to potential laws such as data protection or privacy laws that could apply to certain countries or regions of research. Figure 43 the typical steps of a market study that should be followed by the researcher:

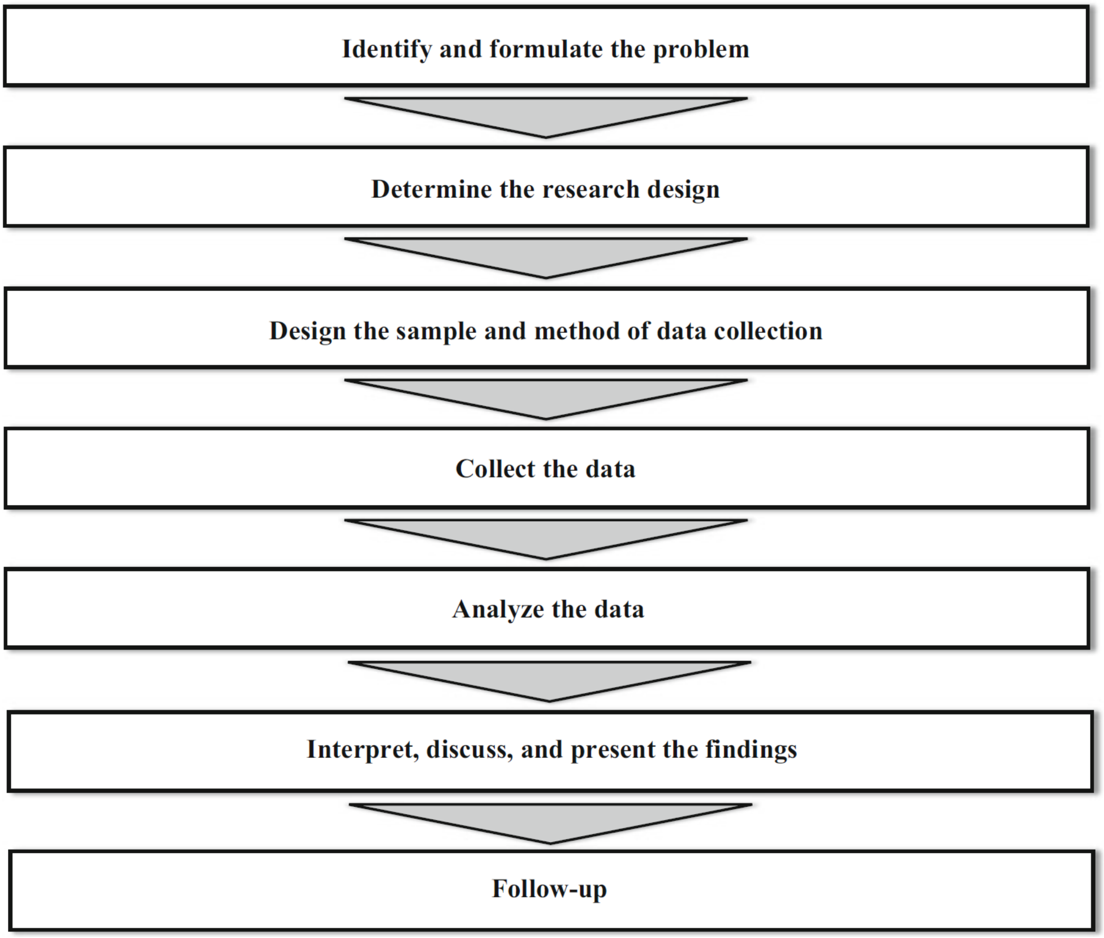

Figure 43: Typical steps of the market research process[83].

7.4.1 Problem definition

The first step of this process would be to come up with an outline of what exactly the research problem is and to formulate goals that should be achieved by this study. Conduction market research can have many different reasons. It might be the decline in sales or market share for a specific product, that can’t be explained, the increase of complaints or a general uncertainty about future market directions that should be understood for proper strategic decision making.

[83] Sarstedt, M.; Mooi, E. , p. 12

Understanding those marketing symptoms is key for smooth start of the research process. Possible research questions that could arise for such a study could be:

- Why is our market share declining?
- What is the greatest growth segment in the next 5 years?
- What technological changes could affect our sales in the future?

The definition of the research problem is not always very clear. The problem could reach from the question “What is the maximum amount the customer is willing to pay for our product?” to less clear questions line “What are the future market trends?”. Therefore the problem definition is generally divided into three categories[84]:

- Ambiguous problems
- Somewhat defined problems
- Clearly defined problems

7.4.2 Research design

The design of a research study is tightly related to the problem that is about to be studied. This planning and designing process can be depicted as a funnel.

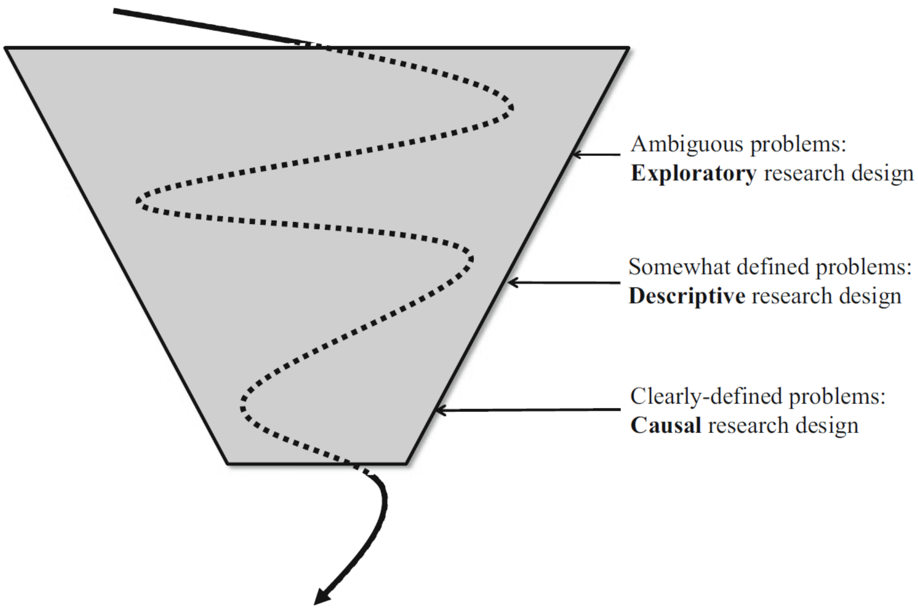

Figure 44: The relationship between the marketing problem and research design[85]

[84] Sarstedt, M.; Mooi, E. , p. 13
[85] Sarstedt, M.; Mooi, E. , p. 14

When there is a novel research problem that has never or poorly researched before it starts with a very wide scope and exploratory research. As the problem becomes somewhat defined descriptive research methods can be applied. And finally as clearly identified problems are set a causal research study can be conducted.

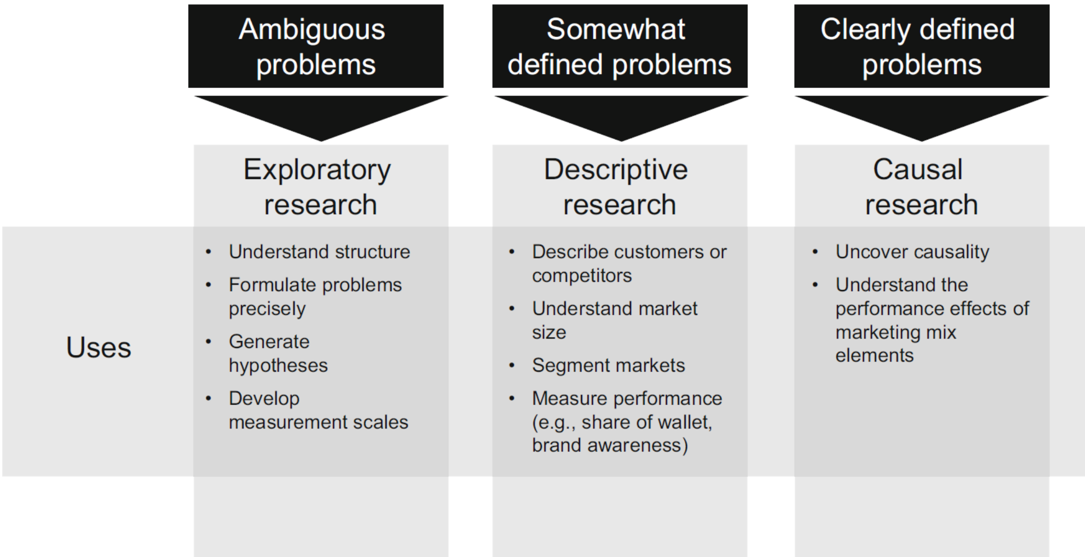

Figure 45: Uses of exploratory, descriptive and causal research[86]

For the purpose of this study the process will mainly revolve around exploratory research. Energy efficiency in compressors systems especially in the compressed air industry is a big issue and has been studied in depth for many years. Many published case studies show the possible gains in energy efficiency and the consequential cost savings that can be achieved by changing few components in the systems. However studies regarding energy efficiency from a lubrication point of view in the compressor market are quite rare. Hence to understand the development in technology and OEM activities for the future is one of the main objectives of this study and the scope of this problem is therefore quite wide and relatively vaguely defined. Each of the shown research methods above utilize different tools which best fit them in order to obtain the best possible results. The most important tools for each are discussed into more detail below with emphasis on the tools used in this study.

[86] Sarstedt, M.; Mooi, E. , p. 14

Exploratory research

The main purpose here is to refine the vaguely defined problems and to find out what is really necessary to know for this study. In order to find the right priorities it is defined what is "nice" to know and what is "important" to know for later stages. Typically used tools at this stage are:

- Depth interviews
- Focus groups
- Projective techniques
- Observational studies
- Ethnographies

Depth interviews are interviews either in person or by telephone where the research has direct contact with the respondent and can control the flow of the conversation dynamically. The big advantage of this tool is that the researcher has the opportunity to gain very valuable key information if the respondent is a respected and influential person in his field or industry such as engineers and executives responsible for key elements that relate to the research problem.

Focus groups normally consist of several respondents who are asked questions or who discuss the topic of the research problem. A moderator initializes and guides the conversation. The respondents have the ability to interact with each other which can give valuable insights which would not be possible with a one on one interview otherwise.

Projective techniques present respondents with different stimuli to which they respond. These could reach from pictures and words to completion tasks where the respondent explains the moderator why he or she answered in a certain way.

Observational studies have the goal to observe the respondents in a certain situation and draw conclusions out of the behavior that could be observed.

In *Ethnographies* the researcher observes the target respondents over a period of time and has the opportunity to observe behavior in the respondents "natural" environment and ask questions.

In exploratory research it is the primary goal to refine and set priorities for possible further market studies that go into more detail in the future. It also includes the research of the already available literature to determine if related studies have already been done in the past and if it is even necessary to repeat the whole process or parts of it again. It also helps to find possible weak spots or knowledge gaps from past studies that can be targeted in particular.

Because energy efficiency in compressor systems especially in compressed air systems is such a big topic in the industry due to its widespread use an already substantial amount of data and knowledge has been gathered in the past years that can be utilized for this study. Later chapters show what data was used and what additional information would be needed or would be "nice to have" from industry professionals.

Descriptive research

In descriptive research the researcher focuses on one or more variables and observes how they behave. These observations often build upon previous exploratory research done in that area that found out more exactly what variables might be valuable and relevant to measure. Some key elements of descriptive research is the gathering the information to describe:

- customers
- competitors
- market segments
- performance

This research methodology describes not the question of how, when and why a variable of characteristic is changing but rather "what" influences the variable in question[87].

For this study descriptive and causal research are less important as shown in later chapters, hence these topics are only discussed on an introductory level.

Causal research

In causal research the researcher goes most into detail from the three methodologies described. Usually this kind of research is done the least frequent due to the high effort and cost. The main purpose in causal research is to uncover causality. Whereas descriptive research will tell what variable of characteristic is changing causal research tells for example by how much a variable is changing in relation to another one.

Causal research is often used to test hypothesis or effects of certain marketing strategies on a predetermined variable. To declare causality on a certain characteristic several requirements have to be met. There has to be a relationship of cause and effect between for example 2 variables such as price and sales volume. The timely sequence of this cause and effect has to be in the right order. Which would mean, for the example above: First the price has to go up in order for the sales volume to come down. A market environment is never fully known and understood. This has to be taking in consideration when conducting a causal research study. For a causality test other possibly influencing factors have to be evaluated as well to account for their effect on the causality claim. When taking the example from above again: Changing the own price might cause the competition to change prices as well which likely influences the relationship between price and sales as well. The fourth requirement that has to be met is that every tested relationship should have a solid theory that explains this effect. If this requirement is not met the relationship can be pure chance instead of an actual cause. The application of statistical methods is crucial in supporting this research method.

[87] Shields, P.; Rangarjan, N. (2013), p. 27

Commonly used tools for causal research are:

- lab experiments
- field experiments
- test markets

When taking a look on the tools shown above it becomes obvious that this research method is likely the most expensive kind of market research that can be done. Hence the often big budgets required to conduct such studies can mostly only be justified for bigger players in the market.

7.4.3 Design method of data collection

The next step is the design of the sampling and data collection method. Knowing what and how to collect data is essential as is takes careful planning to collect the data effectively. The main question the research has to ask himself beforehand is whether there is enough secondary data available to fulfil the requirements of the study or if primary data has to be collected.

Generally secondary data should be preferred because it does not require the willingness of the respondent to share data or to participate. It is also possible that the available data is so outdated or so poorly structured that it is cheaper and simpler to collect new primary data by oneself.

During the planning stage the relationship between accuracy, budget and time has to be taken under consideration as there might be restrictions on one or more of those parameters which can lead to intended trade-offs in some areas.

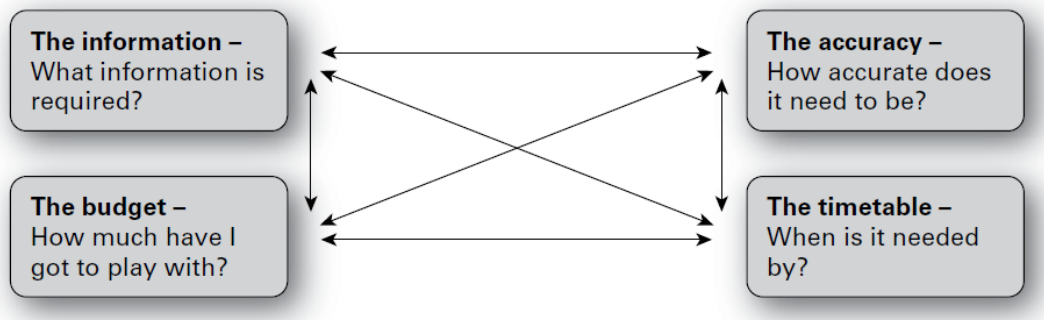

Figure 46: The balance between cost, quality and time[88]

[88] Hague, P. et al. (2016), p. 23

Figure 47 shows a structured overview of the typically available data sources. For the purpose of this study the main source of data will come from external secondary sources, mainly already existing research studies and reports published by various associations and companies as well as books. This data is supplemented with internal data offered by CPI Fluid Engineering. To support the data of the reports depth interviews with selected OEMs will be taken to gain an insight into the most recent technological developments.

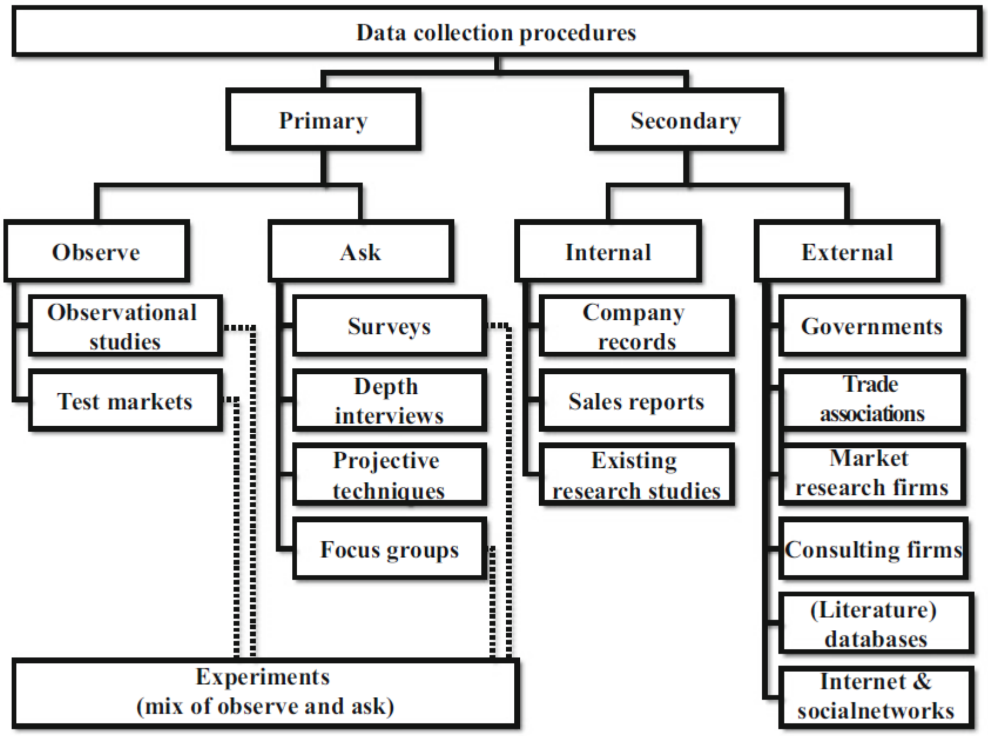

Figure 47: Overview of primary and secondary data sources[89]

7.4.4 Data collection

This is the practical part of the market research process where the researcher collects the data from the planned sources. Often this part contains the most troubles because of the great number of human interaction and the unpredictability of these interactions as well as various other practical problems.

These problems may range from questions how to measure not obvious relationships with the tools available and how to get certain people to respond especially people in management and specialists. The utilization of already established personal contacts by the researcher or his client can help tremendously in that regard.

[89] Sarstedt, M.; Mooi, E. , p. 48

7.4.5 Data analysis, interpretation and follow-up

When the amount of collected data is sufficient for the research and can produce significant statements the data analysis process begins. Especially for quantitative market research the application of sophisticated statistical tools is common to reveal relationships and to prove hypothesis.

For the presentation of the results it is the researcher's task to summarize and communicate the findings and recommendations in a clear and unbiased way.

Sometimes a follow – up of the research is necessary to observe changes over time in a particular research field, this becomes especially important in fast moving consumer markets. Usually in such cases the market research is more of a continuous effort rather than a selective sampling.

7.5 Quantitative and qualitative data

In the chapter above the market research process was explained with some introductory discussion for each step along the way. The data that is collected in market research can differ for different market research requirements.

Generally data is distinguished between quantitative and qualitative data. Quantitative data is data which can be measured and usually consists of numerical values that can then be analyzed by statistical methods. Qualitative data on the other hand is more diverse in its definition as it often contains non-numerical information, concepts and relationships. Typically such data can be found further upstream the research design process when it is not yet clear what should be measured later on.

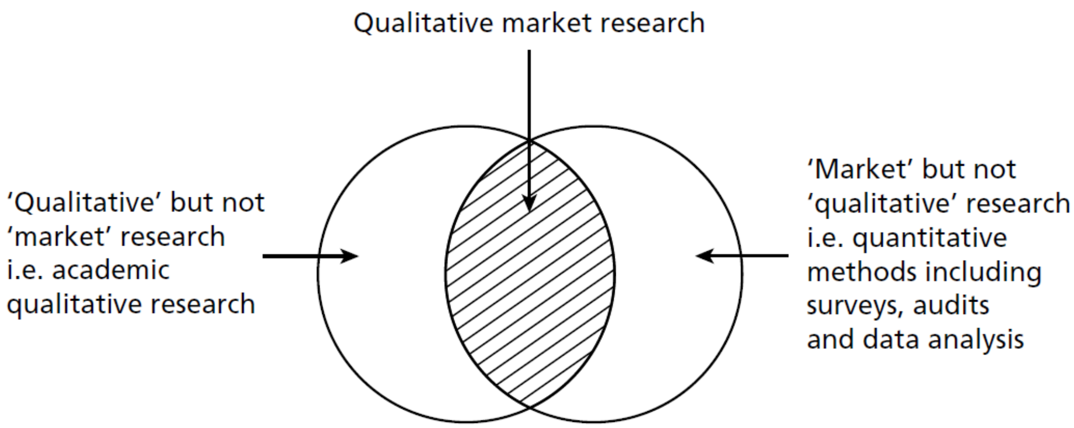

Figure 48: The difficult definition of qualitative market research[90]

[90] Imms, M.; Ereaut, G. (2002), p. 2

Taking the concepts from quantitative research applied to this study in a sense the goal is the gain the most knowledge from a relatively small sample size as the returns diminish for the additional efforts to collect data (Figure 49, Figure 50).

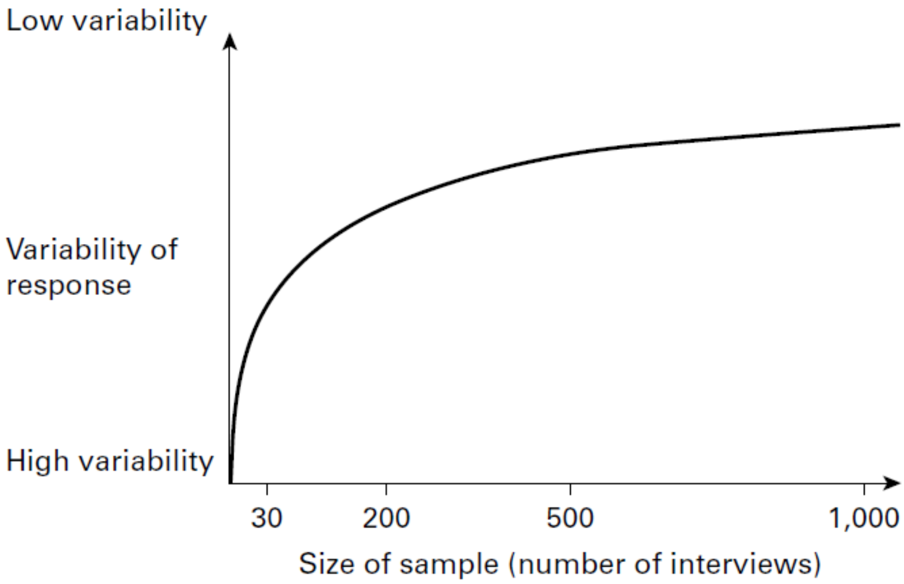

Figure 49: Relationship between variability and sample size[91]

The widely known Pareto principle or 80 – 20 rule also applies in this case. Interviewing fewer big players gives the best result with the restricted timeframe and budget of this study.

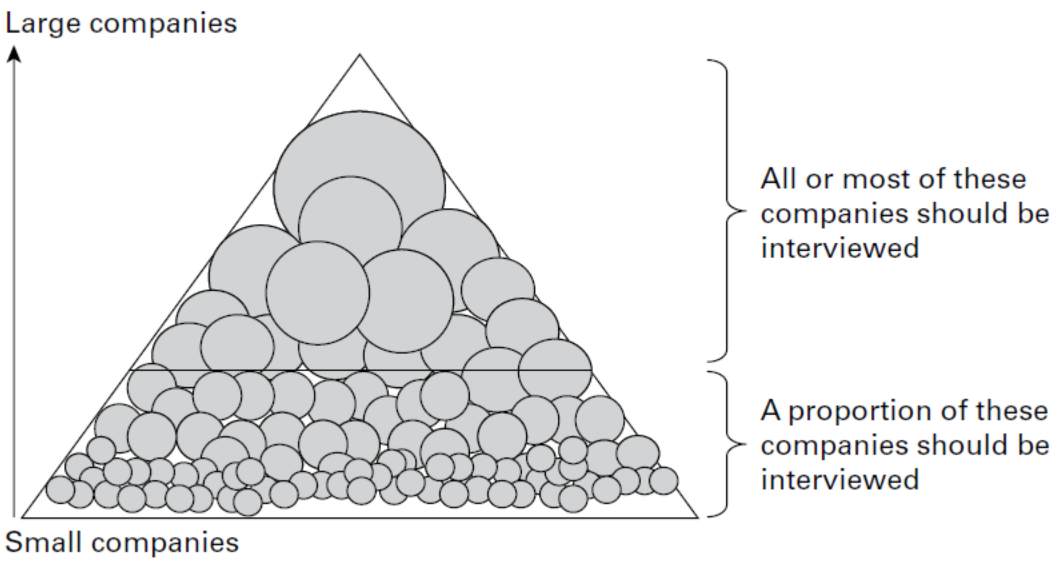

Figure 50: The importance of big companies in a B2B market research study[92]

[91] Hague, P. et al. (2016), p. 113
[92] Hague, P. et al. (2016), p. 122

7.6 Market research tools

To gather the needed data there are several tools available as shortly described before. The most relevant one for this study will be described in more detail in this section.

In order to gain a basic understanding about the already published a thorough literature review is done on the many case study regarding efficiency improvements in compressor systems.

After that the data collection phase is finished with interviews of OEM personnel either via telephone or as a set of questions answered by email or similar means of online communication. The tool used for each OEM depends highly on the contact that can be established with each company and if relevant people are available and willing to contribute.

As this study is restricted in terms of time window and budget there are no other realistic options available for the data gathering process.

7.6.1 Desk research

Desk research also known as secondary research is the process of collecting, summarizing, collating existing research instead of doing own research work in the form of field work or experiments[93].

Energy efficiency for compressor systems is a big and important topic in the industry at the moment. As a result a substantial amount of information is already available through reports, books and industry papers.

Desk research is a method that can reveal a great amount of information that is already in the public domain or available internally in the company but is poorly structured or has been overlooked in the past.

Usually research providers focus on primary research because of the better plannable results and the profits that can be made in that segment.

7.6.2 Depth interview

The interview is a personal interaction between the researcher and the respondent and they exists in several forms. Although it can sometimes seem quite casual the main focus for the researcher is to gain valuable information from the respondent who in most B2B studies is an influential person whose opinion likely is significant for the study.

As already mentioned before the market research processes can be either of a quantitative or a qualitative nature or be a mixed type. Consequently the ideal type of interview is either loosely structured, semi – structured or structured (Figure 51).

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[93] Crouch, S.; Housden, M. (2003), p. 22; (Retrieved: 07.04.2016)

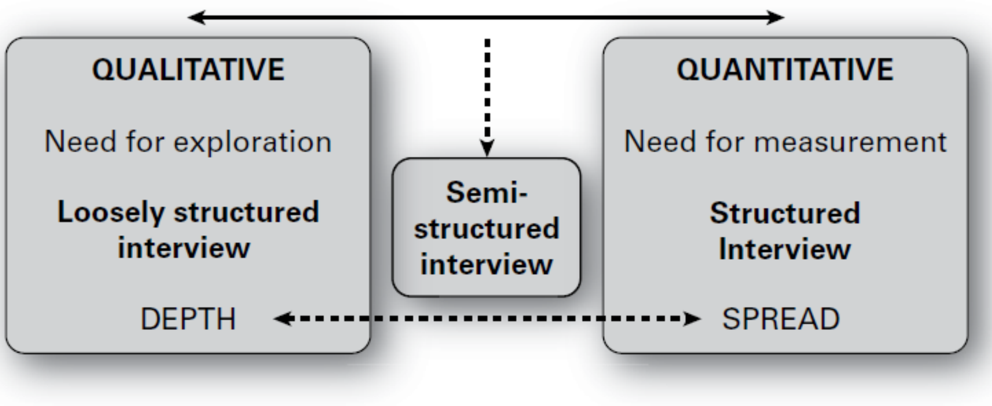

Figure 51: Different interview types depending on the type of research[94]

Each of these types has areas where they fit in the best and are of most use and convenience for both the researcher and the respondent. Those types often come with a preferred method of administration as shown below.

Table 10: The three different types of interviews[95]

Questionnaire type	Area of use	Method of administration
Structured	Large, quantitative studies	Telephone/face to face/online
Semi-structured	Qualitative consumer studies, business-to-business studies	Telephone/face to face
Unstructured	Qualitative studies	Depth telephone/face to face/ group discussions

Interviews often compete with the technique of focus groups due to a variety of reasons mainly cost and complexity in execution. However interviews are preferred in situations where the respondents are geographically scattered, the cross – interaction with respondents is not wanted by the researcher due to the mutual influence of the group's answers, more attention has to be given to each individual which would not be possible in a group setup or sensitive information is shared which should stay anonymous.

[94] Hague, P. et al. (2016), p. 81
[95] Hague, P. et al. (2016), p. 128

The interviewing process is very dynamic and heavily depends on the skills of the interviewer. A good interviewer is a good listener and only slightly guides the conversation in the intended direction. It is his job to make the respondent comfortable so that he gives good and meaningful answers. Figure 52 shows the general emotional state of the respondent during the interview. At the beginning it is often unclear for the respondent if he has the ability to answer the questions satisfactorily shown with increased anxiety and discomfort. In addition the respondent is often uncertain of the interview process and the associated handling of information offered to the researcher. This makes it essential for the interviewer to maintain a confident and professional standard and adhere to the ethical standards set by many of the market research institutions.

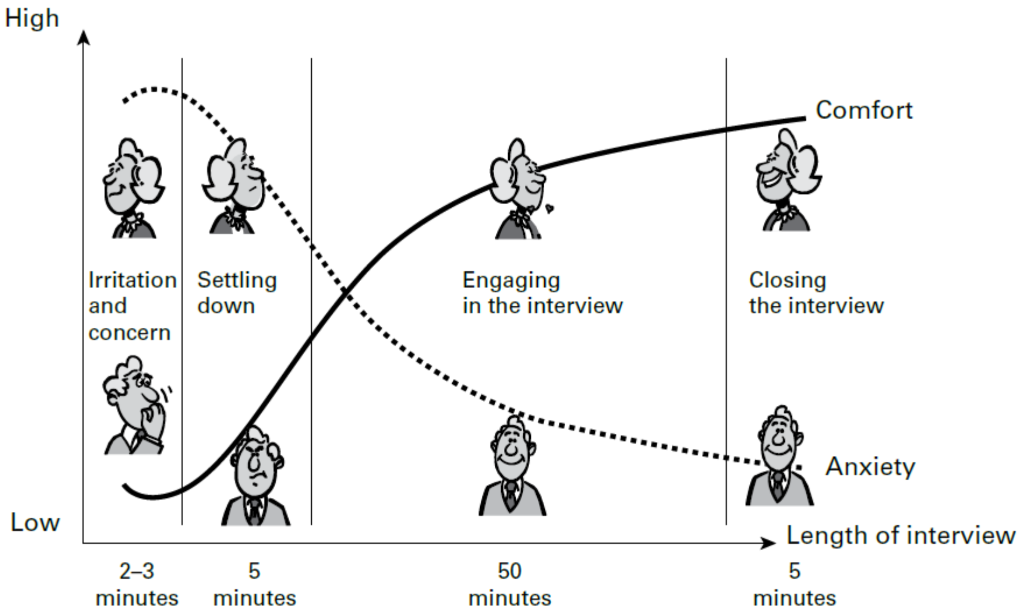

Figure 52: The emotional state of the respondent throughout the interview[96]

No matter what the topic of discussion is, it is the interviewer's responsibility to foster an open and productive conversation by following a sequence of questions that appear natural and build the conversation in depth and open up the follow-up conversation rather than to close the discussion down. Hence there are a couple of general guidelines that show what should be avoided when asking questions in an interview[97]:

- Long and complex questions should be avoided as it could confuse the respondent to how and what to answer exactly. It can also cause difficulties in the evaluation and analyzing phase due to the less obvious structure in the answers.
- Too vague questions should also be avoided because they leave too much room for interpretation in the respondents' side and the answers could lack comparability. Researchers should be aware of unclear terms and should therefore clearly define them for the respondents in order to avoid this confusion.

[96] Hague, P. et al. (2016), p. 87
[97] Hague, P. et al. (2016), p. 81 ff

- The use of technical or industry jargon has to be evaluated carefully before conducting an interview. This might be of a lesser problem in B2B interview but can still cause unintended complications especially if the interviewer is ill – prepared for that.
- Leading questions that prompt or encourage the answers wanted should be avoided as it cannot be evaluated if the answer was legitimate and honest. The goal is the gain unbiased information from the respondents.
- Aggressive or threatening questions should also be avoided as they can easily break the established rapport to the respondent and discourage him from further cooperating.

The conducted depth interview revealed no new insights into the compressor market trends and the willingness of professionals to participate in more interviews was not given. To get a wider view of opinion over a greater spectrum of the compressor industry an online questionnaire was chosen. The questionnaire is a more structured way to extract information from interviewees. It is designed to be send out to a much larger group of people and get more responses due to the relatively short answering time compared to depth interviews. The questionnaire focuses on the key aspects that are sought after for this study and hence allows extract relevant information with a much higher response rate than would be possible with depth interviews. The details on how the questionnaire is designed can be found in chapter 9.

8 Secondary Research

Energy efficiency is a more and more important topic in the compressor industry. Substantial amounts of case studies, energy efficiency reports and guidelines have been published in the past years by different energy agencies, consultancies and other industry stakeholder. In this chapter the most popular energy efficiency measures for compressed air and refrigeration application will be discussed and compared. Due to the wide variety of compressor systems, sizes and applications generalizations on savings potentials can be difficult.

8.1 Variable frequency drive

The variable frequency drive is an electronic control board which controls the frequency of the electric motor. It allows to run the motor at part-load and overcomes the limitations of simple on/off operation. This relatively simple upgrade is often mentioned in energy efficiency literature. VFDs do not only find direct application at the compressor but also in other parts of a system such as evaporator or condenser fans and cooling towers.

Without VFDs electric motors are dependent on the frequency provided by the grid. This frequency defines the speed when the motor is turned on. The VFD allows to reduce the frequency for the motor hence allowing it to run at part-load. The alternating current (AC) is transformed into direct current (DC) by the VFD control board. Then the controller puts out a pulse width modulated signal in accordance to the desired frequency at the motor (Figure 53).

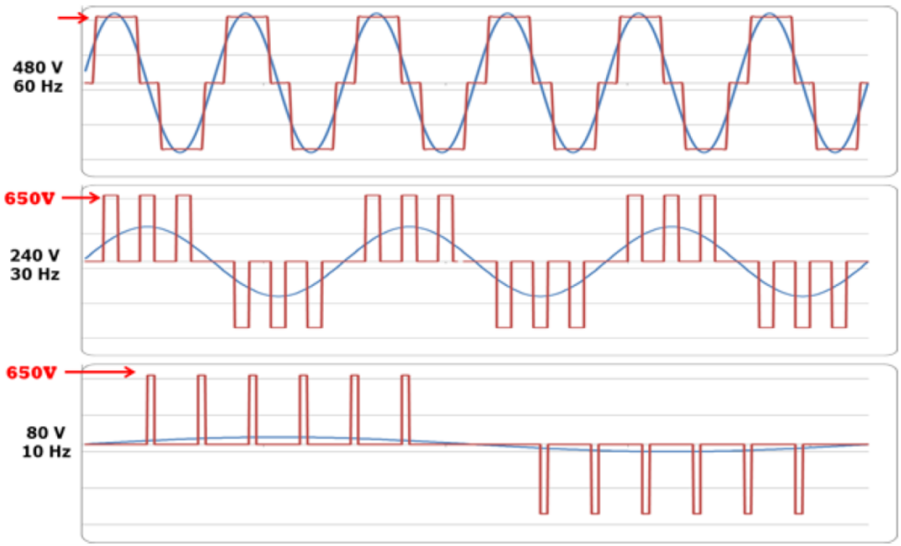

Figure 53: Working principle of a VFD[98]

[98] Bruno, S. (2014), p. 2

The application of the VFD allows to utilize the greater part-load efficiency of it compared to other control methods (Figure 54). In systems with varying demand the addition of a VFD on the peak load compressors can save substantial amounts of energy. However the usefulness of a VFD has to be determined from system to system as for example the addition of a VFD on a base load compressor only decreases the overall energy efficiency as VFDs as a power electronics component itself is not 100% efficient.

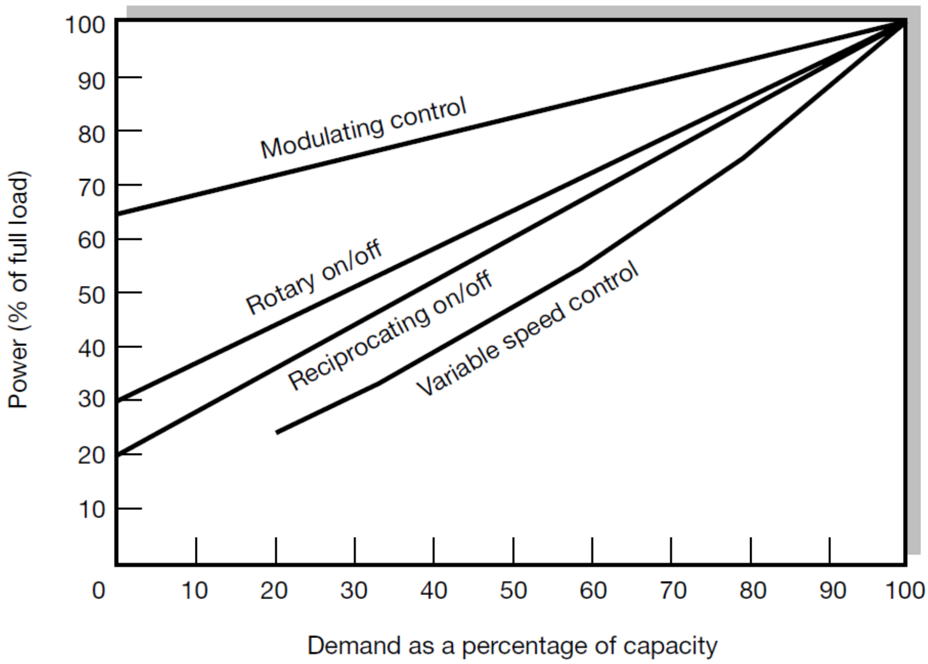

Figure 54: Comparison of VFD part-load operation to other types of operation[99]

[99] ETSU et al. (1998), p. 28

8.2 Heat recovery

Compressor systems emit the majority of their input energy as heat. To further increase overall system efficiency waste heat can be recovered and used as process heat or turned into electricity. Waste heat comes in different qualities whereby the heat rejected by compressor systems is generally classified as low grade waste heat. To recovery the heat several options are available. The most common use is the direct use of the waste heat as process heat. This allows for savings due to reduced heating efforts. Another method is to turn the heat back into electricity. Typically this is done by an Organic Rankine Cycle.

8.2.1 Heat recovery as process heat

The most economical use of low grade waste heat is the direct recycling of the heat without much additional equipment. Depending on the amount of available heat and the overall situation of ambient temperatures and heat requirement in the factory an additional heat pump can be used to upgrade this low grade waste heat to a higher grade more economically than producing it directly by a boiler. Typical uses for low grade waste heat are[100]:

- Pre-heating boiler feed water
- Heating combustion air
- Pre-heating HVAC fresh air
- Process heating or pre-heating
- Desiccant regeneration
- Wash water systems

8.2.2 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is a system to generate electricity from waste heat. It uses an organic fluid with a boiling point below water-steam. Generally ORC is only economical in larger systems where the waste heat is of higher grade hence the ORC efficiency is greater and where the amount of heat is also substantial enough to justify an ORC upgrade. If the need for heat is given studies have shown that the economic value of direct heat recovery or upgraded heat by heat pumps is between 2.5 and 11 time higher than electricity generated by an ORC[101].

[100] O’Brien, D. (2014), p. 4
[101] van de Bor, D. et al. (2015), p. 872

8.3 Lubrication

Proper lubrication of rotating equipment makes sure that friction in the system is reduced. This has two profound advantages, reduced heat creation due to friction and minimized wear on the equipment. Reduced heat creation has an immediate effect on energy efficiency and can be seen by a reduced energy consumption of the equipment. Typically this change is measured directly as reduced power draw at the electric motor. Especially for high performance synthetic lubricants reduced lubricant replacement and increased maintenance cycles lead to reduced maintenance costs after upgrading the lubricant of the system. Although reduced wear and hence reduced maintenance cost and increased reliability have potentially large impacts on savings it is more difficult to quantify exactly before making investment decisions. Therefore the immediate savings seen by lowered energy consumption are very important to justify a lubricant upgrade.

In a study done by Royal Purple the energy savings effect of lubricant upgrades on compressors was tested and quantified[102]. It was conducted on mostly ammonia refrigeration compressors where to most common compressor type were screw compressors (Figure 55).

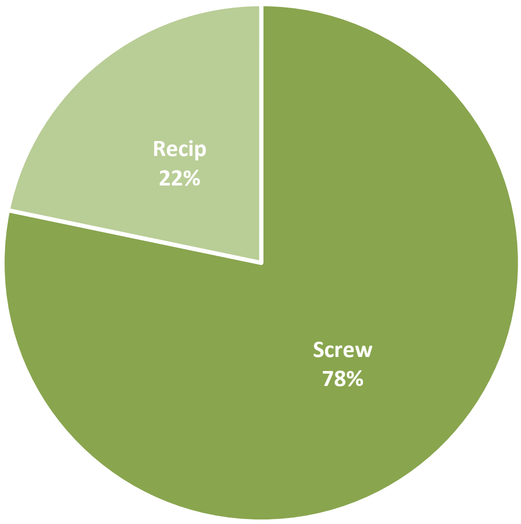

Figure 55: Represented compressor types in the study

The range savings that could be achieved varied relatively much between different compressors (Table 11 and Figure 56). On average an immediate reduction in energy consumption of around 10 percent could be measured. When the large portion of energy that is consumed of the lifetime of a compressor is taken in account this savings, even small ones can have large cost saving as a result. This shows how important proper lubricant design is for a system. Treating lubricants as a commodity can be an expensive mistake for end users. In addition to energy savings proper lubrication can have other beneficial effects such as seen in Royal Purple's study too. Oil carry-over into the cold parts of the refrigeration system could be minimized which prevented potential inefficient cooling.

[102] Royal Purple Synthetic Oil (2001), p. 5

Table 11: Detailed results of improvements after lubricant upgrade[103]

No.	Compressor Type	HP	previous oil	savings percent	savings [$/1000h]
1	screw	75	mineral	9.20	285.97
2	screw	300	synthetic	7.90	785.80
3	recip	300	synthetic	9.19	914.11
4	screw	400	mineral	11.48	2093.47
5	recip	200	mineral	11.53	955.72
6	screw	4500	mineral	6.37	974.18
7	screw	200	mineral	8.37	693.79
8	screw	700	mineral	7.46	1140.87
9	screw	350	mineral	8.48	702.91
10	screw	100	mineral	37.30	2102.42
11	screw	150	mineral	5.70	481.92
12	screw	200	mineral	9.30	1079.23
13	screw	150	mineral	9.00	727.36
14	screw	450	synthetic	8.10	1057.47
15	recip	75	synthetic	4.65	158.99
16	screw	75	mineral	7.80	339.43
17	screw	200	mineral	11.14	766.42
18	screw	500	mineral	10.32	1775.01
19	screw	500	mineral	11.11	1910.88
20	screw	250	mineral	16.97	1758.30
21	screw	400	synthetic	6.99	961.81
22	screw	500	mineral	8.21	680.53
23	screw	400	mineral	4.36	578.24
24	screw	250	mineral	11.27	1167.71
25	screw	400	mineral	9.42	1405.48
26	screw	125	mineral	8.48	527.18
27	screw	500	mineral	4.12	973.29
28	screw	450	mineral	22.77	5296.60
29	screw	500	mineral	4.20	522.21
30	recip	175	mineral	10.80	939.97
31	screw	500	mineral	13.80	2573.73
32	recip	75	synthetic	12.74	530.65
33	screw	450	mineral	9.00	1342.82
34	screw	450	mineral	6.19	923.56

[103] Modified from Royal Purple Synthetic Oil (2001), p. 5

This study showed that in such highly leveraged applications in terms of electrical energy. Upgrading the lubricant to premium synthetic product can still be a viable investment option despite the higher prices of synthetic lubricants.

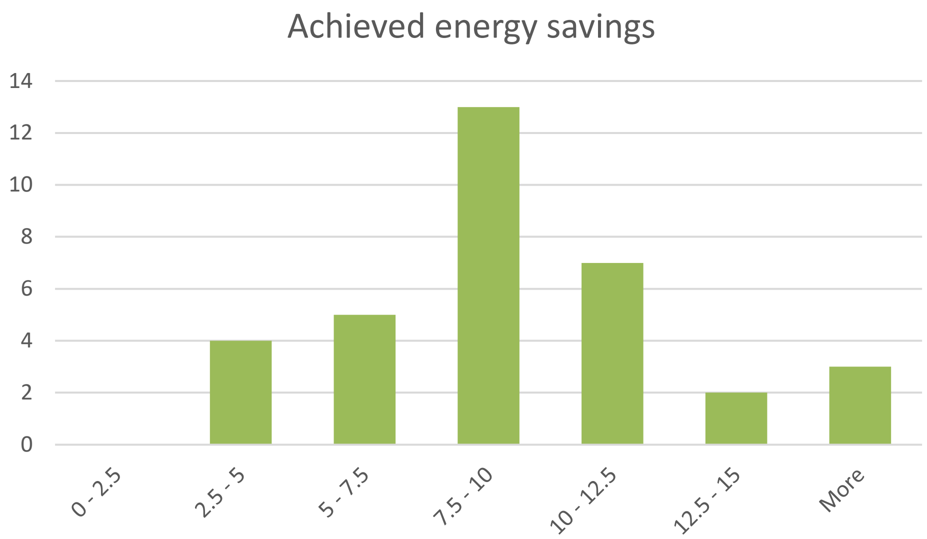

Figure 56: Percent of energy savings that could be achieved by lubricant upgrades

The cost savings achieved by reduced maintenance is more difficult to quantify and likely varies greatly depending on system size and operational setting. Such savings typically need longer studies and are less reliable to base investment decisions on.

Lubricant management is the challenge to design the lubricant for both energy efficiency and reduced wear. Low viscous lubricants might be more energy efficient but increase the wear and too viscous lubricants have increased viscous drag but lower wear. Depending on the application end users might value equipment reliability more that energy efficiency because downtime has much higher cost implications than some percent more energy consumption.

9 OEM survey

To gain an understanding about the opinions of future developments in the compressor industry an online survey is created and sent out to a wide range of compressor manufacturers. The surveyed companies are mostly in the compressed air and refrigeration business and sell products in all size categories. 130 compressor manufacturers could be identified globally with 386 contacts to which the survey is sent to. Further details on the survey setup and detailed results can be found in Appendix A.

The goal of this survey is to get opinions of as many respondents as possible. Hence the survey design is critical to encourage this “unmotivated” respondents to finish the survey. The majority of the contacts are comprised of sales engineers and sales managers. Hence, the survey is designed to be reasonably short so that respondents were able to complete it within 1-2 minutes.

Table 12: Basic survey data

Surveyed OEMs	130
Number of contacts the survey is sent to	386
OEMs geographic regions	Global
Type of respondents	Sales engineers Sales managers

The survey is carried out as an online survey using the well-established market research platform Survey Monkey. This platform allows for a convenient survey design and analysis. Based on secondary research and the general sentiment of the compressor market, 12 market leaders have been identified and surveyed separately to be able to isolate possible trends followed by the big market players (Table 13)[104].

Table 13: List of separately surveyed market leaders

Identified market leaders
Atlas Copco
Ingersoll Rand
Chicago Pneumatic
GE Energy
Bauer Group
BelAir
BOGE
Compair
Emerson
Frick
FS Elliott
Gardner Denver

[104] Allied Market Research (Retrieved: 29.11.2016); Global Market Insights (Retrieved: 29.11.2016); Grand View Research (Retrieved: 29.11.2016); QY Research Reports (Retrieved: 29.11.2016)

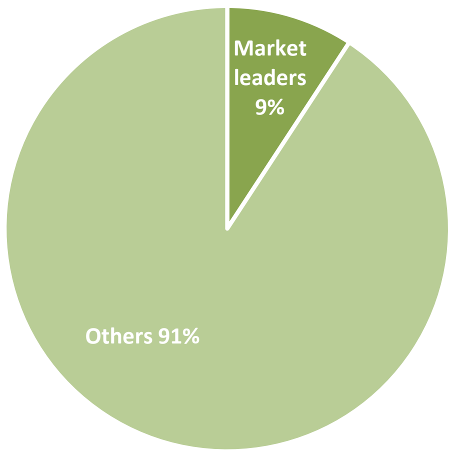

Figure 57: Ratio of sampled number of OEMs divided by market leadership

Due to the larger market share of those market leaders more contacts in the sales force could be established. Hence the ratio of surveyed people in those organizations is less severe as seen in Figure 57. About one quarter of the sampled people are working for market leaders which is shown on the figures below. This ratio stayed quite constant when comparing the number of sent out requests and received answers.

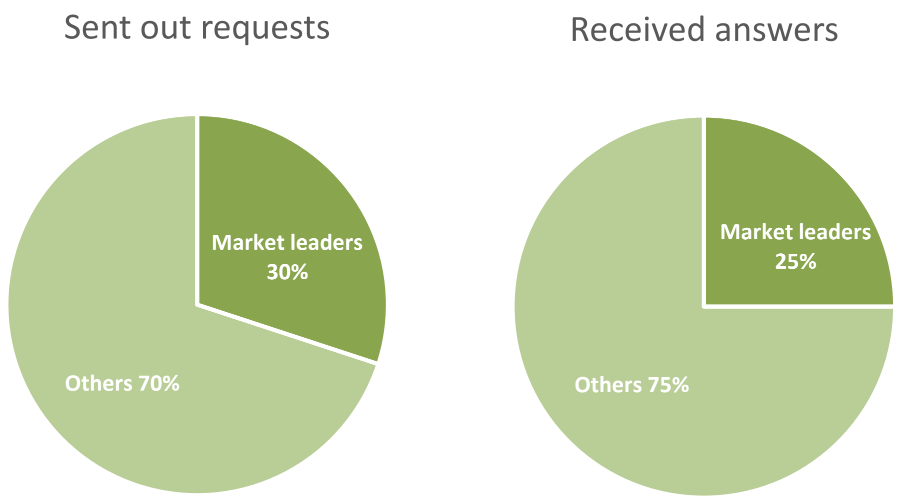

Figure 58: Comparison of sent out requests and received answers among the survey population

Overall a response rate of 8.3% could be achieved which is a reasonable rate for unmotivated B2B market studies (Table 14). Typically respondents in a business environment are busier than other respondents and in addition might not be willing to share information if there is no benefit to gain for them or their company. As the sample population is relatively small for this study, extreme care is given to the survey design in order to ensure high completion rates. The completion rate of a survey is highly dependent on the complexity and amount of asked questions. Due to the high value of each respondent opening the survey in the first place, it requires to structure the survey for maximum completion rate without sacrificing the survey objectives.

Table 14: Response statistics of the survey

	Market leaders	Others	Overall
Sent out requests	116	270	386
Received answers	8	24	32
Response rate	**6.9%**	**8.9%**	**8.3%**

A study done by Survey Monkey among 25000 surveys revealed several key factors contributing to a survey with high completion rates:

- The complexity of asked questions and the required cognitive expense to answer them can make a big difference whether a survey gets completed or not. It is generally a good idea to start with simple opening questions and increase complexity towards the end of the survey. Figure 59 shows the effect the type of open question has on the completion of the survey.

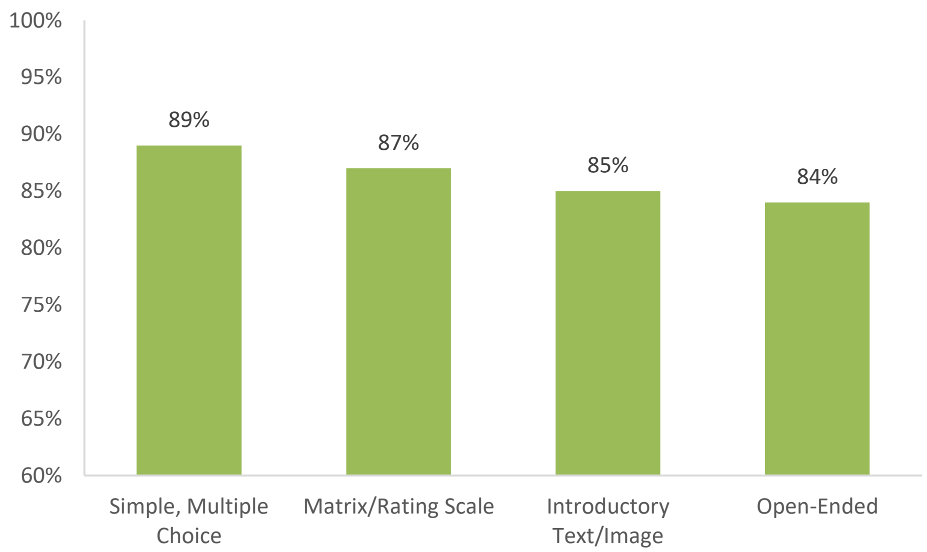

Figure 59: Completion percentage by type of opening question[105]

- The amount of information that is asked in a survey should not be too much, especially with unmotivated respondents and small population sizes where survey completion is of utmost importance. Respondents pay less attention and are less likely to complete surveys that seem long, monotonous or boring. The survey objective has to be clear and the details condensed down to those specific questions that are absolutely necessary. The study showed that with an increasing number of questions contained in the survey the completion rate decreased as more and more respondents "wore out" and eventually quit (Figure 60). Open

[105] Modified from Noble, K. (Retrieved: 20.12.2016)

ended questions such as text boxes should be kept to a minimum. In this survey the open ended questions were kept mandatory to incentivize the respondent to finish the survey even at the cost of possible less completed open ended questions. The likely increase in overall completion rate offsets this sacrifice.

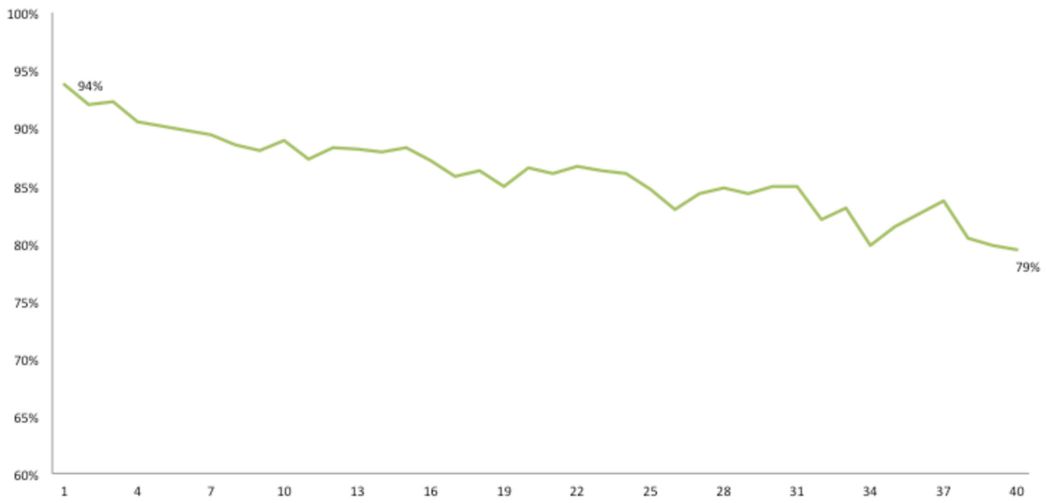

Figure 60: Completion percentage by number of questions[106]

- How questions are worded is another key aspects of a good survey design. The sentences should be simple but yet specific enough to avoid unnecessary guesswork by the respondent. The study conducted by Survey Monkey showed that an increased number of words in questions has a negative effect on the completion rate. If long questions have to be asked they should come at the end of the survey. How questions are asked can in many cases also influence answers in later questions. To ensure unbiased answers emotional and evocative phrasing of questions should be avoided. All possible answers should be anticipated to reduce the cognitive load on the respondent. For example the addition of an “other”, “not applicable” choice or making whole questions optional can achieve that.

[106] Noble, K. (Retrieved: 20.12.2016)

9.1 Survey structure

As shown in the previous chapter the survey is designed and structured with maximum completion rate in mind. Three different question types with increased answering difficulty were applied to ensure a low dropout rate (Figure 61). Overall nine questions were asked in the survey to keep the completion time relatively low. By doing this a median completion time of around 3 minutes could be achieved.

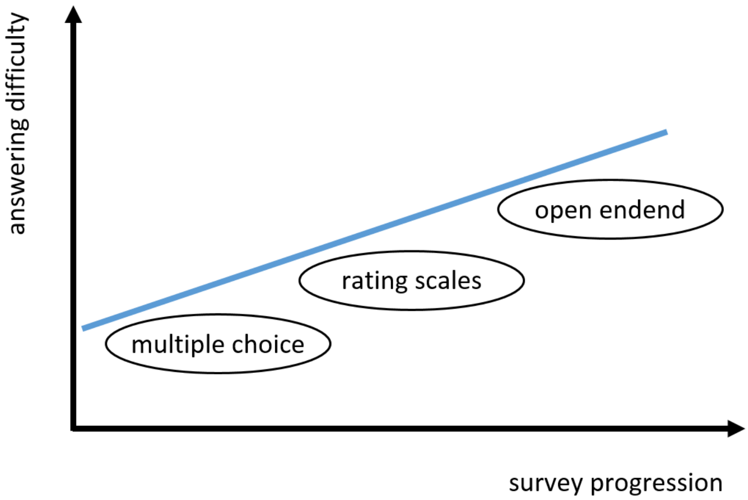

Figure 61: Overview of survey structure and question types

When organizations conduct surveys they typically have a specific set of questions that they want to have answered or at least make it clearer to them in which direction the answer might be going. Figure 62 shows the main objective and the breakdown into specific survey questions for this study.

The main objective of this study is to find out what the future will bring in the compressor market, what developments and technologies will drive the sales in the coming years and whether there is even a demand for more energy efficiency. This objective is broken down into three groups. First the respondent is asked about the current situation of his sales such as compressor type, size, intended compressor application and highest EE demand regions. The information gained here combined with market leader differentiation allows for later analysis of the data based on this properties. In the second group the respondent is asked more specific questions about the customer behavior which includes the demand for oil-free systems, the explicit demand for EE systems and the customers' willingness to pay higher prices for EE products. This questions are measured by a five step rating scale in the form of a rating matrix to get a statistical picture of the market situation:

(1)	(2)	(3)	(4)	(5)
Never	Rarely	Sometimes	Very often	Always

At the end of the survey an open ended question about the respondents' opinion on the market-driving technologies in the compressor market is asked. In this text box based question the respondent is able to describe where he or she personally thinks the market is headed based on their sales experience.

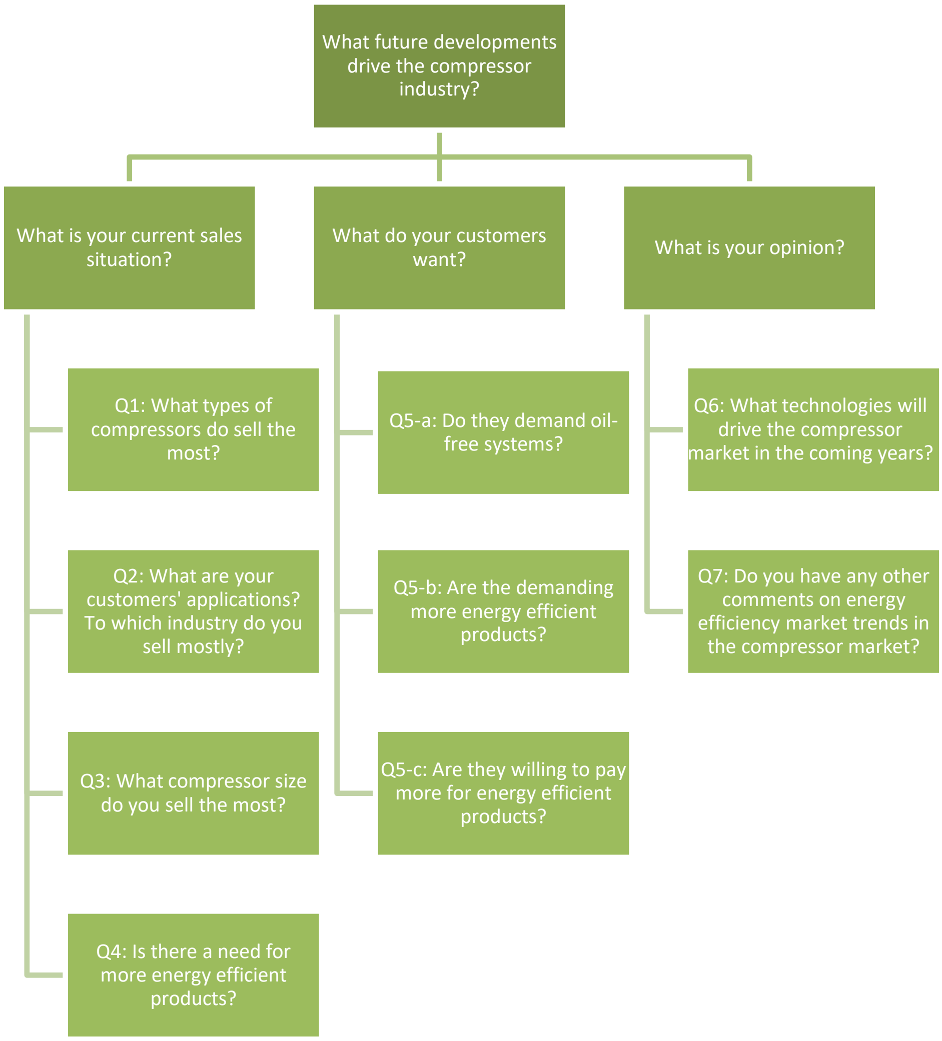

Figure 62: Structure of survey questions

Not all questions are set to be mandatory in order to prevent early quitting. As expected, completion rates between 70 and 90% for non-mandatory questions could be achieved. The last question being an additional comments box as practiced in most surveys achieved an unexpected high completion rate of 47%.

Table 15: Question types and setup

Question	Type	Mandatory	Completion rate
Q1	Multiple Choice	X	n/a
Q2	Multiple Choice	X	n/a
Q3	Multiple Choice	X	n/a
Q4	Multiple Choice		88%
Q5	Rating Matrix	X	n/a
Q6	Text Box		72%
Q7	Text Box		47%

Compressor Market - Energy Efficiency Trends

* 1. What is your most sold type of compressor?

- Piston
- Screw
- Scroll
- Vane
- other

* 2. In what applications are most of your sold compressors used?

- Compressed air
- Refrigeration / HVAC
- other
- not sure

* 3. In what size category are most of your compressor sales?

- < 1 hp (750 W)
- 1 - 100 hp (0.75 - 75 kW)
- 100 - 1000 hp (75 - 750 kW)
- > 1000 hp (0.75 MW)

4. Did you experience increased demand for energy efficient compressors/systems from specific geographic regions?

- Africa
- Asia & Pacific
- Europe
- Latin America & Caribbean
- Middle East
- North America

* 5. How often do you experience ..

	(1) never	(2) rarely	(3) sometimes	(4) very often	(5) always
.. customers specifically requesting energy efficient products?					
.. customers willing to pay higher prices for energy efficiency products?					
.. demand for oil-free compressors?					

6. In your oppinion what technology/innovation in compressor systems will drive the market of energy efficient products in the coming years?

7. Do you have any other comments related to energy efficiency market trends?

Done

Figure 63: Questions and layout of the online survey

9.2 Survey results

The survey was sent out to 386 sales engineers and sales managers in the compressor industry. Out of those, 32 responses were received. This makes a response rate of 8.3% which is an expected rate for small population B2B surveys.

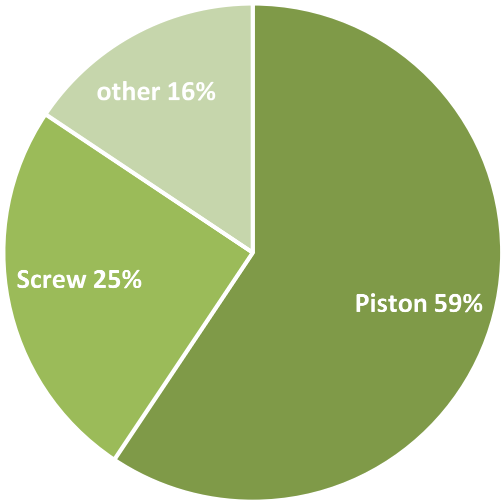

Figure 64: Majority of compressor sells reported by the respondents

The results show that a majority of the sold compressors of the respondents, almost two thirds, are reciprocating compressors. A quarter of the sales consists of screw compressors and the rest of all other types, mostly dynamic compressors as can be assumed by some respondents' comments.

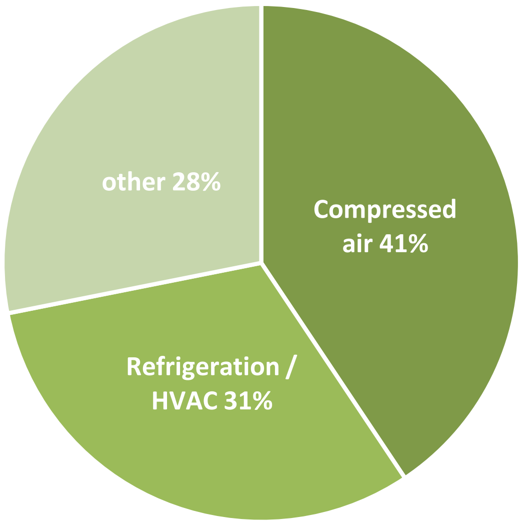

Figure 65: Most common application of sold compressors

Almost three quarters of the intended end-user applications are within the compressed air and refrigeration businesses which are the focus of this thesis. The reported size of sold compressors primarily lies in the category of medium sized compressors of 1-100 hp. Important to note it that this distribution does not represent the total number of compressors sold in each size category (Figure 66). It is more of an approximate view of how many OEMs are represented in each market size. From the figure below can also be concluded that the market for very small and very large compressors is likely confined to fewer manufacturers.

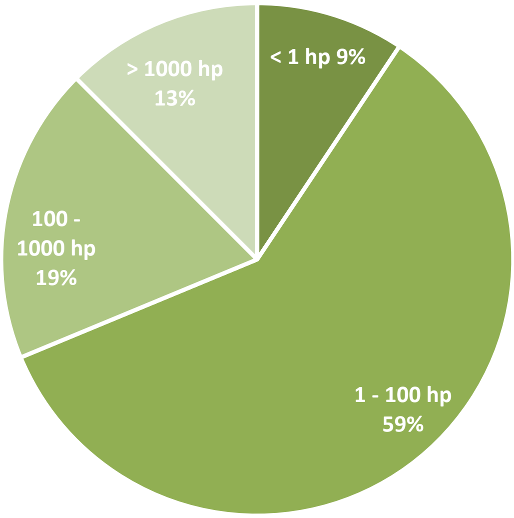

Figure 66: Most sold compressor sizes

The figure below shows the regions in the world where the respondents experienced high demand in EE compressor systems the most. This multiple choice questions allow for more than one regions to be selected. The largest demand for EE compressors overwhelmingly comes from Europe followed by North America and Asia & Pacific.

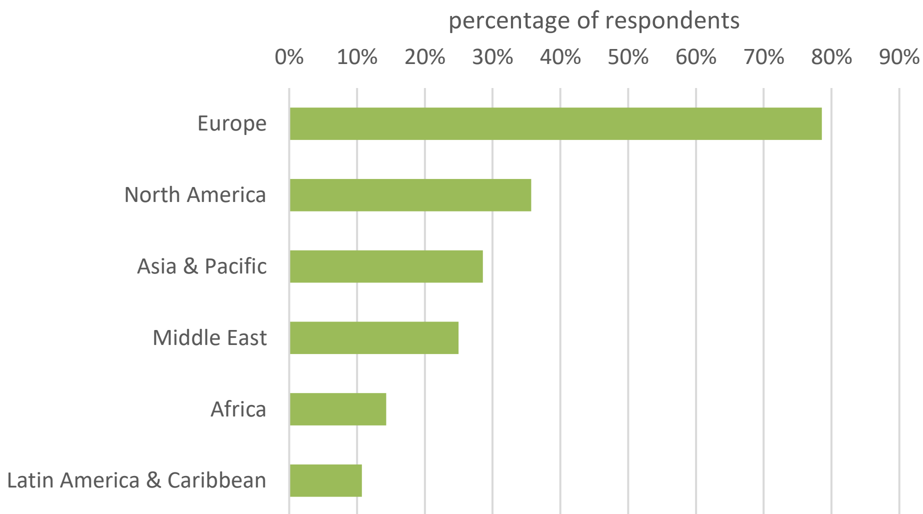

Figure 67: Regions where most demand for EE comes from

When looking at the average electricity costs for industry and household (Figure 68 and Figure 69) the majority of the countries with higher prices are located in Europe.

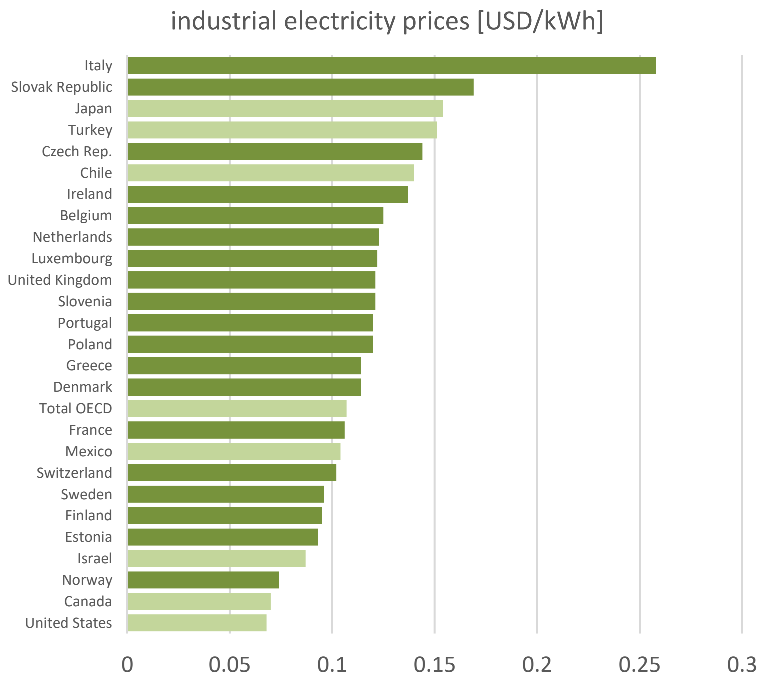

Figure 68: Average industrial electricity prices per country[107]

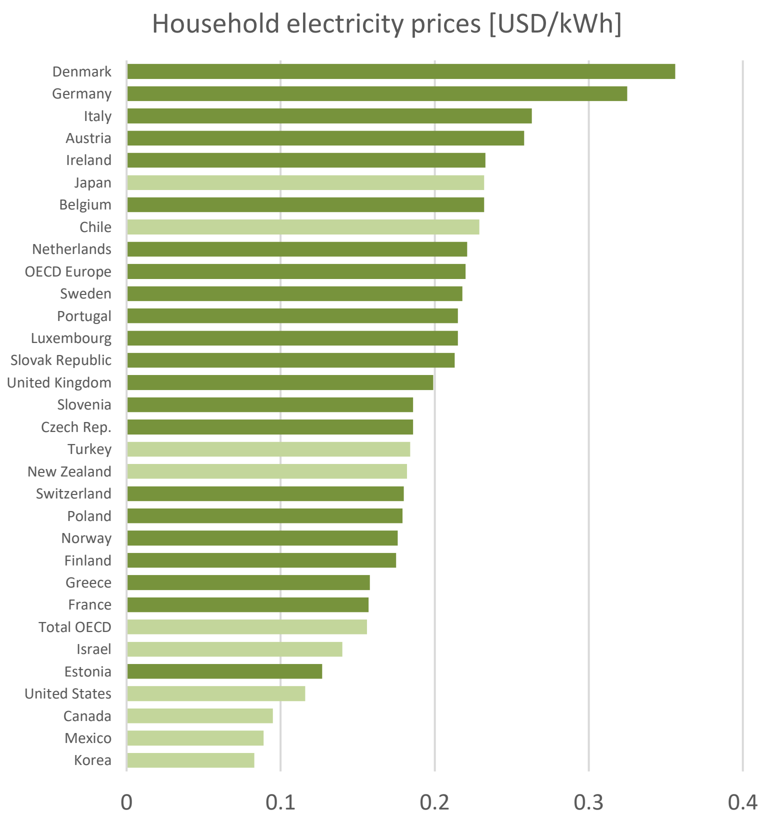

Figure 69: Average household electricity prices per country[108]

[107] International Energy Agency (2011), p. 28
[108] International Energy Agency (2011), p. 29

Consequently customers in such regions profit significantly more by investing in EE compressors opposed to customers in “cheaper” countries. As seen in previous chapters more developed regions have stricter regulations regarding energy efficiency, sustainability and environmental friendliness in many products. Especially the mandatory energy savings each year for companies in the European Union is likely to driver further demand in the coming years. Should the expansion of renewable energy developments and further regulations on energy conservation continue in those regions, which likely drives prices further upwards, sustained demand growth for EE compressor systems can be expected.
In the second part of the survey the respondents were asked about their experiences in day to day business activity with customers who are interested in compressor systems. They were asked on a five point rating scale how often they experience these situations. The trend showed that generally, over the entire population the demand for EE products is there and is more often than not specifically requested.

Figure 70: Customer demand for EE compressors

On the contrary the willingness to pay for the extra efficiency is less prevalent among the majority of compressor customers. This observation can also be confirmed by the open ended responses and the interviews with industry experts. Often tenders are won solely by the initial investment costs, disregarding the higher expenses to be incurred later.

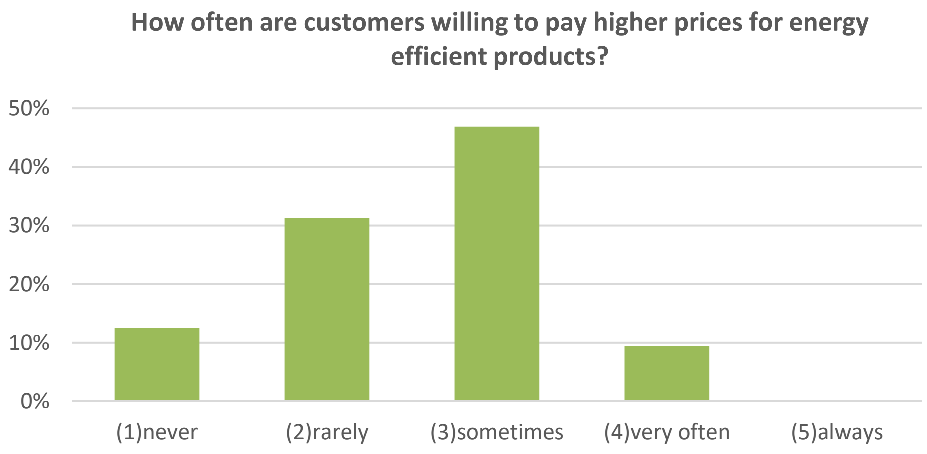

Figure 71: Willingness of customers to pay higher prices for EE compressors

Among the overall responses no trend about the demand for oil-free compressors can be observed. When differentiated by application however it becomes clear that refrigeration and cooling applications are typically not demanded as oil-free systems. This can be explained by the quality standards the compressed gases in air and process gas applications have to meet and that refrigeration systems are close-looped systems where the working fluid usually does not come in contact with the end product.

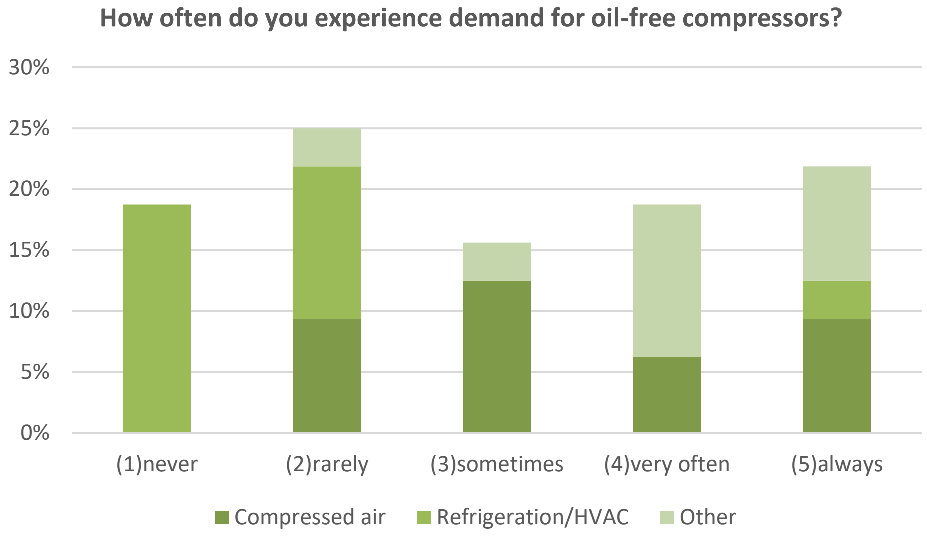

Figure 72: Demand for oil-free compressors differentiated by application

The open ended questions of the survey are intended to give an insight into the opinion and day to day experience and observed trends where the market will move in terms of more energy efficiency. The answers to this questions are unsuitable for a proper statistical analysis but can still give hints where the industry is heading. Figure 73 shows the frequency of mentions for specific technologies and market drivers that can be observed in the open ended answers. Based in this information several key interpretations can be made which are shown in the next section.

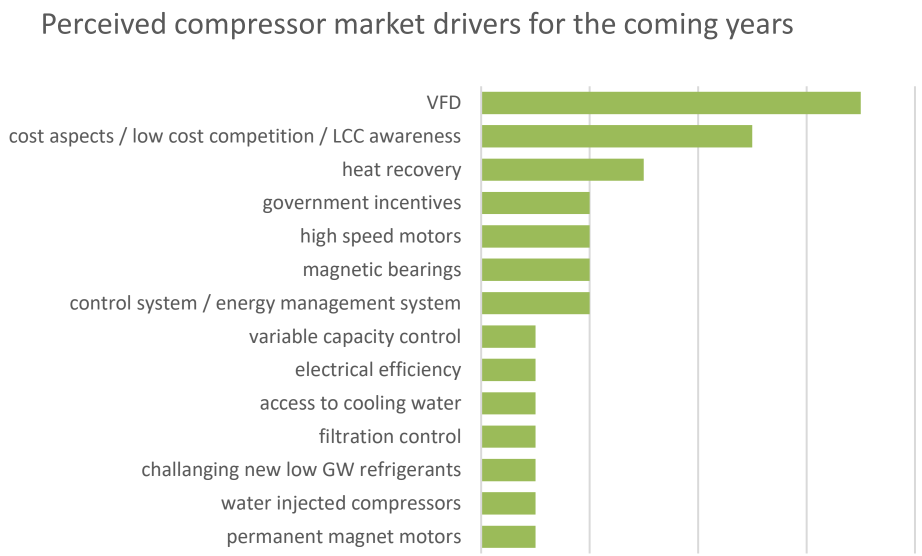

Figure 73: Frequency of mentioned key drivers for EE in the compressor market

Three key aspects stand out in the response analysis. Variable frequency drives, the cost aspect and heat recovery. By far the most often mentioned technology is the VFD. This includes drives for operating compressors at part load with reduced frequencies but also high speed VFD that can generate frequencies higher than those provided by the grid to drive motors at higher speeds allowing to use them without gearboxes at higher overall efficiency.

Many respondents also reported the cost aspect for many customers. They often go just for the cheapest product. Manufacturers of energy efficient and hence more expensive compressor have a hard time to compete with cheaper inefficient products. Selling the benefits of lower ownership costs and the likely unawareness of LCC of customers is seen as a challenge.

When all options to conserve energy are already applied a way to further increase overall system efficiency is the recovery of wasted energy in the form of heat. Because most waste heat in compressor systems is of low quality this option is not always suitable or economical.

It should be noticed that most of the mentioned aspects have little to do with the compressor itself. Many of the mentioned technologies are part of the overall system efficiency but not of the compressor efficiency itself. As also confirmed by the in depth interview the compressor efficiency likely cannot be significantly increased further but others parts of the system leave plenty of opportunity to reduce the inefficiency of gas compression operations.

9.3 Key findings

Based on the responses of this survey several key findings can be concluded:

- By far the most mentioned EE technology for compressors that will drive the market in the coming years is the utilization of VSDs. As also seen in the other research done for this study, VSDs are among the most effective ways to save costs. Upgrading systems with VSDs is often seen as one of the first measures with low investment costs and typically very shore payback periods. Furthermore is the use of VSDs size independent and can be use both in fractional and higher HP compressors.

- The second most often mentioned future technology with large savings potentials is the recovery of waste heat created by the compressor system. Unlike VSDs the application of heat recovery is more limited. Several key factors have to come together in order to make heat recovery a worthwhile investment. Because waste heat from compressor systems is generally of low quality the recovery of heat for process heat is preferred.

- In many cases price is still the key determinant for an investment. For OEMs that sell high efficiency products it can be difficult to compete with cheaper, inefficient Chinese products. The concept of life cycle cost gets in many cases ignored due to lack of responsibility or customers are unaware of it.

- The developed world seems to be the demand driver for energy efficiency. Especially in Europe the demand for EE measures is the highest as the EU pushes heavily on renewable energy and energy conservation.

- Permanent magnetized high speed motors are relatively new in the compressor industry and are seen as another way to increase efficiency of the system. There is less energy needed to magnetize the windings due to the permanent magnets and the high speed allows to run the compressor without a gearbox which reduces both friction losses and lubricants.

- Magnetic bearings especially in smaller compressors are expected to play larger roles in the coming years. They allow to increase energy efficiency by reduced friction and they do not require the lubrication of the bearing which saves lubricant costs.

- In applications with dynamic compressors and for example hydrocarbon gas (excluding methane), where densities can become much higher than air, efficiency is even more important because the energy demand increases proportionally to the density of the compressed gas.

- In applications involving cooling towers the water consumption is not to be overlooked. In hot and dry regions where access to water is either not given, very expensive or otherwise limited the access to cooling water becomes even more important than energy efficiency. The water consumption due to evaporation, drift and blowdown in cooling towers in larger application can be a significant cost driver.

- Government incentives are perceived as important part to drive the investment in new and to be replaced more efficient compressor systems. Especially where lower energy prices would otherwise discourage such investments.

- As also discussed in other chapters the greatest savings potential is not directly at the compressor. Overall system efficiency consist of many partial efficiencies. The inclusion of smart energy management systems and controllers is therefore a key aspect to operate systems as efficiently as possible by optimizing on parameters such as season, outside temperatures, demand peaks, etc.

10 Life cycle cost calculator

As discussed in previous chapters the life cycle cost analysis is a more and more common tool to calculate the life cycle costs of a compressor system that leads to an investment decision.
Secondary research as well as the survey results have shown that life cycle costing is an essential part in the decision making process of a compressor system's purchase or upgrade. In some cases however customers seem to be unaware of the concepts of TCO and LCC. Hence a life cycle cost calculator was created for this thesis to allow potential customers to quickly assess the investment on a life cycle basis. As CPI is in the synthetic lubricants business for compressed air systems it is important to convey the value of an energy efficiency upgrade to the customer and what big impact on life cycle costs small savings can make.
This tool is developed as an interactive web-based application that allows the users to input the data of their current system. Based on these inputs and some economic assumptions potential savings can be calculated if the system gets upgraded for more energy efficiency. The application is specifically developed for compressed air systems but can extended to refrigeration applications in the future. The calculated results of this application allows to evaluate potential upgrading options based on typical investment KPIs. Additionally the included energy flow diagram gives an overview where and how much of the input energy is wasted.

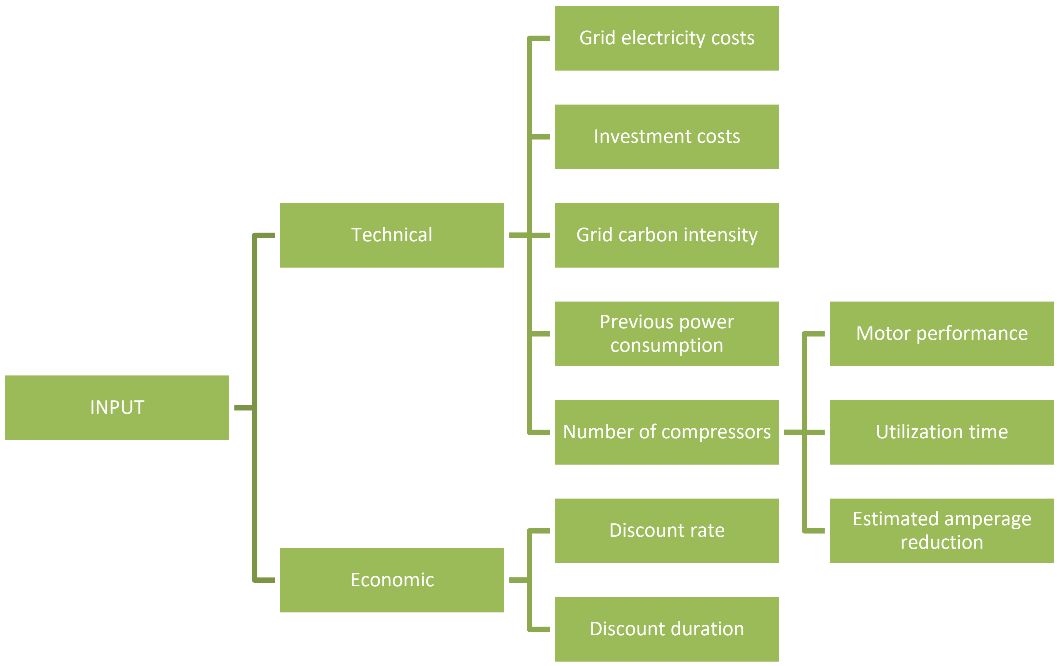

Figure 74: Structure of input parameters

The input parameters entered by the user can be grouped into technical and economic factors. The technical factors are related to the actual compressor system of the user and various cost components. For the economic parameters reasonable estimates or the organization's project assessment criteria can be used. Other parameters such as inflation rate and other cost escalators are neglected for simplicity reasons. Most compressor upgrade projects are chosen based on short to very short payback periods which is reflected in this model where unnecessary complexity is seen counter-productive for a value selling tool.

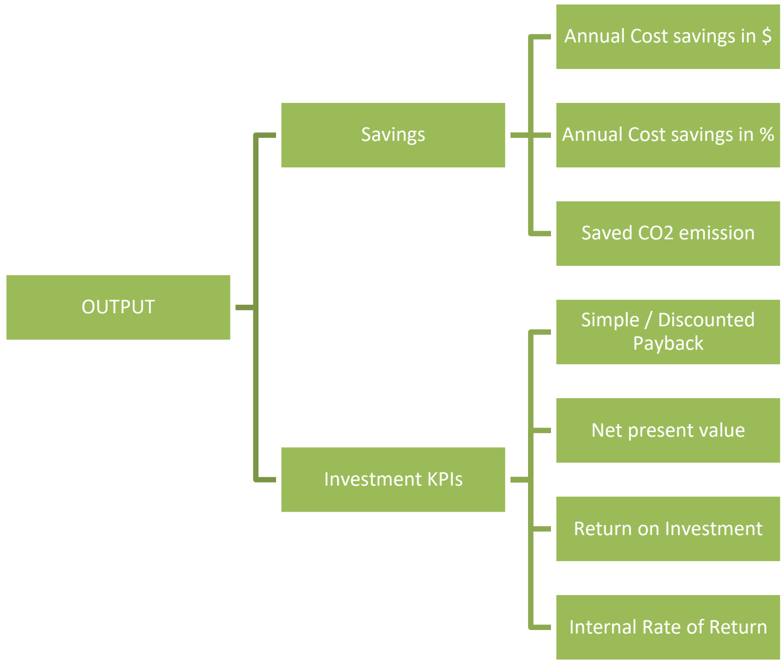

Figure 75: Structure of the output parameters

The outputs the user receives from the model can be grouped into savings achieved by the upgrade and typical investment KPIs (Figure 75). Based on those results the customers is able to quickly assess potential upgrading options and understand their impact on the total outcome.

The model outputs seen above are derived from the annual monetary savings which are calculated by the sum of all the energy savings estimated for each compressor.

$$S_m = C_E - C_G \sum_{i=1}^{n} P_i \cdot U_i \cdot \left(1 - \frac{E_i}{100}\right) \qquad (9)$$

S_m ... annual monetary savings [$/year]

C_E ... overall electricity costs of previous year [$]

C_G ... grid electricity costs [$/kWh]

P_i ... full-load motor performance of compressor i [kW]

U_i ... annual compressor utilization of compressor i [h/year]

E_i ... estimated reduction of electricity consumption of compressor i [%]

Figure 76 shows the layout of the application with the input fields at the top left and output fields on the top right. It allows the users to add and remove compressors in order to replicate their system. At the bottom of the application an energy flow diagram shows the users an estimate on how many kWh are wasted where to highlight potentials for further system optimization and heat recovery. The waste heat fractions used by default in this model are taken from typical compressed air systems and can be changed by the user in the expandable options panel. The gird carbon intensity chosen as default is the value for the US power grid and is also changeable to fit the users' situation.

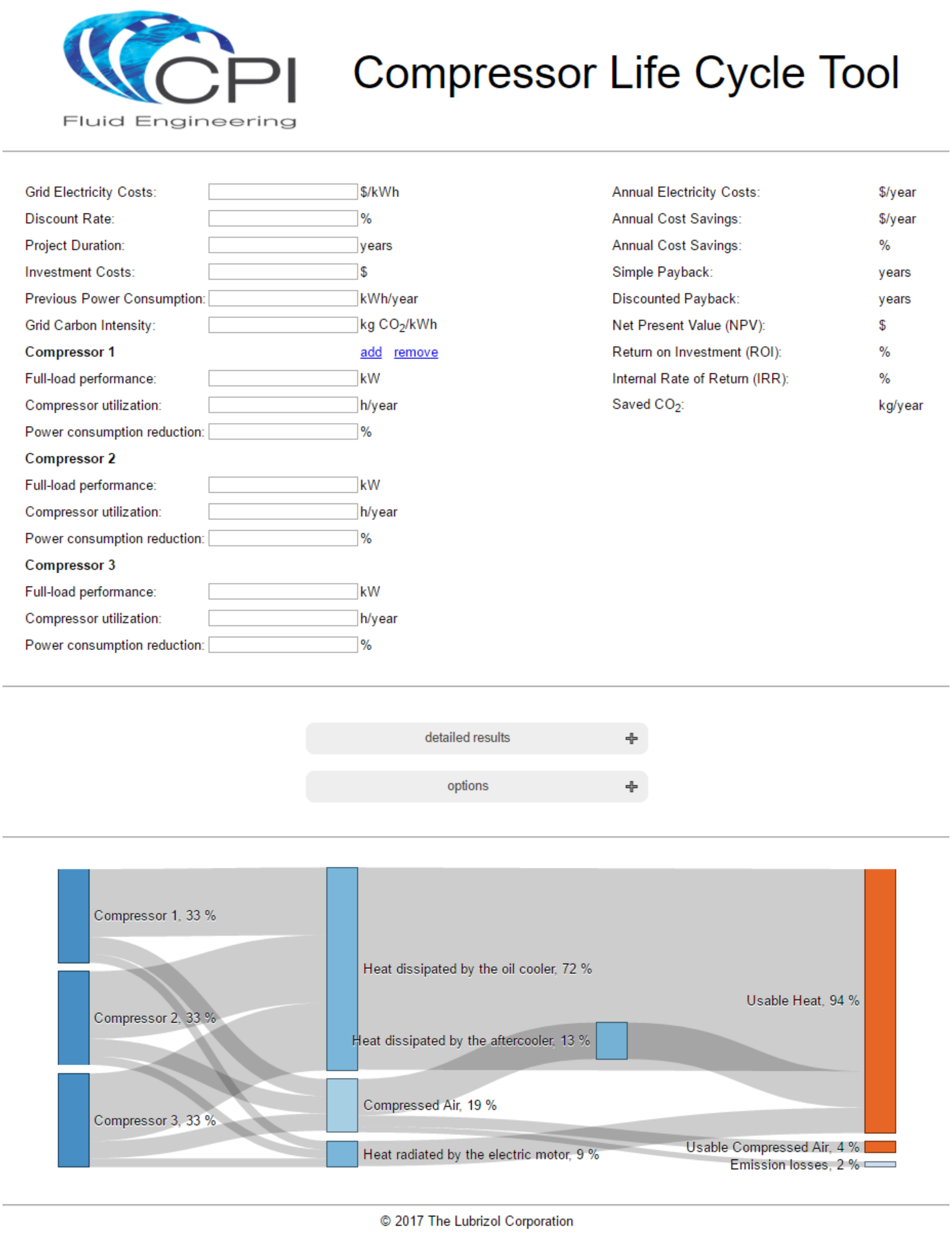

Figure 76: Layout of the web application

In the detailed results panel the users can see the detailed calculations presented in a table. It shows the cash flows created by the savings and can easily transferred to programs like Excel for further analysis.

detailed results +

Year	Investments	Savings	CF	CF cum	Disc.CF	Disc.CF cum
1	$ -85,000	$ 27,200	$ -57,800	$ -57,800	$ -57,800	$ -57,800
2	$ -	$ 27,200	$ 27,200	$ -30,600	$ 24,480	$ -33,320
3	$ -	$ 27,200	$ 27,200	$ -3,400	$ 22,032	$ -11,288
4	$ -	$ 27,200	$ 27,200	$ 23,800	$ 19,829	$ 8,541
5	$ -	$ 27,200	$ 27,200	$ 51,000	$ 17,846	$ 26,387
6	$ -	$ 27,200	$ 27,200	$ 78,200	$ 16,061	$ 42,448
7	$ -	$ 27,200	$ 27,200	$ 105,400	$ 14,455	$ 56,903
8	$ -	$ 27,200	$ 27,200	$ 132,600	$ 13,010	$ 69,913
9	$ -	$ 27,200	$ 27,200	$ 159,800	$ 11,709	$ 81,622
10	$ -	$ 27,200	$ 27,200	$ 187,000	$ 10,538	$ 92,159

Figure 77: Detailed results of example calculation

When the application is started an initialization routine is run. After that the program remains in a waiting mode and listens for inputs. If the user puts data into the model all calculations are updated and the outputs as well as the Sankey diagram are redrawn. If the necessary input data is incomplete the output fields remain blank until the first successful calculation is completed.

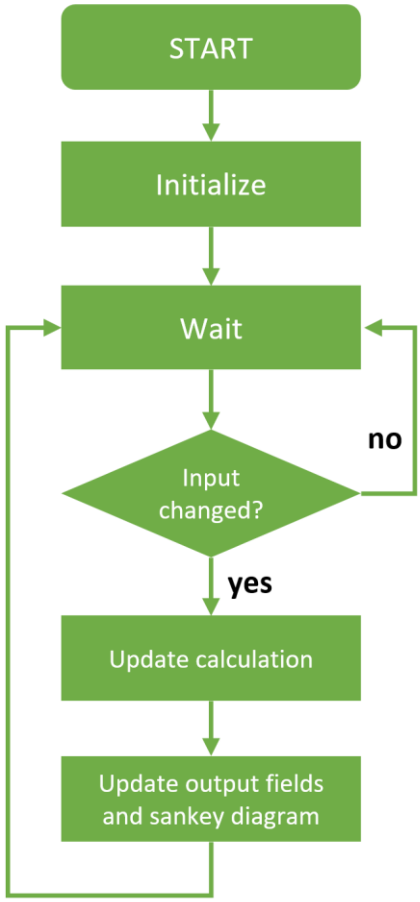

Figure 78: Simplified flow diagram of the program

11 Conclusion and outlook

Compressor systems are cornerstones of the modern world and can be found in almost every facet of life. They are hidden work horses for most economies and consume substantial parts of the global electricity production. Because of the inefficiency of gas compression a large portion of the consumed electricity gets wasted as heat and artificial demand. Due to the increased push for reduced carbon intensity and energy conservation and at the same time rapidly increasing demand for compressor systems, especially in the developing world manufacturers are continuously trying to improve the efficiency of their products. Additionally higher energy prices, emission penalties and increasing government regulations incentivize compressor customers to take the live cycle impact of their purchases more seriously and invest in more efficient compressor systems or system upgrades.

Goal of this thesis is it to focus specifically on the applications of compressed air and refrigeration. The current state of the industry should be analyzed in terms of technologies that are implemented to increase energy efficiency in such systems and what savings they potentially can achieve through mapping the different approaches and technologies by their effectiveness to harness efficiency improvements and investment attractiveness as well as applicability. Further a calculator application should be developed as a value selling tool that allows customers to define their system and calculate saving potentials based on a system upgrade for a multi-compressor system. To understand the future growth prospects of the compressor industry in terms of energy efficiency a market study should be conducted to obtain an insight into the anticipated growth potentials and upcoming technologies of compressor manufacturers.

In the first part of the thesis an overview is given about the relevant types of compressors and the various details of gas compression, compressed air and refrigeration systems. For the practical parts of the thesis introductions are given to life cycle costing and market research methodologies. Energy efficiency is a very important topic in the compressor industry and has increased in relevance in the last years. A large amount of data is available on this topic published by different energy agencies and compressor efficiency interest groups. To analyze the potential savings for the most popular technologies the choice was made to conduct secondary research and analyze the large amount of published data such as case studies and best practices. Based on this data the current state of technology and its potential is shown. The developed calculator application was designed as a web-based application that allows users to quickly assess potential upgrading projects in terms of monetary and emission savings. The underlying model is based on simplified life cycle costing principles in order to provide the users with a holistic estimate of what they can expect of a lubricant upgrade. To gain further expert opinion on the future of the compressor industry two types of market research tools were applied. In depth interviews and structured online surveys. Conducting depth interviews showed that no relevant new information could be gained by that. Further the willingness to participate in a B2B depth interviews is very low. Therefore the use of an online survey was pursued further for this thesis as it enabled to collect responses of a much larger group of people in the industry and hence allows to give more statistical relevant predictions about the future growth potentials.

The results show that there is still a lot of unrealized potential for energy savings in the compressor landscape. Both the secondary research and the questionnaires confirm that often the end-users are unaware of the potentials that energy savings can bring over the lifetime of a system or after an upgrade. It was further shown that a huge challenge for compressor manufacturers is the unwillingness of customers to pay premiums for more energy efficient products. In some market segments the competition of low cost, low efficiency compressors is fierce and makes it hard to compete with higher priced and more efficient products. When considering the efficiency of a compressor system this efficiency consists of many different partial efficiencies. The research has shown that most improvements in overall system efficiency can be made in places other than directly at the compressor. By far the most popular energy efficiency measure is the utilization of a variable frequency drive. It allows to run compressors at part-load which can achieve large savings for little initial investment. Most VFD projects have a very short payback period and are therefore very attractive investments and can easily retrofitted in most motors. Many case studies showed that EE projects in poorly designed systems can have immediate payback such as fixing leaks, lowering system pressure and eliminating artificial demand. In larger systems the recovery of waste heat is deemed as a promising growth technology. Recovery of such a low quality heat however is more costly and not always applicable. Such a technology is expected to make financial sense if all the other low hanging fruits mentioned above are already taken. By a majority of the survey respondents the developed world shows the largest demand for EE products. This can be explained by the increasing electricity costs and stricter regulations which make investments in EE products a good choice. The savings calculator was developed as a first prototype for compressed air systems. To develop it further customer feedback is required to be taken into account. Choices whether complexity of the underlying model should be increased or decreased can be made based on this feedback. Results obtained from CPIs compressor laboratory can possibly implemented in the future to more exactly convey savings potentials that can be achieved by CPIs lubrication products.

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Appendix A: OEM data

Table 16: List of surveyed compressor OEMs

OEM	Country	Weblink
A.D.I ATACHI CORPORATION SDN BH	Malaysia	http://www.adachi.com.my/
ABAC	United Kingdom	http://www.abacaircompressors.com/
Adicomp Srl	Italy	http://www.adicomp.com/
Aerzener Maschinenfabrik GmbH	Germany	https://www.aerzen.com/
AF Compressor	Belgium	http://www.afcompressors.com/
Air Line Compressori	Italy	http://www.aircompline.it/index.php?main_page=index&language=en
Air Squared	USA	https://airsquared.com/
Air Systems International	USA	http://www.airsystems.com/
Aircom S.r.l.	Italy	http://www.aircomsrl.it/eng/index.php
AIRKO	Austria	http://www.airko.at/
AIRMAN HOKUETSU Industries CO.,LTD.	Japan	http://airman.co.jp/index_e.html
Airpol	Poland	http://www.airpol.com.pl/site.php/en
AIRPRESS	Netherlands	http://www.airpress.nl/index.asp?taal=4
ALMIG Kompressoren	Germany	https://www.almig.com/
Alup Kompressoren	Germany	http://www.alup.com/us/
Anest Iwata	USA	http://anestiwata.com/
ARGE	Austria	http://www.agre.at/
Ariel	USA	https://www.arielcorp.com/
Atlas Copco Compressors	USA	http://www.atlascopco.us/usus/
AYKOM	Russia	http://aykomcompressor.ru/index.php/en/anasayfa
BAUER KOMPRESSOREN GmbH	Germany	http://www.bauercomp.com/en
Belaire	USA	http://www.belairecompressors.com/#
biokomp srl	Italy	http://www.bio-komp.com/
BITZER	Germany	https://www.bitzer.de/us/us/
Blackmer	USA	http://www.psgdover.com/en
BOGE	Germany	http://www.boge.com/en
BORSIG ZM Compression GmbH	Germany	http://zm.borsig.de/en/home.html
Burckhardt Compression AG	Switzerland	https://www.burckhardtcompression.com
Carlyle Compressors	USA	https://www.carlylecompressor.com/carlyle/en/worldwide/

Ceccato Aria Compressa	Italy	http://www.ceccato-compressors.com/us/
Chongqing General Industry (Group) Co., Ltd	China	http://en.cqgic.com/more_ety.php?d=ety_main
COMPAIR	United Kingdom	http://www.compair.com/
Compresores Josval, S.L.	Spain	http://www.compresoresjosval.com/en
CP	USA	http://www.cp.com/
Cubigel Compressors	Spain	http://www.huayicompressor.es/
Daikin	Japan	http://www.daikin.com/
DALGAKIRAN KOMPRESOR	Turkey	http://www.dalgakiran.com/
Dalian Sanyo Compressors	China	http://www.sanyocomp.com/english/default_1024.asp
DANFOSS Refrigeration & Air Conditioning	Denmark	http://refrigerationandairconditioning.danfoss.com/home/
Dekker Vacuum Technologies	USA	https://www.dekkervacuum.com/
Dinamik Compressor Europe	Belgium	http://www.dinamikcompressor.eu/eng/index.html
Dresser-Rand	USA	http://www.dresser-rand.com/
EKOM	Slovakia	http://www.ekom.sk/en/
ELGI	India	http://www.elgi.com/
Elmo Rietschle	Germany	http://www.gd-elmorietschle.com/
Emerson Climate Technologies	USA	http://www.emersonclimate.com/en-US/pages/default.aspx
EMMECOM SRL	Italy	http://www.emmecomsrl.com/en/
ENVE-ERVOR	France	http://www.ervor.com/en
ERA Machinery & Energy	Turkey	http://www.erakompresor.com/
Esam	Italy	http://www.esam.it/gb/
FAPMO	France	http://www.ensival-moret.com/
FIMA Maschinenbau GmbH	Germany	http://www.fima.de/en/
FINI	Italy	http://www.finicompressors.com/en/
FONTECK INDUSTRIES	Netherlands	http://www.fonteck.com/
FRASCOLD	Italy	http://www.frascold.it/en/
Frick by Johnson Controls	USA	http://www.johnsoncontrols.com/buildings/refrigeration/industrial-refrigeration
FS Elliott	USA	http://www.fs-elliott.com/
Fusheng Industrial	Taiwan	http://www.fusheng.com/?r_reg=en-us
GARDNER DENVER	USA	http://www.gardnerdenver.com/
Gardner Denver srl - Divisione Robuschi	USA	http://www.gardnerdenver.com/robuschi
Gardner Denver Thomas	Germany	http://www.gd-thomas.com/
GAST	USA	http://gastmfg.com/
GE Compressors	USA	https://www.geoilandgas.com/oilfield/gas-processing-compression
GEA Bock	Germany	http://www.gea.com/global/en/index.jsp

Gentilin S.R.L.	Italy	http://www.gentilincompres-sors.com/en
GMCC	China	http://www.gmcc-welling.com/
GrassAir Compressoren	Netherlands	http://www.alup.com/us/
GREE	China	http://global.gree.com/
Guangdong Ganey Precision Machinery Co., Ltd	China	http://ganey.com.cn/en
Hanbell	Taiwan	http://www.hanbell.com/
HAUG Kompressoren AG	Switzerland	http://www.haug.ch/en.html
Hertz Kompressoren GmbH	Germany	http://www.hertz-kompres-soren.com/
Highly	China	www.highly.cc
Hofer Hochdrucktechnik GmbH	Germany	http://www.andreas-ho-fer.de/en/home/
Howden BC Compressors	France	http://www.howden.com/Pages/home.aspx
Hydrovane	USA	http://www.hydrovaneproducts.com/
INGERSOLL RAND	USA	http://www.ingersollrandprod-ucts.com/
J & E Hall International	England	http://www.jehall.com/
J.P. Sauer & Sohn Maschi-nenbau GmbH	Germany	http://www.sauercompres-sors.com/en/
JAB-Becker	Germany	http://www.jab-becker.de/en/start.html
Josef Mehrer GmbH & Co KG	Germany	http://www.mehrer.de/en/homep-age/
Kaeser Compressors	Germany	http://www.kaeser.com/int-en/
Kaishan	China	http://kaishantechnologies.com/in-dex.html
Kobelco	Japan	http://www.kobelco.co.jp/english/
KÖHLER & HÖRTER GmbH	Germany	http://www.koho-kompres-sor.de/en/home/
KTC Srl	Italy	http://www.ktc-air.com/en/homep-age.html
Kulthorn	Thailand	http://compressor.kulthorn.com/
Leobersdorfer Maschinen-fabrik GmbH & Co.KG	Austria	http://www.lmf.at/
LG	South Korea	http://www.lg.com/in/refrigerator-compressors
LUPAMAT AIR COMPRES-SORS	Turkey	http://www.lupamat.com/en
MAN Diesel & Turbo	Germany	http://turbomachinery.man.eu/
MAPRO International S.p.A.	Italy	http://www.maproint.com/en-gb/sitePages/home.aspx
MATTEI	Italy	http://www.matteigroup.com/
Maximator GmbH	Germany	https://www.maxima-tor.de/flycms/en/web/1/-/Startseite.html
Misubishi heavy industries	Japan	http://www.mhicompressor.com/en/

MOUVEX	France	http://www.psgdo-ver.com/en/mouvex/home#
NARDI COMPRESSORI	Italy	http://www.nardicompres-sori.com/en/
Neumann Esser	Germany	http://www.neuman-esser.de/
NOVAIR - OXYPLUS TECH-NOLOGIES	France	http://www.oxyplus-technolo-gies.com/?lang=en
Oerlikon Leybold Vacuum	USA	http://www.leybold.com/
Officine Mario Dorin Spa	Italy	http://www.dorin.com/
Oxywise, s.r.o.	Slovakia	http://www.oxywise.com/
Ozen Kompresor	Turkey	http://www.ozenkompresor.com/en
Panasonic	China	http://papcdl.panasonic.cn/eng-lish/default_1024.asp
Parise Compressori	Italy	http://www.parise.it/de-fault.asp?lang=eng
Pneumofore	Italy	http://www.pneumofore.com/
Power System	Italy	http://www.powersystem.it/in-dex.php/en/
Quincy Compressor	USA	http://www.quincycompressor.com/
Reavell	USA	http://www.gardnerden-ver.com/brands/reavell/
Rechi	Taiwan	http://www.rechi.com/en/index.do
RefComp	China	http://www.snowkey.com/compres-sor/en/index.php/Product/index/clas-sid/18
Remeza	Belarus	http://eng.remeza.com/
RENNER Kompressoren	Germany	http://www.renner-kompres-soren.de/en/home0.html
RIX Industries	USA	http://www.rixindustries.com/
RKR Gebläse und Verdichter GmbH	Germany	http://www.rkr.de/?dm=1&_l=3
ROTAIR SPA	Italy	http://www.rotairspa.com/
Schneider Druckluft GmbH	Germany	https://www.schneider-airsys-tems.com/Pages/index.aspx
Secop GmbH	Germany	http://www.secop.com/
setkom kompresor	Turkey	http://www.setkomkompre-sor.com/eng-anasayfa.php
SHREE YANTHRA EQUIP-MENTS	India	http://www.yanthracompres-sors.com/
SULLAIR	USA	http://www.sullair.com/global/en
SWAN AIR COMPRESSOR	Taiwan	http://www.swanair.com.tw/eng-lish/index.aspx
tamsan compressor	Turkey	http://www.tamsan.com.tr/in-dex_en.php
TECUMSEH	USA	http://www.tecumseh.com/en/Eu-rope
Toshiba	Japan	http://www.toshiba-car-rier.co.jp/global/
Ural Compressor Plant, JSC	Russia	http://www.ukz.ru/en/
VACUUMATTEIS	Italy	http://www.vacuumatteis.it/?lang=en

Vortex Compressor	Turkey	http://www.vortexcompres-sor.com/en/
Wärtsilä	Finland	http://www.wartsila.com/
Worthington Creyssenssac	United Kingdom	http://www.airwco.com/us/

Survey responses

Table 17: Survey responses for question 1 to 4

Response Nr	Q1	Q2	Q3	Q4
1	screw	compressed air	1 - 100 hp (0.75 - 75 kW)	
2	other	compressed air	more than 1000 hp (0.75 MW)	Europe Middle East North America
3	other	refrigeration	more than 1000 hp (0.75 MW)	Africa
4	screw	refrigeration	100 - 1000 hp (75 - 750 kW)	Europe
5	screw	refrigeration	100 - 1000 hp (75 - 750 kW)	Europe
6	piston	compressed air	1 - 100 hp (0.75 - 75 kW)	North America
7	screw	compressed air	1 - 100 hp (0.75 - 75 kW)	Europe
8	screw	compressed air	1 - 100 hp (0.75 - 75 kW)	Asia & Pacific
9	piston	compressed air	1 - 100 hp (0.75 - 75 kW)	Europe
10	other	other	more than 1000 hp (0.75 MW)	Africa Asia & Pacific Europe Latin America & Caribbean Middle East North America
11	piston	compressed air	100 - 1000 hp (75 - 750 kW)	Africa Asia & Pacific Europe
12	piston	compressed air	1 - 100 hp (0.75 - 75 kW)	Africa Europe
13	piston	compressed air	100 - 1000 hp (75 - 750 kW)	Asia & Pacific Europe Latin America & Caribbean Middle East North America
14	other	compressed air	100 - 1000 hp (75 - 750 kW)	
15	screw	other	1 - 100 hp (0.75 - 75 kW)	Europe
16	piston	refrigeration	1 - 100 hp (0.75 - 75 kW)	Asia & Pacific Europe Middle East North America
17	piston	other	1 - 100 hp (0.75 - 75 kW)	Europe
18	piston	other	1 - 100 hp (0.75 - 75 kW)	
19	piston	compressed air	1 - 100 hp (0.75 - 75 kW)	Europe
20	piston	other	1 - 100 hp (0.75 - 75 kW)	
21	piston	other	1 - 100 hp (0.75 - 75 kW)	Europe North America
22	piston	other	1 - 100 hp (0.75 - 75 kW)	Asia & Pacific
23	piston	refrigeration	below 1 hp (750 W)	Asia & Pacific Europe Middle East

24	other	other	more than 1000 hp (0.75 MW)	Asia & Pacific Europe Latin America & Caribbean Middle East North America
25	screw	other	1 - 100 hp (0.75 - 75 kW)	Europe
26	screw	compressed air	1 - 100 hp (0.75 - 75 kW)	Europe
27	piston	refrigeration	1 - 100 hp (0.75 - 75 kW)	Europe
28	piston	refrigeration	1 - 100 hp (0.75 - 75 kW)	Europe
29	piston	refrigeration	below 1 hp (750 W)	North America
30	piston	refrigeration	1 - 100 hp (0.75 - 75 kW)	Middle East
31	piston	refrigeration	1 - 100 hp (0.75 - 75 kW)	Europe North America
32	piston	refrigeration	below 1 hp (750 W)	Europe North America

Table 18: Survey responses for question 5

Response Nr	Q5.a	Q5.b	Q5.c
1	sometimes	rarely	rarely
2	very often	sometimes	always
3	always	sometimes	rarely
4	very often	sometimes	rarely
5	sometimes	rarely	rarely
6	sometimes	sometimes	rarely
7	sometimes	sometimes	sometimes
8	rarely	sometimes	sometimes
9	sometimes	rarely	rarely
10	always	very often	very often
11	very often	sometimes	very often
12	sometimes	sometimes	very often
13	very often	very often	always
14	very often	sometimes	always
15	sometimes	sometimes	rarely
16	always	rarely	never
17	sometimes	rarely	very often
18	rarely	never	sometimes
19	sometimes	rarely	sometimes
20	rarely	rarely	always
21	sometimes	sometimes	always
22	very often	rarely	very often
23	very often	sometimes	rarely
24	always	sometimes	very often
25	sometimes	never	always
26	always	very often	sometimes
27	very often	sometimes	never
28	sometimes	never	never
29	sometimes	rarely	never
30	rarely	never	never
31	very often	sometimes	always
32	always	rarely	never

Table 19: Survey responses for question 6 and 7

Response Nr	Q6	Q7
1		
2	Electrical efficiency and efficient variable capacity control	
3	Cost - folks want energy efficient solutions at a low price	Water usage is becoming increasingly important, more so than energy efficiency. Doesn't matter how efficient your chiller is if there is no water and you can't run your chiller. This is one issue. The other is price. Most customers just don't want to pay more for efficient chillers.
4	heat pumps	
5	lower priced medium voltage VFD controllers	
6	Government incentives that pay back companies for using energy efficiency.	It can be tough at times to sell people on energy efficiency because the return on investment can take a couple years to see. People want cheap right now.
7		
8		
9	Better filtration control	
10	High speed motors and magnetic bearings can eliminate lubrication oil systems.	Your questions indicate a focus on industrial air applications. Do not overlook oil and gas applications. Due to much higher densities, power is much higher and efficiency is therefore critical.
11	optimization, energy efficiency & solar power	Will be major issue in years to come. Compressors use 10% of electricity in west. Cannot decarbonize the world without decarbonizing air compression.
12		
13	Heat recovery	
14	FS-Elliott manufactures only centrifugal, oil free air compressors for both API and Industrial applications. Centrifugal air compressors are generally the most efficient of all compressor technologies. Highly efficient 3D impellers and integral inter-stage air coolers are already employed by most tier one suppliers. Very often, performance envelopes mandated by client technical specifications lead to over-sized and inefficient compressor selections due to excessive air blow-off at normal operation. The introduction of technologies facilitating	In most instances, for compressor duties over 200kW, centrifugal compressors offer significant total cost of ownership benefits compared with screw compressors. Centrifugal compressors are generally more efficient (>10%) and have longer maintenance intervals and lower parts consumption. However, in the current low cost environment (where plant construction contracts are always given to the lowest bidder), engineering contractors tend to push for low Capex screw type solutions in order maximize profits, even though it is generally not in the interests of the end user who will be suffering higher Opex costs for 20+ years. It

	variable speed operation (traditionally a challenge with complex multi-shaft machines) will help in this regard.	is up to the OEMs to sell the benefits of centrifugal technology to end users early in the project cycle.
15		The bio methane sector is particularly interested in high energy efficiency and energy recovery. We expect this sector to drive also some neighboring markets (biogas, gas compression for CHP, etc.).
16	Variable speed motor drive	The industry is facing with challenges on how to deal with new refrigerants with low GW which usually are of flammable characteristic.
17	new regulations, energy price	
18		
19	Difficult to say	No
20		
21		
22	Hybrid (Electric and Fuel)	No
23	Compressors units with high cycles (HZ)	The manufacturers in my region are not willing to pay the price for higher COP compressors but however we have to make the sacrifices since there is very competitive market from low efficiency Chinese products
24	Hermetic Sealed compressors with Mag bearing and no Sealing required	Life Cycle cost is one of the most critical parts for any bidder to have success in any project. the calculation for this differs from country to country. Hope we could be of help, good luck Benedikt.
25	Noise level, capacity, weight, energy consumption	
26	the water injected compressors	Applying best energy management practices and purchasing energy-efficient equipment can lead to significant savings in compressed air systems. Economy – Efficient Processes Reduce Costs Energy – Saving Energy Saves Money Environment – Less Waste Benefits Everyone
27	variable speed driven compressors	It will take longer as expected due to the postponement of energy Regulation rules.
28	Permanent magnet motors & variable speed compressors	
29		
30	not sure what new technology is available for efficient compressor systems	No comments as of now. Going with the flow
31	Heat Recovery / Good partial load regulation / Compressor Management Systems	
32	variable speed	

Survey summary

Question 1: What is your most sold type of compressor?

Table 20: Detailed response breakdown of question 1

Answer Choices	Responses	n
Piston	**59.4%**	19
Screw	**25.0%**	8
Scroll	**0.0%**	0
Vane	**0.0%**	0
other	**15.6%**	5
Total		**32**

Table 21: Characteristics of question 1

Question Type	**Multiple Choice / Single answer**
Mandatory	**yes**
Answered	**32**
Skipped	**0**

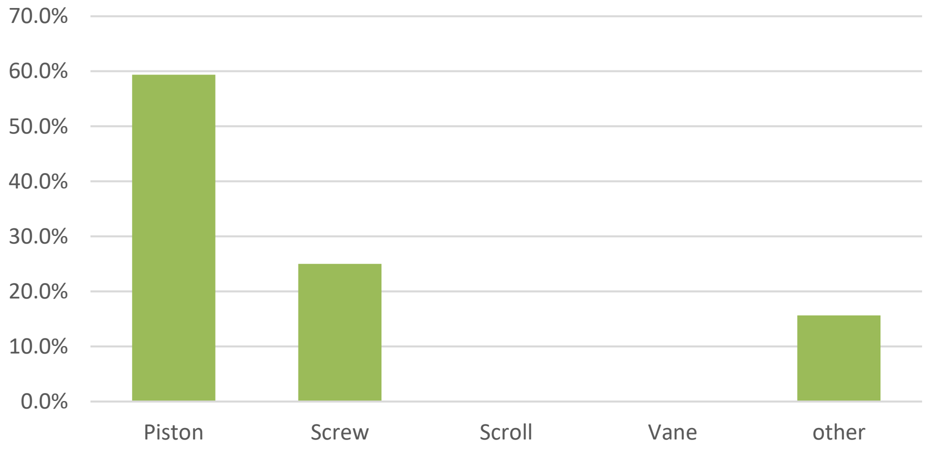

Figure 79: Overall responses of question 1

Question 2: In what applications are most of your sold compressors used?

Table 22: Detailed response breakdown of question 2

Answer Choices	Responses	n
Compressed air	**40.6%**	13
Refrigeration / HVAC	**31.3%**	10
other	**28.1%**	9
not sure	**0.0%**	0
Total		**32**

Table 23: Characteristics of question 2

Question Type	**Multiple Choice / Single answer**
Mandatory	**yes**
Answered	**32**
Skipped	**0**

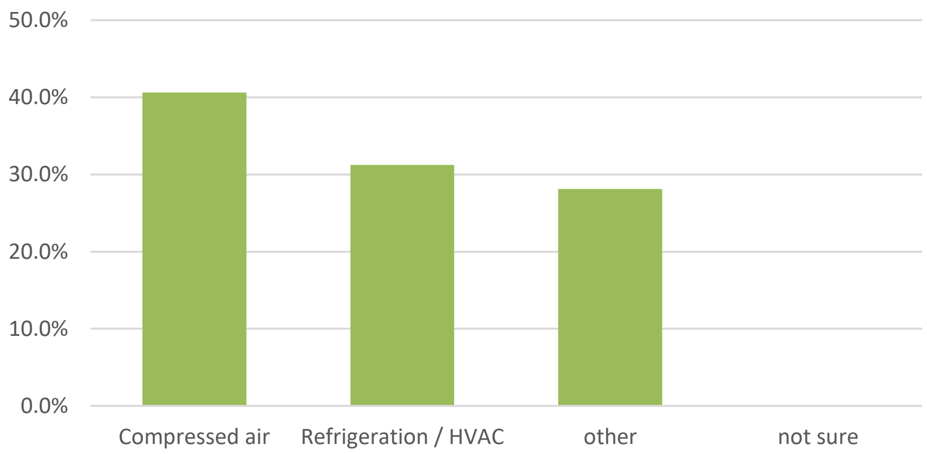

Figure 80: Overall responses of question 2

Question 3: In what size category are most of your compressor sales?

Table 24: Detailed response breakdown of question 3

Answer Choices	Responses	n
< 1 hp (750 W)	**9.4%**	3
1 - 100 hp (0.75 - 75 kW)	**59.4%**	19
100 - 1000 hp (75 - 750 kW)	**18.8%**	6
> 1000 hp (0.75 MW)	**12.5%**	4
Total		**32**

Table 25: Characteristics of question 3

Question Type	**Multiple Choice / Single answer**
Mandatory	**yes**
Answered	**32**
Skipped	**0**

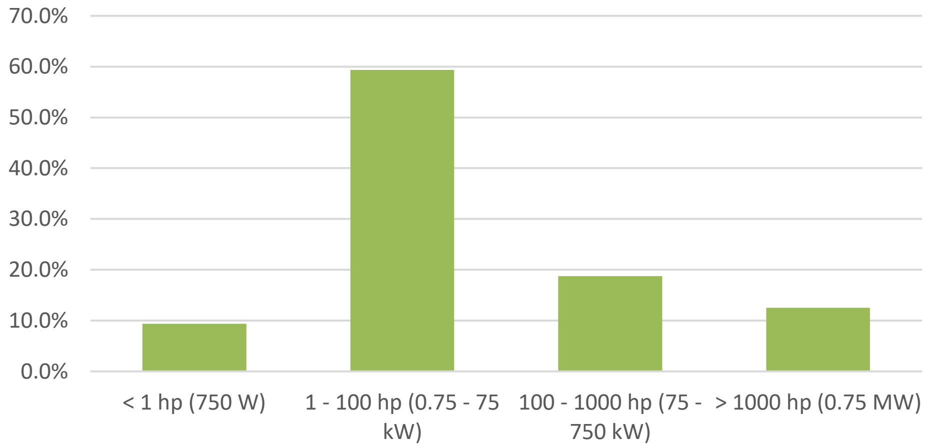

Figure 81: Overall responses of question 3

Question 4: Did you experience increased demand for energy efficient compressors/systems from specific geographic regions?

Table 26: Detailed response breakdown of question 4

Answer Choices	Responses	n
Africa	**14.3%**	4
Asia & Pacific	**28.6%**	8
Europe	**78.6%**	22
Latin America & Caribbean	**10.7%**	3
Middle East	**25.0%**	7
North America	**35.7%**	10
Total Respondents		**28**

Table 27: Characteristics of question 4

Question Type	**Multiple Choice / Multiple answers**
Mandatory	**no**
Answered	**28**
Skipped	**4**

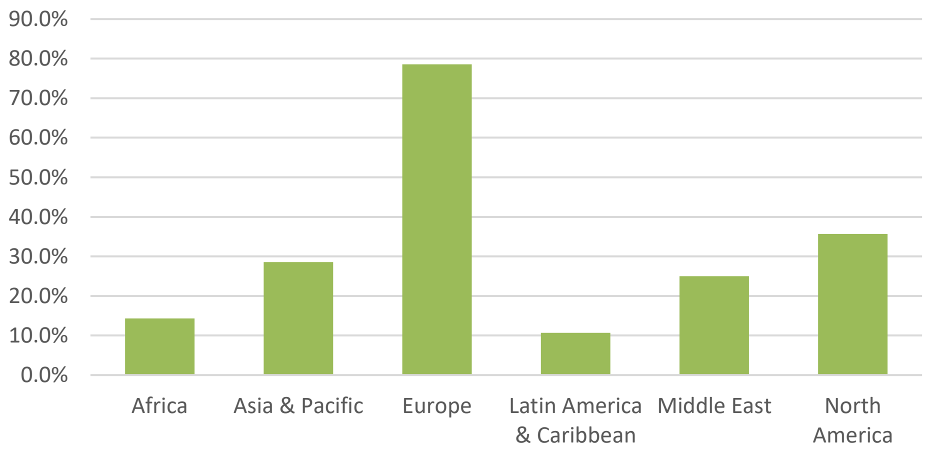

Figure 82: Overall responses of question 4

Question 5: How often do you experience ..

Table 28: Detailed response breakdown of question 5

	(1)never	(2)rarely	(3)some-times	(4)very often	(5)always	Total
Q 5-a .. customers specifically re-questing energy efficient products?	**0.00%**	**12.50%**	**40.63%**	**28.13%**	**18.75%**	
	0	4	13	9	6	32
Q 5-b .. customers willing to pay higher prices for energy effi-cient products?	**12.50%**	**31.25%**	**46.88%**	**9.38%**	**0.00%**	
	4	10	15	3	0	32
Q 5-c .. demand for oil-free com-pressors?	**18.75%**	**25.00%**	**15.63%**	**18.75%**	**21.88%**	
	6	8	5	6	7	32

Table 29: Characteristics of question 5

Question Type	**Multiple Choice / Single answers**
Mandatory	**yes**
Answered	**32**
Skipped	**0**

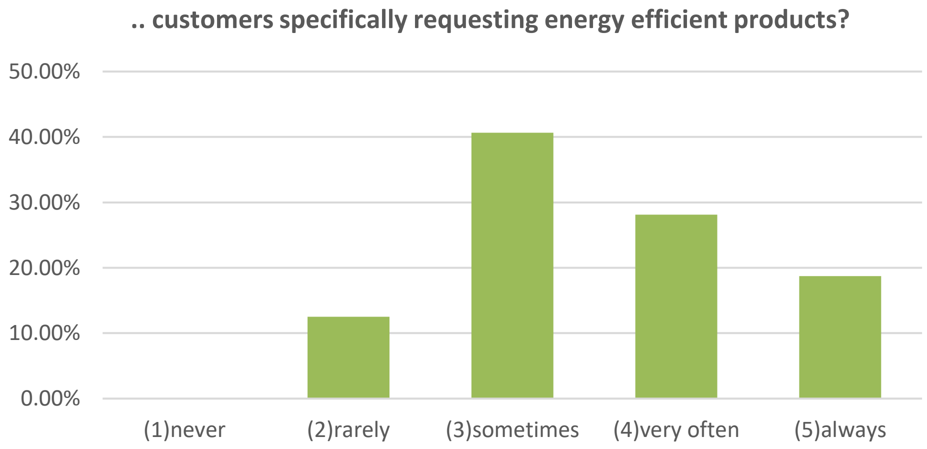

Figure 83: Overall responses of question 5-a

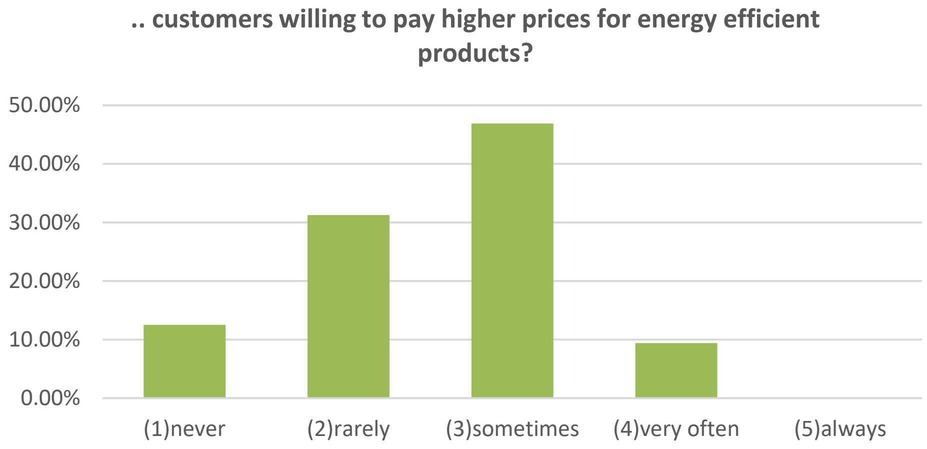

Figure 84: Overall responses of question 5-b

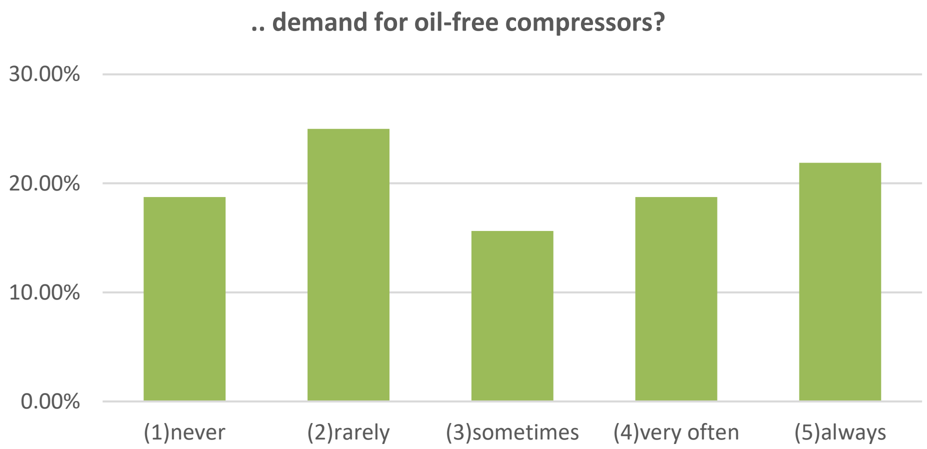

Figure 85: Overall responses of question 5-c

Question 6: In your opinion what technology/innovation in compressor systems will drive the market of energy efficient products in the coming years?

Table 30: Characteristics of question 6

Question Type	**Text box / open ended question**
Mandatory	**no**
Answered	**23**
Skipped	**9**

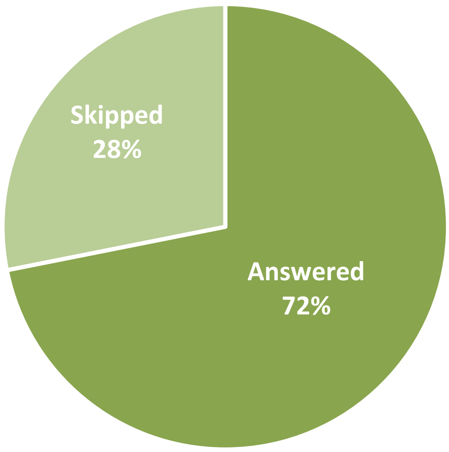

Figure 86: Overall responses of question 6

Question 7: Do you have any other comments related to energy efficiency market trends?

Table 31: Characteristics of question 7

Question Type	**Text box / open ended comment**
Mandatory	**no**
Answered	**15**
Skipped	**17**

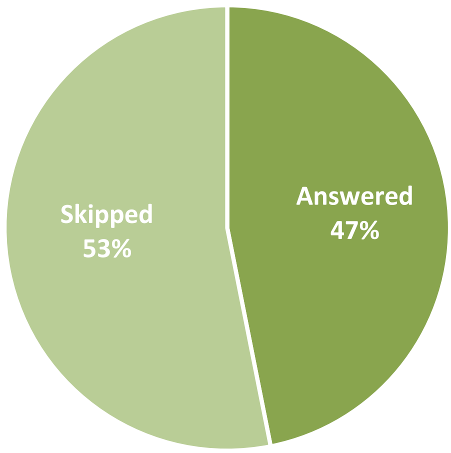

Figure 87: Overall responses of question 7

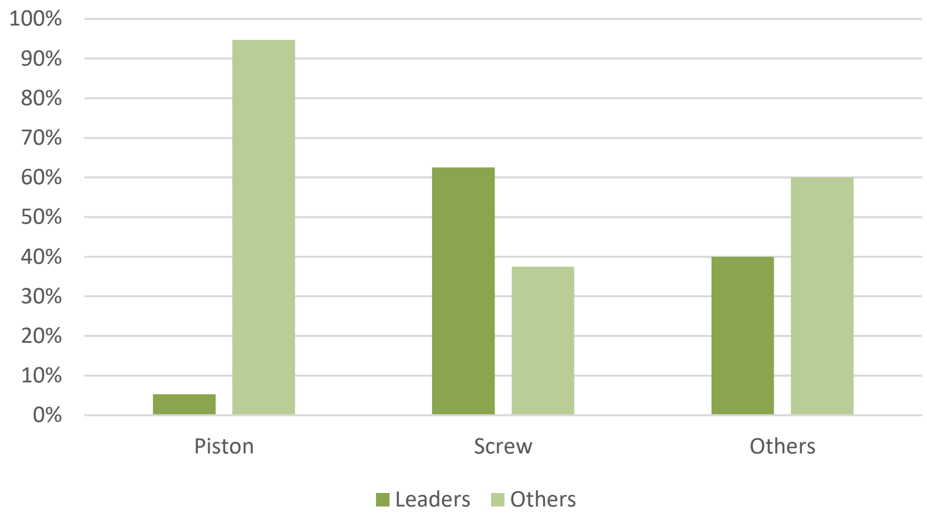

Figure 88: Market leader representation in compressor types

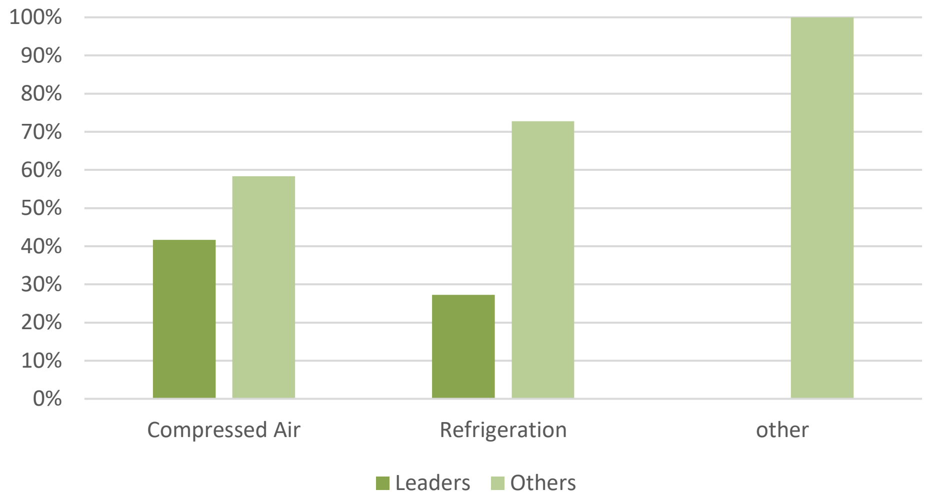

Figure 89: Market leader representation in end applications

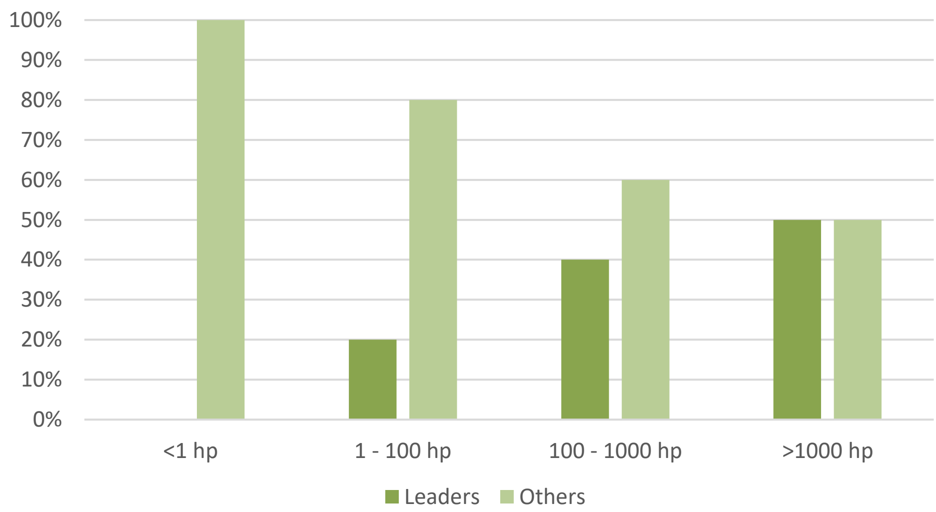

Figure 90: Market leader applications in compressor sizes

Response timeline

Table 32: Sent survey requests and received responses

Day	Responses	Sent out
1	0	116
2	3	0
3	4	0
4	0	0
5	1	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	3	109
14	4	41
15	0	0
16	0	0
17	6	120
18	8	0
19	3	0

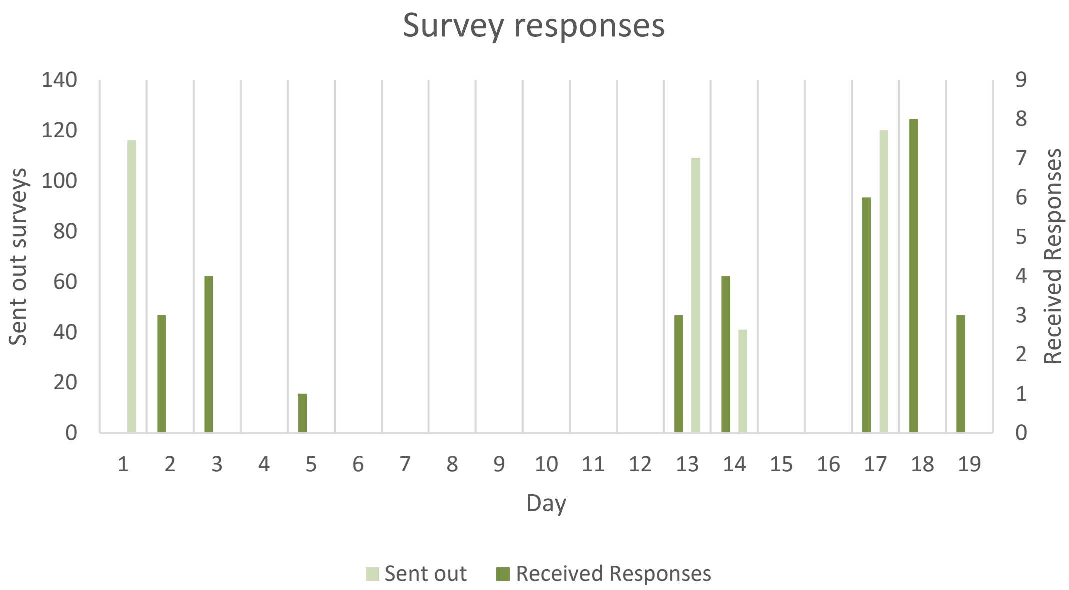

Figure 91: Surveys response timeline

Response time

Table 33: Individual survey answering times

Nr	Time to complete [mm:ss]
1	01:31
2	04:46
3	10:48
4	04:00
5	01:41
6	11:46
7	01:47
8	00:47
9	01:46
10	05:15
11	02:56
12	01:40
13	03:37
14	23:31
15	03:53
16	09:48
17	03:56
18	01:15
19	00:29
20	01:06
21	00:40
22	03:52
23	07:35
24	02:59
25	03:37
26	05:08
27	03:37
28	02:53
29	01:00
30	04:51
31	02:58
32	01:37
Mean	04:17
Median	03:18

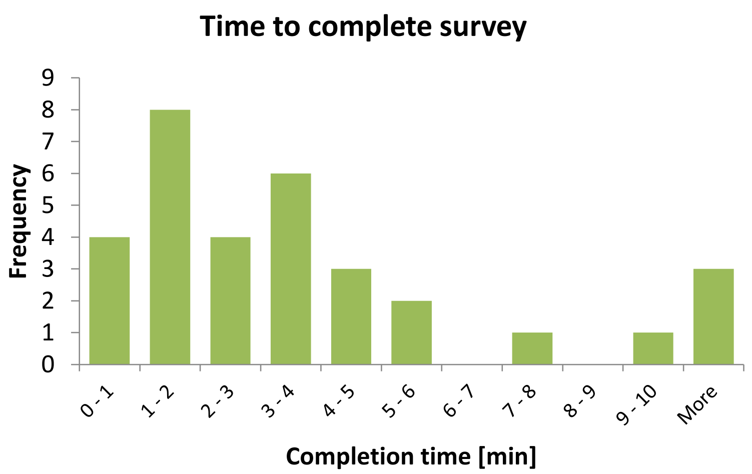

Figure 92: Distribution of answering times

OEM interview questions

Table 34: Test interview questions conducted with Frick by Johnson Controls

Question 1	What type of compressor would you say is your primary product e.g. large HP screw, fractional HP compressors etc. and what is the approximate breakdown for these categories?
Question 2	What are some of the main markets that you serve and is any one market demanding more for efficiency Vs. another?
Question 3	What are the market drivers for efficiency in the industries you serve – government regulation, customer demand, proactive efforts on your part to differentiate products on the basis of efficiency?
Question 4	Are customers asking (or actually setting targets) for specific efficiency improvements in a compressor design?
Question 5	Is there a geographic variation in demand for energy efficient designs for examples is there more demand in Europe Vs. USA?
Question 6	How do you define compressor efficiency – e.g. is isentropic efficiency sufficient especially when a “package” is involved?
Question 7	What are some of the most commonly used design changes to improve compressor efficiency – of the compressor and of the package?
Question 8	How many of these are unique to your compressor design or are these generic to the compressor type e.g. variable speed drive being a generic approach?
Question 9	Is the compressor sold as a modular unit to which ancillary efficiency improvement equipment may be added by customer or do you prefer to sell a package?
Question 10	What role can a lubricant play in improving efficiency?
Question 11	What plumbing and lubrication application methods impact efficiency and do you incorporate these?
Question 12	Is there a point of diminishing returns on compressor design and efficiency and where are you there today in this spectrum?
Question 13	Is compressor design in different continents different to meet efficiency needs or mandates (aside from current and voltage and such differences)?
Question 14	What do you do proactively so that your customers actually realize the efficiency that you publish for your compressor?
Question 15	How do you advertise efficiency – e.g. degree of throughput, cost of ownership?
Question 16	Does improving efficiency allow you to command a higher price (since the customer will be saving during operation)?

OEM interview findings

- The majority of our sales are rotary screw compressors followed by reciprocating compressors and chiller business.
- Natural gas gathering is an important market for us. Energy efficiency is less important here more attention is given to reliability.
- At least half of our business is in the food and beverage market.
- In the ammonia compression business segment HSE aspects play a role, efficiency is important.
- In process refrigeration (propane, propylene glycol) efficiency is important but more important is reliability.
- For bare block compressors we try to get the efficiency as high as possible.
- The market driver for efficiency is the compressed air segment.
- The demand for energy efficient compressor systems is higher in the EU than in the US. Low payback periods are important for investment decisions.
- We define efficiency by volumetric efficiency, pump vs. theoretic volume and adiabatic efficiency.
- The best compressors can achieve an efficiency of 83%, 87% with perfect conditions and magnetic bearings.
- Reciprocating compressors had their heydays in the early eighties.
- The most commonly used design changes to improve energy efficiency are:
    - Shape of the rotor profile
    - Tighter clearance
    - Huge improvement with oil flooding
    - Lower pressure drop
    - Lower oil carryover
    - Heat recovery oil cycle
    - Secondary heat exchanger
    - Heat pump
    - Oil miscibility in refrigeration systems, challenging
    - VSD (Variable speed drives), about 25% of the market
    - Computer control systems
- A lot can be done for overall system efficiency.
- Retrofitting inefficient systems is sometimes possible with VSD, controls, cooling, resonance, liquid injection. Mostly done by contractors.
- In today’s state of the art compressors should be no mechanical wear. Primarily there is fatigue in bearings and screws. 83% efficiency is the maximum.
- We don’t use magnetic bearings in screw compressors because the loads are too big.

- Much work is done to make customers aware of the efficiency gains in the new products.
- We work with nano – coatings.
- Heat exchangers become better every year.
- We try to get compressors as tight and as low cost as possible.
- It is very hard to advertise efficiency right now, there is a bad market/economy, low prices for energy.
- Most of the time the lowest price wins in tenders.
- Energy efficient products only allow for a slight increase in selling prices.

Appendix B: LCC calculator

Web application file structure

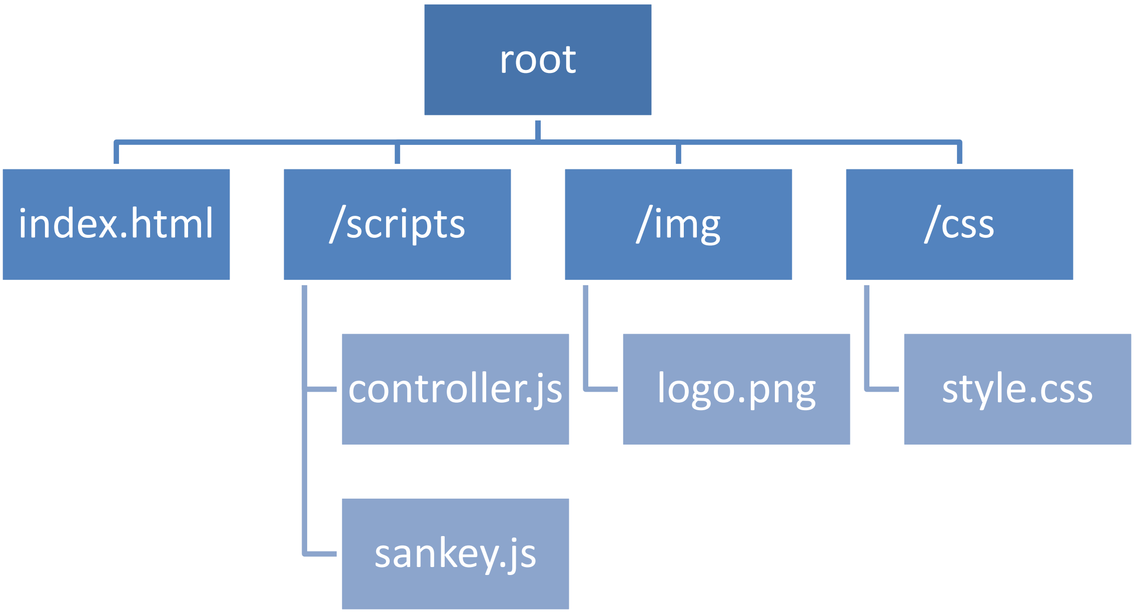

Figure 93: File structure overview of the LCC calculator web application

Source codes

index.html

```
<html>

<head>
   <title>Life Cycle Tool</title>
   <link rel="stylesheet" href="style.css" />
   <script src="https://ajax.googleapis.com/ajax/libs/jquery/1.12.4/jquery.min.js"></script>
   <script src="controller.js"></script>
   <script src="http://d3js.org/d3.v3.js"></script>
   <script src="sankey.js"></script>
   <!--<script src="line.js"></script>-->
</head>

<body>


   <div class="calculator box">
      <div class="top box">
         <div class="logo box"></div>
         <div class="topSpacer box"></div>
         <div class="heading box"><h2>Compressor Life Cycle Tool</h2></div>
      </div>

      <div>
            <div><hr/><br/>
               <div class="io box">
                  <div class="input box">
                     <table class="input box" align="center" border="0">
                        <tr class="row">
                           <td>Grid Electricity Costs:</td>
                           <td><input type="number" id="electricityCost" onkeypress='return event.charCode >= 48 && event.charCode <= 57' oninput="update()"
min="0"></td>
                           <td>$/kWh</td>
                        </tr>
                        <tr class="row">
                           <td>Discount Rate:</td>
                           <td><input type="number" id="discountRate" oninput="update()" min="0"></td>
                           <td>%</td>
                        </tr>
                        <tr class="row">
                           <td>Discount Duration:</td>
                           <td><input type="number" id="discountDuration" oninput="update()" min="0"></td>
                           <td>years</td>
                        </tr>
                        <tr class="row">
                           <td>Investment Costs:</td>
                           <td><input type="number" id="initialInvestment" oninput="update()" min="0"></td>
                           <td>$</td>
                        </tr>
                        <tr class="row">
                           <td>Previous Power Consumption:</td>
                           <td><input type="number" id="previousConsumption" oninput="update()" min="0"></td>
                           <td>kWh/year</td>
                        </tr>

                        <tr class="row">
                           <td><b>Compressor 1</b></td>
                           <td></td>
                           <td><a  class="add_button" href="javascript:void(0);">add</a>   <a class="remove_button" href="javascript:void(0);">re-
move</a></td>
                        </tr>
                        <tr class="row">
                           <td>New Power Consumption:</td>
                           <td><input type="number" id="newConsumption1" oninput="update()" min="0"></td>
                           <td>kWh/week</td>
                        </tr>
                     </table>
                  </div>

                  <div class="midSpacer box"></div>

                  <div class="output box">
                     <table class="input box" align="center">
                        <tr class="row">
                           <td>Annual Electricity Costs:</td>
                           <td id="el" width="100px"></td>
                           <td>$/year</td>
                        </tr>
                        <tr class="row">
                           <td>Annual Cost Savings:</td>
                           <td id="costsavingsDollar"></td>
                           <td>$/year</td>
                        </tr>
                        <tr class="row">
                           <td>Annual Cost Savings:</td>
                           <td id="costsavingsPercent"></td>
                           <td>%</td>
                        </tr>
                        <tr class="row">
                           <td>Simple Payback:</td>
                           <td id="payback"></td>
                           <td>years</td>
                        </tr>
                        <tr class="row">
                           <td>Discounted Payback:</td>
```

```
                <td id="discPayback"></td>
                <td>years</td>
            </tr>
            <tr class="row">
                <td>Net Present Value (NPV):</td>
                <td id="npv"></td>
                <td>$</td>
            </tr>
            <tr class="row">
                <td>Return on Investment (ROI):</td>
                <td id="roi"></td>
                <td>%</td>
            </tr>
            <tr class="row">
                <td>Internal Rate of Return (IRR):</td>
                <td id="irr"></td>
                <td>%</td>
            </tr>
            <tr class="row">
                <td>Saved CO<sub>2</sub>:</td>
                <td id="co2"></td>
                <td>kg/year</td>
            </tr>
        </table>
    </div>
</div>
<br /><br /><hr>
<div class="details box">
    <div><br /><button class="accordion results" >detailed results</button></div>
    <div class="results box"></div>
</div>
<div class="settings box">
    <div><button class="accordion options">advanced options</button></div>
    <div class="options box">*WIP*</div>
</div>
<br/><hr>
<div class="charts box">
    <div class="sankey box">
        <p id="chart">
            <script>

                var units = "%";

                var margin = { top: 10, right: 10, bottom: 10, left: 10 },
                    width = 1000 - margin.left - margin.right,
                    height = 370 - margin.top - margin.bottom;

                var formatNumber = d3.format(",.0f"),    // zero decimal places
                    format = function (d) { return formatNumber(d) + " " + units; },
                    color = d3.scale.category20();

                // append the svg canvas to the page
                var svg = d3.select("#chart").append("svg")
                    .attr("width", width + margin.left + margin.right)
                    .attr("height", height + margin.top + margin.bottom)
                  .append("g")
                    .attr("transform",
                        "translate(" + margin.left + "," + margin.top + ")");

                // Set the sankey diagram properties
                var sankey = d3.sankey()
                    .nodeWidth(36)
                    .nodePadding(10)
                    .size([width, height]);

                var path = sankey.link();

                // load the data
                d3.json("sankey.json", function (error, graph) {

                    var nodeMap = {};
                    graph.nodes.forEach(function (x) { nodeMap[x.name] = x; });
                    graph.links = graph.links.map(function (x) {
                        return {
                            source: nodeMap[x.source],
                            target: nodeMap[x.target],
                            value: x.value
                        };
                    });

                    sankey
                        .nodes(graph.nodes)
                        .links(graph.links)
                        .layout(32);

                    // add in the links
                    var link = svg.append("g").selectAll(".link")
                        .data(graph.links)
                      .enter().append("path")
                        .attr("class", "link")
                        .attr("d", path)
                        .style("stroke-width", function (d) { return Math.max(1, d.dy); })
                        .sort(function (a, b) { return b.dy - a.dy; });

                    // add the link titles
                    link.append("title")
                          .text(function (d) {
                              return d.source.name + " → " +
                                      d.target.name + "\n" + format(d.value);
                          });
```

```
                    // add in the nodes
                    var node = svg.append("g").selectAll(".node")
                      .data(graph.nodes)
                     .enter().append("g")
                      .attr("class", "node")
                      .attr("transform", function (d) {
                        return "translate(" + d.x + "," + d.y + ")";
                      })
                     .call(d3.behavior.drag()
                      .origin(function (d) { return d; })
                      .on("dragstart", function () {
                        this.parentNode.appendChild(this);
                      })
                      .on("drag", dragmove));

                    // add the rectangles for the nodes
                    node.append("rect")
                      .attr("height", function (d) { return d.dy; })
                      .attr("width", sankey.nodeWidth())
                      .style("fill", function (d) {
                        return d.color = color(d.name.replace(/ .*/, ""));
                      })
                      .style("stroke", function (d) {
                        return d3.rgb(d.color).darker(2);
                      })
                     .append("title")
                      .text(function (d) {
                        return d.name + "\n" + format(d.value);
                      });

                    // add in the title for the nodes
                    node.append("text")
                      .attr("x", -6)
                      .attr("y", function (d) { return d.dy / 2; })
                      .attr("dy", ".35em")
                      .attr("text-anchor", "end")
                      .attr("transform", null)
                      .text(function (d) { return d.name + ", " + format(d.value); })
                     .filter(function (d) { return d.x < width / 2; })
                      .attr("x", 6 + sankey.nodeWidth())
                      .attr("text-anchor", "start");

                    // the function for moving the nodes
                    function dragmove(d) {
                      d3.select(this).attr("transform",
                        "translate(" + (
                          d.x = Math.max(0, Math.min(width - d.dx, d3.event.x))
                        ) + "," + (
                          d.y = Math.max(0, Math.min(height - d.dy, d3.event.y))
                        ) + ")");
                      sankey.relayout();
                      link.attr("d", path);
                    }
                  });

                </script>
              </div>

            </div>

          </div>
        </div>
    </div>
    <div class="footer box"><hr />&copy; 2016 The Lubrizol Corporation</div>
  </body>
</html>
```

controller.js

```
function init() {                                           // set initial values
    x = 1;

    $('#electricityCost').val(0.1);
    $('#discountRate').val(10);
    $('#initialInvestment').val(0);
    $('#discountDuration').val(10);
};

function update() {
        electricityCost = 0;
        discountRate = 0;
        initialInvestment = 0;
        discountDuration = 0;
        newConsumption = 0;
        costsavingsDollar = 0;
        costsavingsPercent = 0;
        simplePayback = 0;
        discountedPayback = 0;
        roi = 0;
        co2 = 0;
        npv = 0;

        var arrayYears = new Array(discountDuration);
        var arrayInvestments = new Array(discountDuration);
        var arraySavings = new Array(discountDuration);
        var arrayCashflow = new Array(discountDuration);
        var arrayCashflowCum = new Array(discountDuration);
        var arrayCashflowDc = new Array(discountDuration);
        var arrayCashflowDcCum = new Array(discountDuration);
        dataSet = new Array();

        // get all input field values
        electricityCost = parseFloat($('#electricityCost').val());
        discountRate = parseFloat($('#discountRate').val());
        initialInvestment = parseFloat($('#initialInvestment').val());
        discountDuration = parseFloat($('#discountDuration').val());
        previousConsumption = parseFloat($('#previousConsumption').val());

        // sum up all compressor inputs
        for (i = 1; i <= x; i++) {
            newConsumption += parseFloat($('#newConsumption' + i).val()) * 52 * electricityCost;
        }

        // set new consumption field
        //console.log('new annual costs: ' + newConsumption + '$/year');
        $('#el').text(newConsumption.toFixed(0));

        // calculate and set dollar cost savings
        costsavingsDollar = previousConsumption * electricityCost - newConsumption;
        $('#costsavingsDollar').text(costsavingsDollar.toFixed(0));

        // calculate and set relative cost savings
        costsavingsPercent = (costsavingsDollar / (previousConsumption * electricityCost)) * 100;
        $('#costsavingsPercent').text(costsavingsPercent.toFixed(1));

        // calculate and set simple payback
        simplePayback = initialInvestment / costsavingsDollar;
        $('#payback').text(simplePayback.toFixed(1));

        // cashflow calculations
        arrayInvestments[0] = -initialInvestment;
        for (i = 0; i < discountDuration; i++) {
            arrayYears[i] = i + 1;
            if (i != 0) { arrayInvestments[i] = 0 }
            arraySavings[i] = costsavingsDollar;
            arrayCashflow[i] = arrayInvestments[i] + arraySavings[i];
            arrayCashflowDc[i] = arrayCashflow[i] * Math.pow((1 - (discountRate / 100)), i);
            if (i == 0) {
                arrayCashflowCum[i] = arrayCashflow[i];
                arrayCashflowDcCum[i] = arrayCashflowDc[i]
            }
            else {
                arrayCashflowCum[i] = arrayCashflowCum[i - 1] + arrayCashflow[i];
                arrayCashflowDcCum[i] = arrayCashflowDcCum[i - 1] + arrayCashflowDc[i];
            }
            npv += arrayCashflowDc[i];
        }

        // set npv
        $('#npv').text(Math.round(npv));

        // claculate and set roi  (discounted roi)
        roi = (npv / initialInvestment) * 100;
        $('#roi').text(roi.toFixed(1));

        // calculate and set discounted payback
        for (i = 0; i < discountDuration; i++) {
            if (arrayCashflowDcCum[i] < 0) {
                discountedPayback++;
                if (arrayCashflowDcCum[i + 1] >= 0) {
                    discountedPayback += (-arrayCashflowDcCum[i]) / (-arrayCashflowDcCum[i] + arrayCashflowDcCum[i + 1]);
                }
            }
            else {
                break;
            }
        }
```

```
    $('#discPayback').text(discountedPayback.toFixed(1));

    //calculate and set irr
    $('#irr').text(irr(arrayCashflow));

    // calculate and set saved CO2
    co2 = (costsavingsDollar / electricityCost) * 0.43;
    $('#co2').text(co2.toFixed(0));

    dataSet = [arrayYears, arrayInvestments, arraySavings, arrayCashflow, arrayCashflowCum, arrayCashflowDc, arrayCashflowDcCum];
    drawDetails();
  };

function drawDetails() {
  var background = '';
  $('.results.box').html('');
  $('.results.box').append('<table class="details table" align="center" cellspacing="0"></table>');
  var table = $('.results.box').children();
  table.append('<tr bgcolor="#ddd">\
          <th class="details header year">Year</th>\
          <th class="details header">Investments</th>\
          <th class="details header">Savings</th>\
          <th class="details header">CF</th>\
          <th class="details header">CF cum</th>\
          <th class="details header">Disc.CF</th>\
          <th class="details header">Disc.CF cum</th>\
          </tr>');
  for (i = 0; i < dataSet[0].length; i++) {
    if (i % 2 != 0) { background = 'bgcolor="#eee"' } else { background = '' }
    table.append('<tr ' + background + '>' +
          '<td class="details year">' + Math.round(dataSet[0][i]) + '</td>' +
          '<td>$ ' + Math.round(dataSet[1][i]) + '</td>' +
          '<td>$ ' + Math.round(dataSet[2][i]) + '</td>' +
          '<td>$ ' + Math.round(dataSet[3][i]) + '</td>' +
          '<td>$ ' + Math.round(dataSet[4][i]) + '</td>' +
          '<td>$ ' + Math.round(dataSet[5][i]) + '</td>' +
          '<td>$ ' + Math.round(dataSet[6][i]) + '</td>' +
          '</tr>');
  }
};

$(document).ready(function () {
  init();
  update();

  var max_compressors = 20;

  $(".accordion.results").click(function () {
    $('.results.box').toggle('active');
    $('.button.accordion.results').classList.toggle('active')
  });

  $('.accordion.options').click(function () {
    $('.options.box').toggle('active');
    $('.button.accordion.options').classList.toggle('active')
  });

  $('.add_button').click(function (e) {                    // add compressor
    e.preventDefault();
    if (x < max_compressors) {
      x++;

      $('.input .box').append('<tr class="row comp'+ x +'">\
                <td><b>Compressor ' + x + '</b></td>\
                <td></td>\
                <tr class="row comp' + x + '">\
                <td>New Power Consumption:</td>\
                <td><input type="number" id="newConsumption'+ x +'" oninput="update()" min="0"></td>\
                <td>kWh/week</td></tr>');
    }
    update();
  });

  $('.remove_button').click(function (e) {                    // remove compressor
    e.preventDefault();
    if (x > 1) {
      $('.comp'+ x).remove();
      x--;
    }
    update();
  });
});

function irr(cf) {                                          // calculate IRR
  var irrnpv = 0;
  var rate = 0;
  var ink = 0.00001;

  do {
    rate += ink;
    irrnpv = 0;
    for (var i = 0; i < cf.length; i++) {
      irrnpv += cf[i] / Math.pow((1 + rate), i);
    }
    if (rate > 1) { break }
  } while (irrnpv > 0)

  return (rate * 100).toFixed(1);
}
```

sankey.js

```
d3.sankey = function () {
 var sankey = {},
     nodeWidth = 24,
     nodePadding = 8,
     size = [1, 1],
     nodes = [],
     links = [];

 sankey.nodeWidth = function(_) {
   if (!arguments.length) return nodeWidth;
   nodeWidth = +_;
   return sankey;
 };

 sankey.nodePadding = function(_) {
   if (!arguments.length) return nodePadding;
   nodePadding = +_;
   return sankey;
 };

 sankey.nodes = function(_) {
   if (!arguments.length) return nodes;
   nodes = _;
   return sankey;
 };

 sankey.links = function(_) {
   if (!arguments.length) return links;
   links = _;
   return sankey;
 };

 sankey.size = function(_) {
   if (!arguments.length) return size;
   size = _;
   return sankey;
 };

 sankey.layout = function(iterations) {
   computeNodeLinks();
   computeNodeValues();
   computeNodeBreadths();
   computeNodeDepths(iterations);
   computeLinkDepths();
   return sankey;
 };

 sankey.relayout = function() {
   computeLinkDepths();
   return sankey;
 };

 sankey.link = function() {
   var curvature = .5;

   function link(d) {
     var x0 = d.source.x + d.source.dx,
         x1 = d.target.x,
         xi = d3.interpolateNumber(x0, x1),
         x2 = xi(curvature),
         x3 = xi(1 - curvature),
         y0 = d.source.y + d.sy + d.dy / 2,
         y1 = d.target.y + d.ty + d.dy / 2;
     return "M" + x0 + "," + y0
          + "C" + x2 + "," + y0
          + " " + x3 + "," + y1
          + " " + x1 + "," + y1;
   }

   link.curvature = function(_) {
     if (!arguments.length) return curvature;
     curvature = +_;
     return link;
   };

   return link;
 };

 // Populate the sourceLinks and targetLinks for each node.
 // Also, if the source and target are not objects, assume they are indices.
 function computeNodeLinks() {
   nodes.forEach(function(node) {
     node.sourceLinks = [];
     node.targetLinks = [];
   });
   links.forEach(function(link) {
     var source = link.source,
         target = link.target;
     if (typeof source === "number") source = link.source = nodes[link.source];
     if (typeof target === "number") target = link.target = nodes[link.target];
     source.sourceLinks.push(link);
     target.targetLinks.push(link);
   });
 }

 // Compute the value (size) of each node by summing the associated links.
 function computeNodeValues() {
   nodes.forEach(function(node) {
```

```
      node.value = Math.max(
        d3.sum(node.sourceLinks, value),
        d3.sum(node.targetLinks, value)
      );
    });
  }

  // Iteratively assign the breadth (x-position) for each node.
  // Nodes are assigned the maximum breadth of incoming neighbors plus one;
  // nodes with no incoming links are assigned breadth zero, while
  // nodes with no outgoing links are assigned the maximum breadth.
  function computeNodeBreadths() {
    var remainingNodes = nodes,
        nextNodes,
        x = 0;

    while (remainingNodes.length) {
      nextNodes = [];
      remainingNodes.forEach(function(node) {
        node.x = x;
        node.dx = nodeWidth;
        node.sourceLinks.forEach(function(link) {
          nextNodes.push(link.target);
        });
      });
      remainingNodes = nextNodes;
      ++x;
    }

    //
    moveSinksRight(x);
    scaleNodeBreadths((size[0] - nodeWidth) / (x - 1));
  }

  function moveSourcesRight() {
    nodes.forEach(function(node) {
      if (!node.targetLinks.length) {
        node.x = d3.min(node.sourceLinks, function(d) { return d.target.x; }) - 1;
      }
    });
  }

  function moveSinksRight(x) {
    nodes.forEach(function(node) {
      if (!node.sourceLinks.length) {
        node.x = x - 1;
      }
    });
  }

  function scaleNodeBreadths(kx) {
    nodes.forEach(function(node) {
      node.x *= kx;
    });
  }

  function computeNodeDepths(iterations) {
    var nodesByBreadth = d3.nest()
        .key(function(d) { return d.x; })
        .sortKeys(d3.ascending)
        .entries(nodes)
        .map(function(d) { return d.values; });

    //
    initializeNodeDepth();
    resolveCollisions();
    for (var alpha = 1; iterations > 0; --iterations) {
      relaxRightToLeft(alpha *= .99);
      resolveCollisions();
      relaxLeftToRight(alpha);
      resolveCollisions();
    }

    function initializeNodeDepth() {
      var ky = d3.min(nodesByBreadth, function(nodes) {
        return (size[1] - (nodes.length - 1) * nodePadding) / d3.sum(nodes, value);
      });

      nodesByBreadth.forEach(function(nodes) {
        nodes.forEach(function(node, i) {
          node.y = i;
          node.dy = node.value * ky;
        });
      });

      links.forEach(function(link) {
        link.dy = link.value * ky;
      });
    }

    function relaxLeftToRight(alpha) {
      nodesByBreadth.forEach(function(nodes, breadth) {
        nodes.forEach(function(node) {
          if (node.targetLinks.length) {
            var y = d3.sum(node.targetLinks, weightedSource) / d3.sum(node.targetLinks, value);
            node.y += (y - center(node)) * alpha;
          }
        });
      });

      function weightedSource(link) {
```

```
      return center(link.source) * link.value;
    }
  }

  function relaxRightToLeft(alpha) {
    nodesByBreadth.slice().reverse().forEach(function(nodes) {
      nodes.forEach(function(node) {
        if (node.sourceLinks.length) {
          var y = d3.sum(node.sourceLinks, weightedTarget) / d3.sum(node.sourceLinks, value);
          node.y += (y - center(node)) * alpha;
        }
      });
    });

    function weightedTarget(link) {
      return center(link.target) * link.value;
    }
  }

  function resolveCollisions() {
    nodesByBreadth.forEach(function(nodes) {
      var node,
          dy,
          y0 = 0,
          n = nodes.length,
          i;

      // Push any overlapping nodes down.
      nodes.sort(ascendingDepth);
      for (i = 0; i < n; ++i) {
        node = nodes[i];
        dy = y0 - node.y;
        if (dy > 0) node.y += dy;
        y0 = node.y + node.dy + nodePadding;
      }

      // If the bottommost node goes outside the bounds, push it back up.
      dy = y0 - nodePadding - size[1];
      if (dy > 0) {
        y0 = node.y -= dy;

        // Push any overlapping nodes back up.
        for (i = n - 2; i >= 0; --i) {
          node = nodes[i];
          dy = node.y + node.dy + nodePadding - y0;
          if (dy > 0) node.y -= dy;
          y0 = node.y;
        }
      }
    });
  }

  function ascendingDepth(a, b) {
    return a.y - b.y;
  }
}

function computeLinkDepths() {
  nodes.forEach(function(node) {
    node.sourceLinks.sort(ascendingTargetDepth);
    node.targetLinks.sort(ascendingSourceDepth);
  });
  nodes.forEach(function(node) {
    var sy = 0, ty = 0;
    node.sourceLinks.forEach(function(link) {
      link.sy = sy;
      sy += link.dy;
    });
    node.targetLinks.forEach(function(link) {
      link.ty = ty;
      ty += link.dy;
    });
  });

  function ascendingSourceDepth(a, b) {
    return a.source.y - b.source.y;
  }

  function ascendingTargetDepth(a, b) {
    return a.target.y - b.target.y;
  }
}

function center(node) {
  return node.y + node.dy / 2;
}

function value(link) {
  return link.value;
}

return sankey;
};
```

style.css

```
.top{
    display: inline-flex;
}
.topSpacer{
    width: 50px;
}
.heading{
    font-family: Arial;
    font-size: 35px;
}
.logo{
    background-image: url("logo.PNG");
    background-size: contain;
    background-repeat: no-repeat;
    background-position: center;
    width: 300px;
}
.calculator{
    text-align: center;
    padding: 10px;
    font-family: Arial;
    line-height: 1.5;
}
.io{
    display: inline-flex;
    align-items: center;
}
.input {
}
.midSpacer{
    width: 200px;
}
.output{
}
.charts{
    display: inline-flex;
    align-content: center;
}
.sankey{
}
.bottomSpacer{
    width: 200px;
}
.footer{
    text-align: center;
    font-family: Arial;
}
h2{
    font-weight: lighter;
    text-align: center;
}
.radiolist{
    vertical-align: middle;
}
.row{
    height: 30px;
}
button.accordion{
    background-color: #eee;
    color: #444;
    cursor: pointer;
    padding: 10px;
    margin: 10px;
    width: 400px;
    text-align: center;
    border: none;
    outline: none;
    transition:.6s ease-in-out ;
    border-radius: 10px;
}
button.accordion.active, button.accordion:hover {
    background-color: #ddd;
}
div.results {
    display: none;
    min-width: 100%;
    align-content: center;
}
div.results.show {
    display: block;
}
div.options {
    display: none;
    min-width: 100%;
}
div.options.show {
    display: block;
}
button.accordion:after {
    content: '\02795'; /* Unicode character for "plus" sign (+) */
    font-size: 13px;
    color: #777;
    float: right;
    margin-left: 5px;
```

```
}
button.accordion:active::after{
    content: "\2796"; /* Unicode character for "minus" sign (-) */
}
/*----------------------------Sankey Chart-------------------------------------*/
        .node rect {
            cursor: move;
            fill-opacity: .9;
            shape-rendering: crispEdges;
        }

        .node text {
            pointer-events: none;
            text-shadow: 0 1px 0 #fff;
        }

        .link {
            fill: none;
            stroke: #000;
            stroke-opacity: .2;
        }

        .link:hover {
            stroke-opacity: .5;
        }
/*--------------------------------------------------------------------------------*/
input::-webkit-outer-spin-button,
input::-webkit-inner-spin-button {
    /* display: none; <- Crashes Chrome on hover */
    -webkit-appearance: none;
    margin: 0;
}
input[type='number'] {
    -moz-appearance:textfield;
}
.details.header {
    background-color: darkgray;
    color: white;
    height: 25px;
    width: 120px;
    font-style: normal;
    padding-bottom: 5px;
    padding-top: 5px;
    font-family: Arial, Helvetica, sans-serif;
}
.details.table {
    text-align: left;

}
.details.header.year {
    padding-left:5px;
}
.details.year {
    padding-left:5px;
}
```