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Mitro Misenko

# Means for Improving the Energy Efficiency of Pressure Systems

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The aim of this Bachelor's thesis was to examine what the positive adjustments in compressed air systems in an industrial setting were. The thesis was done for Sarlin Oy Ab. Another aim of this thesis was to produce material which could be used as internal training material for Sarlin Oy Ab and could also be utilized in general training settings for customers and subcontractors.

In this thesis project, the basics and principles of compressed air were examined. Also, directives of compressed air regulations and the equipment used in production and control of pressurized air were studied.

The thesis introduces three different case studies from Sarlin Oy Ab, all of which, showcase the common problems and noteworthy issues in the pressure system. The correction adjustments for the problems are compared to the manufacturing facilities historical trends of energy efficiency, and then it is examined why some adjustment affected positively or negatively.

The results of the data analysis showed that the majority of the issues within the system were caused by older equipment, too high-pressure level or lack of guidance for the compressors. In each case study, the problems were solved gradually by first starting from the largest problem, such as renewing the main air producing compressors. Often every single equipment in the system was added to Sarlin Balance -guiding system, allowing for optimization of air production and pressure levels.



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|---|---|
| Keywords | compressors, compressed air, Sarlin Balance |

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Tämän opinnäytetyön tarkoituksena oli tutkia mahdollisuuksia ja menetelmiä energiansäästöön teollisten paineilmajärjestelmien parissa. Tarkoituksena oli myös tuottaa osittain koulutuksessa käytettävää materiaalia englanninkielellä, jolloin materiaalia voidaan hyödyntää kansainvälisissä tilaisuuksissa alihankkijoiden ja asiakkaiden perehdytyksessä. Työ tehtiin Sarlin Oy Ab:lle.

Työssä käsitellään alustavasti paineilman perusteita teoriatasolla, paineilmanlaadun ISO-säännöksiä ja laitteistoa millä paineilmaa tuotetaan ja hallitaan.

Opinnäytetyössä esitellään kolmen Sarlin Oy Ab:n asiakkaan asiakasraportit, joissa esitellään yleiset ongelmat ja huomiot järjestelmissä. Näitä muutoksia vertaillaan laitoksen ilman- ja tehonkulutuksen historiaan ja pohditaan syitä, miksi jokin toimenpide vaikutti positiivisella tai heikentävällä vaikutuksella.

Analyysissä selvisi, että usein teollisten laitosten paineilmatehokkuuden heikkous johtui vanhentuneesta kalustosta, liian korkeasta painetasosta paineilmajärjestelmässä tai kompressorien ohjauksen puutteesta. Jokaisessa asiakastapauksessa ongelmakohdat korjattiin keskittymällä ensiksi vakavimpiin ongelmiin, kuten uusimalla pääkompressorit, joilla suurimmat ilmamäärät tuotettiin. Kaikki laitteistot liitettiin usein Sarlin Balance -ohjausjärjestelmään, jonka avulla kyettiin optimoimaan järjestelmän ilmantuotto ja painetaso.

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|---|---|
| Avainsanat | kompressorit, paineilma, Sarlin Balance |

## Contents

## List of Abbreviations

| | |
|---|---|
| IGV | Inlet gauge valve. Directs air flow in turbo compressors |
| BOV | Blow-off valve. Pressure release system in turbo compressors |
| VSD | Variable speed drive rotary screw compressor |
| BLS | Base load sequencing. Compair’s compressor controller system |
| SP | Specific Power, i.e., energy efficiency. Unit $\frac{\frac{kW}{m^3}}{min}$ |
| W | Watt, unit for work. SI-unit, $W = \frac{J}{s} = \frac{kgm^2}{s^3}$ |

## 1 Introduction

Compressors and pressurized air networks in industrial setting require a large amount of energy annually. Generally, the energy consumption of pressure networks takes 10% of the total energy needed by the facility. This requirement means that, given how many pre-existing industrial facilities there are already in the world, there is a large market open and vast improvement to be made regarding energy efficiency.

This thesis was done for Sarlin Oy Ab. Sarlin Oy Ab specializes in sustainable energy technology, automation and pressurized air.

This thesis aims to familiarize the reader with compression systems, pressure networks and the challenges they bring to the industrial facilities. It also studies three different case stories about manufacturing facilities issues with pressure production and sudden pressure drops in the network and shows how Sarlin Oy Ab gradually managed to solve these problems at the facilities.

# 2 Compressed Air

## 2.1 Theory of air compression

Compressed air is very energy-consuming to produce. It takes considerably more energy to compress air than it provides at the point of usage, but its advantage is that it is generally not harmful to humans as it does not cause burns, shocks nor it does cause danger if inhaled.

Compression of air can happen in several different ways. There is kinetic, static or pressure increase through the counterflow

In kinetic compression, the suction and pressure chambers are continuously connected to each other and the dynamic forces of the gas itself prevent the backflow of the gas out of the compression chamber.

In static compression, however, the air is trapped into a chamber whose volume is then changed, leading into compression. An example of this process would be a piston chamber filled with gas and its volume reducing as the piston pushes towards the chamber ceiling leading into pressurized gas. This is based on the equation of ideal gas:

$$p = \frac{mRT}{V} \tag{1}$$

In ideal gas equation *p* is the pressure of the gas, *m* is the mass of the gas, *R* is the gas constant and for air its value is 287 J/kg*K, *T* is the temperature of the gas and *V* is the volume of the gas. Air follows the equation of ideal gas very accurately in average temperatures and less than 20 bar pressure; thus, ideal gas equation can be used to cross-check estimations. (Lappalainen 2019.)

According to the 1$^{st}$ Law of thermodynamics, the following is valid during compression of air:

$$Q + E = \Delta W \tag{2}$$

If energy is substituted with air's internal energy (*U*), this means that pressurized air's internal energy increases whenever there is work (*W*) done or heat (*Q*) brought to the system.

In isentropic compression (*Q)* is 0 and the internal energy scales directly with work added on the system.  Isentropic compression follows the equations given below. (Airila et al., 1983:16).

$$p_f = p_b \left(\frac{V_b}{V_f}\right)^{\gamma} \tag{3}$$

$$T_f = T_b \left(\frac{V_b}{V_f}\right)^{\gamma - 1} \tag{4}$$

$$T_f = T_b \left(\frac{p_f}{p_b}\right)^{\frac{\gamma - 1}{\gamma}} \tag{5}$$

$p_f$ is the final pressure level after compression
$p_b$ is the pressure level in the before compression
$T_f$ is the temperature of air after compression
$T_b$ is the temperature of air before compression
$V_f$ is the volume of the air after the compression
$V_b$ is the volume of the air before the compression
$\gamma$ is the isentropic exponent for air, which is 1.4

In isothermal compression, the work done by compression is directed to the surroundings as in the form of heat and temperature of the air stays constant. Isothermal compression never happens because the system where the compression happens would have to be a completely closed system; thus, preventing heat exchange occurring with surroundings of the compressor. The closest you can get to the isothermal compression is when you use water cooled compressors and especially during winter when the cooling waters temperature nears its freezing point.

A better model for real life compression systems would be polytropic compression. As seen in Figure 1, its work process is close to the isothermal compression, therefore, isothermal compression can be substituted with polytropic compression.

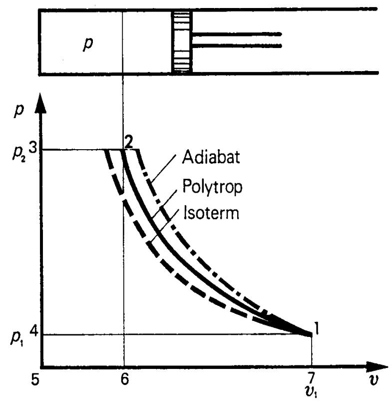


Figure 1. Different types of compression in relation to volume and pressure (General. 2015)

In polytropic compression part of the work done by compression is transferred into the surroundings and rest of it increases the internal energy of the air. Polytropic compression follows the equations. (Airila et al., 1983:26.)

$$p_f = p_b \left(\frac{V_b}{V_f}\right)^n \tag{6}$$

$$T_f = T_b \left(\frac{V_b}{V_f}\right)^{n-1} \tag{7}$$

$$T_f = T_b \left(\frac{p_f}{p_b}\right)^{\frac{n-1}{n}} \tag{8}$$

$p_f$ is the final pressure level after compression

$p_b$ is the pressure level in the before compression

$T_f$ is the temperature of air after compression

$T_b$ is the temperature of air before compression

$V_f$ is the volume of the air after the compression

$V_b$ is the volume of the air before the compression

$n$ is the polytropic exponent

One of the ways to lessen the amount of work needed for compression is to divide the workload between different stages and cool the air down in between the compression stages. This can be seen, when comparing work required for various stages. Work needed for different stages of compression, when examining discharge pressure of 8 bar is calculated as follows:

$$W_1 = \frac{K}{K-1} * p_{atm} * \dot{V}_1 * \left[\left(\frac{p_d}{p_{atm}}\right)^{\frac{K-1}{K}} - 1\right] = \frac{1.4}{1.4-1} * 1000000 * 1 * \left[\left(\frac{8000000}{1000000}\right)^{\frac{1.4-1}{1.4}} - 1\right]$$

$$W_1 = 283\ 900\ W \tag{9}$$

$$W_2 = 2 * \frac{K}{K-1} * p_{atm} * \dot{V}_1 * \left[\left(\left(\frac{p_d}{p_{atm}}\right)^{\frac{1}{2}}\right)^{\frac{K-1}{K}} - 1\right] = 2 * \frac{1.4}{1.4-1} * 1000000 * 1 * \left[\left(\sqrt{8}\right)^{\frac{1.4-1}{1.4}} - 1\right]$$

$$W_2 = 242\ 200\ W \tag{10}$$

$$W_3 = 3 * \frac{K}{K-1} * p_{atm} * \dot{V}_1 * \left[\left(\left(\frac{p_d}{p_{atm}}\right)^{\frac{1}{3}}\right)^{\frac{K-1}{K}} - 1\right] = 3 * \frac{1.4}{1.4-1} * 1000000 * 1 * \left[\left(\sqrt[3]{8}\right)^{\frac{1.4-1}{1.4}} - 1\right]$$

$$W_3 = 229\ 600\ W \tag{11}$$

$W_n$ is the work done by a different type of compression, $n = 1 \ldots 3$
$K$ is the adiabatic exponent, in this situation, same as the isentropic exponent
$\dot{V}_1$ is the volume flow the compressor uses every second
$p_d$ is the discharge pressure of the compressor
$p_{atm}$ is the atmospheric pressure, rounded off to 1 bar

Saving energy with two or three stages compared to one stage compression

$$\eta_{12} = \left(1 - \frac{W_2}{W_1}\right) * 100 = \left(1 - \frac{242.2\ kW}{283.9\ kW}\right) * 100 = 14.7\% \tag{12}$$

$$\eta_{13} = \left(1 - \frac{W_3}{W_1}\right) * 100 = \left(1 - \frac{229.6\ kW}{283.9\ kW}\right) * 100 = 19.1\% \qquad (13)$$

Work required for single stage compression $W_1$ is 283.9 kW for 1 cubic meter of air flow per second. For two stage compression, the equivalent energy required $W_2$ is 242.2 kW and for three stage, the energy required $W_3$ is 229.6 kW. Comparing the work done by the different stages, shows that even by adding one more stage to the compression process saves approximately 15 % of the energy required. (Compressed. 2015.)

## 2.2 Air Quality

Air used in compression always contains contaminants which affect the air quality and usage of compressors and usage of the produced air in the network itself. The contaminants used in compressed air system can be attributed to the quality of air that is used during compression, the type of compressor used in compression and storage devices and distribution systems used for compression air. The air in an industrial environment contains typically approximately 140 million dirt particles in each cubic meters of air. 80% of the dust particles are too small to be captured by the compressor's intake filters and will pass into the air system. (Hunt. 2004.)

Along with the dust particles, the air also contains water vapor. Air's ability to hold water vapor is dependent upon its temperature. This means that, during the compression, the air temperature rises and allows the air to retain the moisture. After the compression, air typically is cooled back to a suitable temperature. The cooling process reduces air's ability to keep the water vapor in gaseous form, and water gets condensed into liquid form. As the air further cools down in the network, more water condenses into a liquid in the network. This leads to corrosion within storage and distribution systems, damages on production equipment and to the end product. There is usually a refrigerating compressor after the compressor which condenses the water vapor and that liquid is then directed to the drainage network.

Other fluid that can be found in the air is oil, either in liquid or gaseous form and typically oil vapor concentrations can vary between 0.05 mg and 0.5 mg per cubic meter of ambient air. This is because nearly all of the compressors use oil itself in the compression stage for sealing, general lubrication and for cooling processes. As the oil gets into the compressor processes, it mixes with water vapor, and the product of the two becomes acidic which causes damage to the air storage, pressure network, equipment which uses the air and the final product itself. Both water and oil is removed from the air directly after compression with the combination of dryers and filters. (Hunt. 2004.)

### 2.2.1 ISO 8573 standard for compressed air

ISO 8573-1:2010 dictates for industrial air what the acceptable contaminant levels of dust, water, and oil in the compressed air are. For breathing air, the EN 12021 -the standard is used because it has stricter quality standards than ISO 8573. The number of contaminants and their maximum prohibited size can be seen in Figure 2.

| ISO8573-1:2010 CLASS | Solid Particulate | | | | Water | | Oil |
|---|---|---|---|---|---|---|---|
| | Maximum number of particles per m³ | | | Mass Concentration mg/m³ | Vapour Pressure Dewpoint | Liquid g/m³ | Total Oil (aerosol liquid and vapour) |
| | 0.1 - 0.5 micron | 0.5 - 1 micron | 1 - 5 micron | | | | mg/m³ |
| 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 |

Figure 2. ISO 8573-1:2010 chart showing requirements for different classes (Sullair. 2019).

The end use for the compressed air dictates what quality the air should be. This can be seen comparing the quality of normal paper mill factory and component factory. Normally paper mill factory would require a class of 1.2.1 and component factory would use 1.1.1. due to high restrictions in dust, water and oil residues.

Examples of how to write air quality specification in accordance with ISO 8573-1:2010 class 1.2.1 are listed below:

- Class 1 dictates that in 0.1 – 0.5-micron range, particle amount should not exceed 20.000 particles, 0.5 – 1-micron range should not exceed 400 particles or in 1 – 5-micron range particle count should not exceed 10 particles per one cubic meter of compressed air.

- Class 2 dictates that pressure dew point should be -40°C or lower and no liquid is allowed.
- Class 1 instructs that no more than 0.01 milligrams per cubicle meters of compressed air, is allowed.

### 2.2.2 Purification equipment

Coalescing filters remove aerosols of water and oil from compressed air. They also remove small solid particles. Normally, coalescing filters are installed in pairs because the first filter acts as a general filter and filters out larger particles out of the air. The second filter uses the high-efficiency filter, which specializes in removing smaller particles out of the air. Reversing the order of the filters would result in a clogged filter system which would lead to pressure drop in the network after the filters.

Water vapor can be usually found directly after compressors due to high temperatures, but at some point, vapor temperature decreases under its dew point and condenses into liquid form. Because water in its liquid form is harmful to the network due to corrosion or freezing it may cause, it’s crucial to install water separators along with the dryers to remove water from the air.

The amount water in the network can be also controlled with pipeline geometry by aligning the pipe vertically or making a reversed U-shaped notch after dryers, as seen in Figure 3, filters and water separator, preventing the water from moving on to the network.

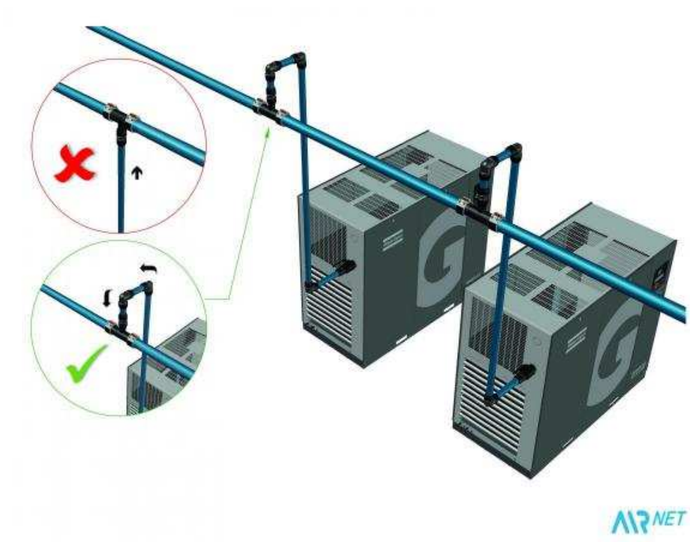


Figure 3. Pipeline geometry for preventing liquids from proceeding to the pressure network (Bruno 2019).

Some of the bacteria and viruses perish during the compression process due to the high temperature, but the majority of them still gets passed into the network. In a standard industrial setting, this is not a problem, but it will pose a threat in chemical, medical or food industries. Both bacteria and viruses can be filtered out by using heat-sterilized filters, which are either membrane, syringe or capsule filters.

Adsorption dryers might leak dust into the network due to the solid, dry pebbles that are used in them to bind moisture from the compressed air. This dust is usually removed by a set of filters which are installed after the dryer.

## 2.3 Compressors

Compressors come in either dynamic or displacement compressors, which can be seen in Figure 4. Positive displacement includes reciprocating compressors, orbital compressors and different types of rotary compressors, with the exception of variable speed (VSD) compressor. The basic idea behind positive displacement compressors is that the air is drawn inside one or more compression chambers where gradually the volume of each chamber is decreased internally until desired pressure has been reached. After reaching nominated pressure level a port or a valve is opened and the air discharges into the network.

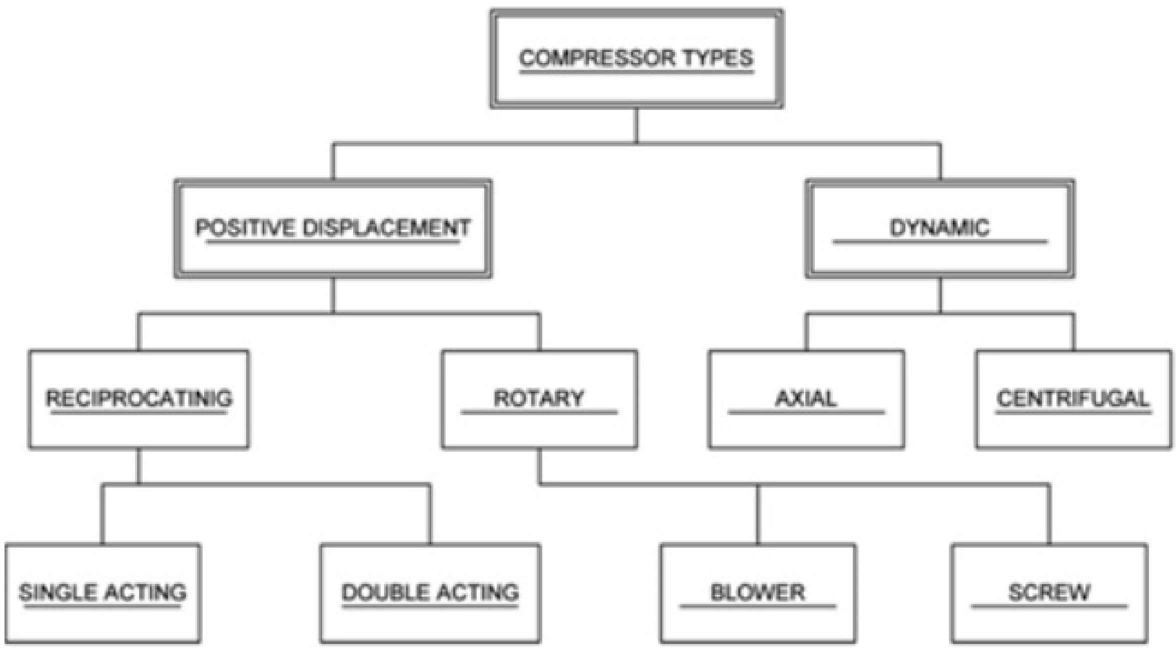


Figure 4. Compressor family tree (Piping-Engineering. 2019).

In dynamic compressors, the air is drawn between rapidly rotating blades where the air is accelerated into high velocity. Then the gas gets discharged through a diffuser, where its kinetic energy is transformed into static pressure. Each impeller speed has both an upper and a lower speed limit. Gas flow's sonic velocity is the upper limit. The lower limit instead means that once the counter pressure becomes greater than the pressure build-up inside the compressor, the airflow would return back into the compressor. This would result in pulsation and noise, which would risk mechanical damage to the compressor itself. (Atlas Copco.2019.)

The amount of air compressors produce, even if they are made by the same manufacturer and are the same models, is not always the same. There are multiple different factors that affect how compressors work. The air temperature, pressure and humidity all affect pressure production; thus, compressor positioning matters greatly.

### 2.3.1 Reciprocating compressors

Piston compressors work by having a smaller pressure in the cylinder than atmospheric pressure, which causes the air flowing into the cylinder. As the piston compresses the air, it starts flowing into the network once the compressed air pressure exceeds the pressure in the network. Once the air has exited the cylinder, it leaves an empty space between the piston and cylinder head. Suction starts again once a vacuum generates into the cylinder.

The piston cannot empty the chamber completely, and there are residues of compressed air left within clearances and nooks of valves. This residual volume is approximately 3 to 10% of the stroke volume.

Piston compressors have a wide output range from 0.001 to 100 m3/min and wide pressure range from 1 to 1000 bar. 1-stage compressors are used to generate up till 10 bar range, 2-stage compressors from 5 to 30 bar, 3-stage compressors from 20 to 350 bar and 4-stage piston compressors are used to generate a pressure of 200 – 600 bars. (Airila et al., 1983:26.)

### 2.3.2 Vane compressors

Vane compressors work with multiple chambers attached to the off-centered shaft. As the shaft rotates around, Air enters the vane housing as its volume is at its largest and exists the housing when the volume is at its smallest.

Oil-less vane compressors are used for smaller pressure levels. For normal 8 bar pressure, vane compressors are usually oil-lubricated models. Vane compressors used above 8 bar are usually 2-staged models for eliminating leaks and decreasing mechanical stress.

Regulating the air intake in vane compressors happens by chocking the incoming air; thus, lessening the amount of air compressor receives. Controlling the produced air output can also be done by adjusting the counterpressure on the compressors pressure network side.

Vane compressors are generally used in smaller machine shops as they only generate air up to 10 m3/min and, the pressure ranges from 5 to 10 bars.

### 2.3.3 Rotary blower compressor

The most known type of rotary blower compressor type is Root's blower. Its chamber consists of two symmetrical rotating lobes with synchronized movement. As the gas enters from the inlet side the lobes spin and traps the gas (see Figure 5.) between the casing and the lobe. As this happens, the gas gets compressed and is eventually released on the discharge side as the lobes keep turning.

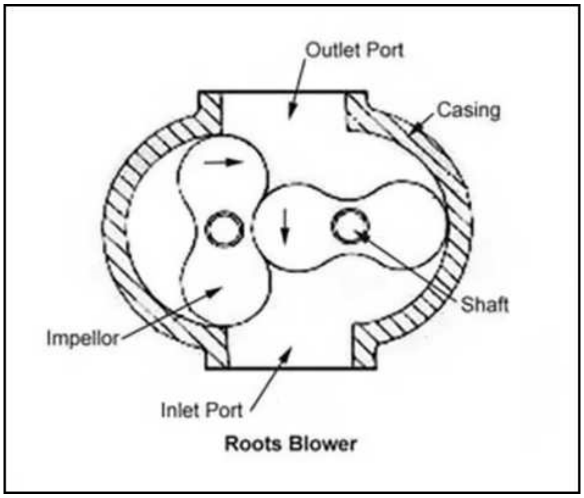


Figure 5. Root's compression chamber (Shreejiblower 2019).

Root's blowers are usually oil-less and cooled by air, but in rare cases, water cooled blowers can be found. Due to their lower efficiency limits, they are generally used in low-pressure applications, such as vacuum pumps.

### 2.3.4 Rotary screw compressors

The principle on how rotatory screw compressors operate is that the compressor chamber features two meshing rotors that suck in air through intake hole when the rotor blades are aligned with the intake orifice. As the rotors spin, the meshing point closes the intake orifice and seals the air inside the frame in a sealed space. As the blades keep rotating, space keeps decreasing; thus, the air gets compressed. At desired output pressure, the compressed air flows out of the compressor into a receiver.

Oil-less screw compressors usually have rotation speeds of from 100 to 180 rounds per second. Lubricated compressors have lower rates at 50 to 120 rounds per second. Peripheral velocity in oil-less compressors is usually lower than 120 meters per second and in lubricated compressors less than 50 meters per second.

Rotary screw compressors differ from other models in that they also have variable speed models. Fixed speed compressors either produce the amount of air defined by its nominal output during full load -phase or produce nothing, which is its unloading stage as seen in Figure 6. Variable speed drive (VSD) compressors are dynamic compressor variants, which means, that they produce anywhere between 30-100% of their nominal output.

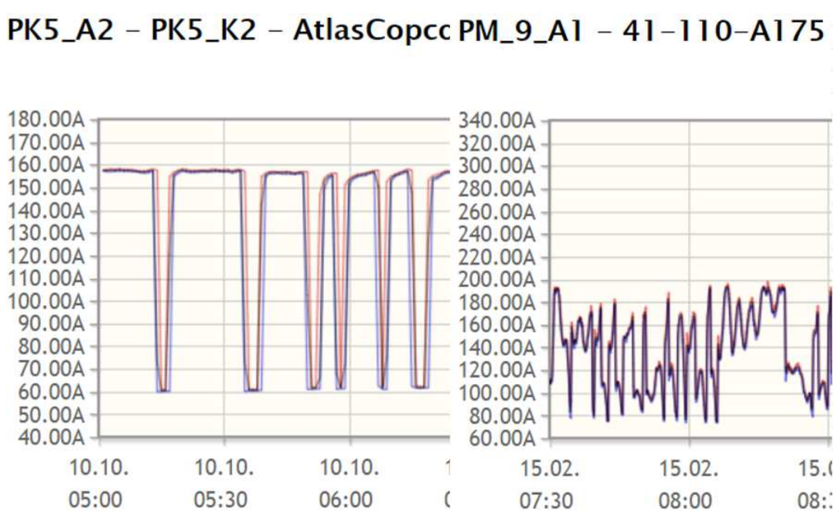


Figure 6. Difference in current profile of fixed speed (left) and variable speed (right) compressors

Using variable speed drive compressors have benefits over fixed speed compressors. They can start or stop under full system pressure with no need for unloading. Removing the unloading phase from the cycle saves energy and time. As variable speed drive compressors can operate on lower pressure settings, they put the pressure network to lesser stress, causing fewer pressure leakages in the pipelines.

### 2.3.5 Turbo compressors

Turbo compressors are either centrifugal or axial compressors, both which, are dynamic compressors. They generate pressure through kinetic compression and their output depends on pressure (Figure 7).

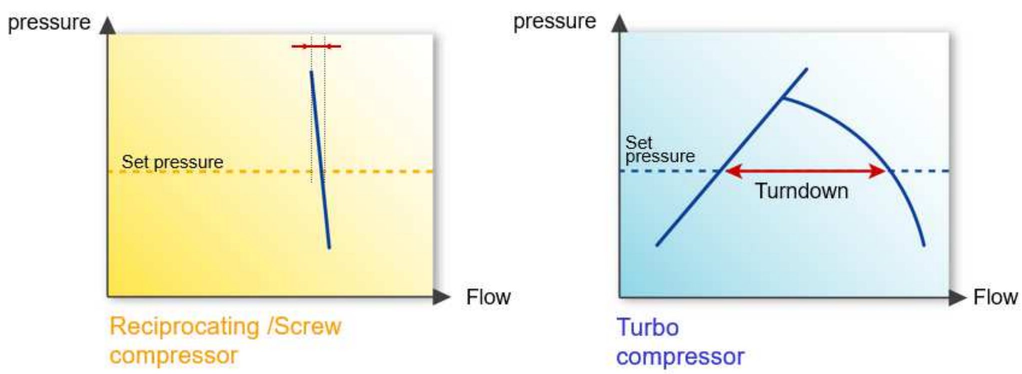


Figure 7. Statically compressing compressor and turbo compressor's relative air output dependency of relative end pressure (Samsung.2004).

Turbo compressor cannot operate properly if its output is throttled too much as this leads to a phenomenon named Surge. Surge is where the compressors rotary system cannot overcome backpressure from pressure network and this leads into backflow of air into the compressors. This backflow causes a rise in air temperature and vibration in the components; thus, eventually causing damage to the compressor itself. If the compressor reaches a surge area while operating, the compressors control unit will open a blow-off valve (BOV) to discharge pressure, preventing further surging.

In Figure 8, the red line indicates surge-line through testing by the manufacturer. The blue surge control line can be determined but it is dependent on external conditions. But in general, the control line has a 7% margin from the surge line based on the rated current.

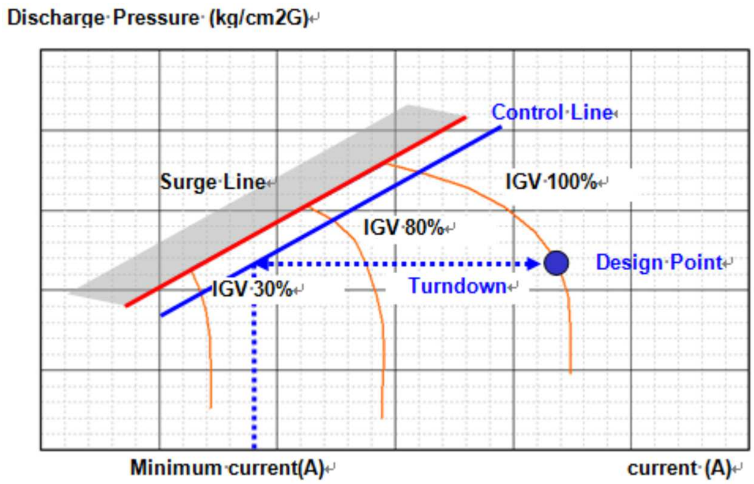


Figure 8. Discharge pressure depends on motor current (Samsung.2014).

Inlet guide valve (IGV), seen in Figure 9, is a device that adjusts the amount of gas being sucked into the compressor. Without the inlet guide valve, the compressor would suck air into the compressor without any regulation. This means that without inlet guide valve, the compressor would pull fixed flow of air into the compressors without any regard on what loading phase the compressor would be going through and the compressor could not meet the demands of a pressure network efficiently.


Figure 9. Both IGV and BOV seen on the compressor.

The use of inlet guide valve needs to be regulated, however. If the amount of compression gas increases and system pressure lowers, the control system opens the inlet guide valve gradually to maintain system pressure at the desired level. If the air consumption keeps increasing and the inlet guide valve opens up too much, overloads could occur in the motor. Therefore, to protect the motor, opening of the inlet guide valve is limited.

Advantages of using turbo compressors are that they have high power density, meaning they take less space compared to different compressor models which equal the same nominal air output. They are reliable because it is already proven technology from the aerial industry, as they use technology than turbines.

Disadvantages from using turbo compressors would be a high discharge temperature, which would cause challenges for dryers as high air temperature causes moisture in the air, hence more risk for corrosion in the pipelines.

### 2.4 Sarlin Balance

Sarlin Balance is a control unit which can be used to control all types of compressors simultaneously, with a goal of keeping the pressure levels steady and providing information out of pressure network. This results in better air quality and energy savings up to 30% compared to a compressor system without Sarlin Balance -control unit.

Sarlin Balance usually consists of a main controller unit, although using multiple controlling units is possible, depending on how many compressor stations there are. Pressure sensors are installed into the network at compressed air usage points, which monitor and send a signal to the controller unit whenever the pressure levels are too low or high. Control unit recognizes this and adjusts compressor system to match the air usage by either decreasing or increasing production in one or multiple compressors.

Sarlin Balance has a visual display or interface, seen in Figure 10, which provides an entire process schematic from air intakes to final use in production. It is compatible with all of the compressed air systems and compressor types even if compressors were from different manufacturer or type, e.g., a combination of turbo compressors, rotary screw compressors with either fixed speed or variable speed models.

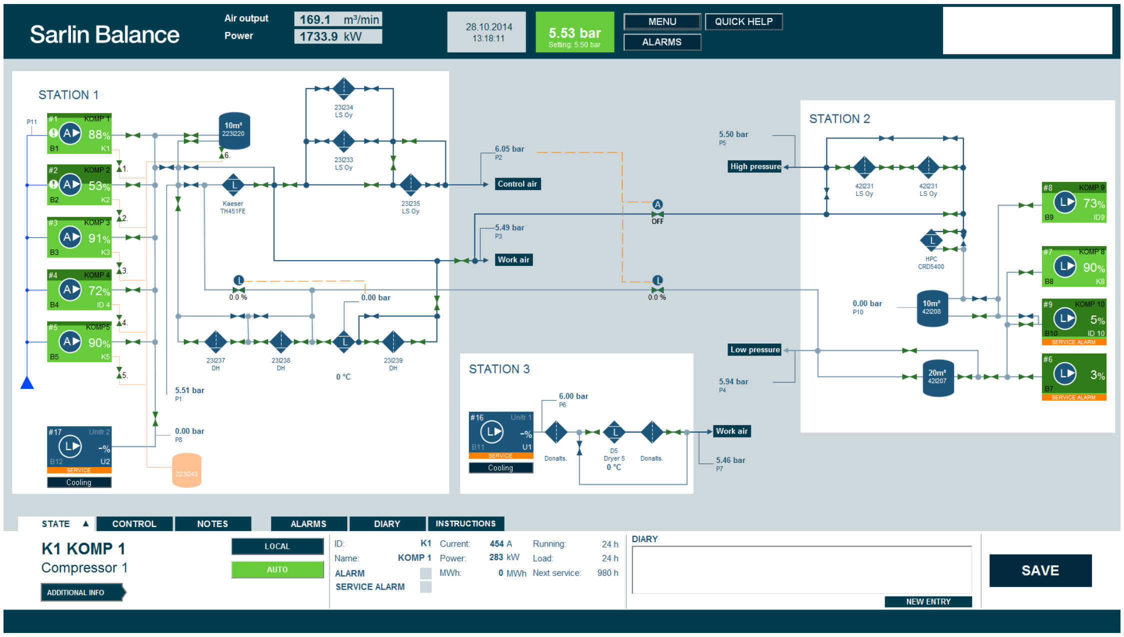


Figure 10. Sarlin Balance main display.

Sarlin Balance allows the user to observe the pressure system and receive all of the critical information of every device in the delivery system. It also allows personnel rearrange processes remotely in every situation.

The controlling method behind Balance guidance system allows it to minimize the number of compressor start and stops, loads compressors at a lower pressure than they usually would and introduces reserve capacity in the network faster, when needed.

Balance allows analyzation, which enables improvements and savings for maintenance. The system records the whole history of events and is able to analyze the system performance quickly and locates the primary causes for decreased performance.

The benefits Sarlin Balance gives for the production itself is seen in reliable air supply and steady pressure, which are critical components in most of the production processes. Production of quality improves with steady pressure as raw material usage is optimized.

The savings Sarlin Balance produces for the user are both direct and indirect savings. Direct savings are generated from energy consumption by lowering the general network pressure as the energy required to produce the said energy is also decreased. Decreasing the pressure also lowers the risk of network leakages which brings direct savings to the user. As Balance is able to keep the pressure steadier, it also allows the optimization of the use of air, therefore saving energy and money. As Balance allows more precise use of compressors, it eliminates effectively simultaneous use of unloading compressors, and as a result generates energy savings. Indirect effects would be accrued from lower maintenance and repair costs, lessened operator hours bound to air supply system as the controlling is automated with Balance. Another would be because, as the pressure is lowered it causes less strain on equipment which instead causes savings in replacement investments.

# 3 Customer-based reports

Specific power (SP) comes from the power required by the whole system divided by the free air delivery, which roughly shows how much energy is used per air produced.

## 3.1 Case study A

Sarlin Balance was installed at the beginning of 2011, and regular observing periods of the pressure system was held during the first year quarterly and 2012 onwards every half a year. Based on the data received, system improvements were proposed to the factory. Pressure system layout seen in Sarlin Balance interface, Figure 11.

The factory has three different stations: station one “paper mill” (PM), station two “welding station” (W) and station three “after treatment” (AT). Station one holds six different compressors: five rotary screws and one turbo compressor, Cooper TA3000. Station two has four compressors, all rotary screws. Station three has one turbo compressor, Ingersoll-Rand Centac.

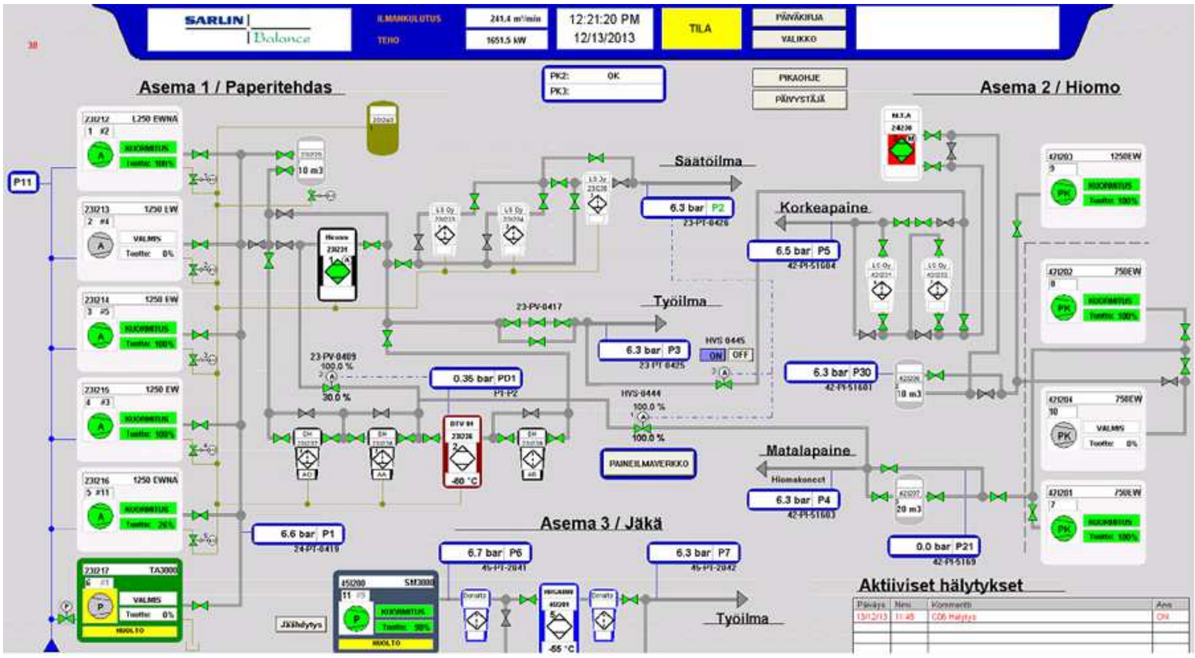


Figure 11. Overview of the factory compressor system.

During the first quarter of 2011, the average air consumption was approximately 140 cubic meters per minute and power of 1.2 megawatts specific power of 8.57.

There is a significant issue with pressure capacity, as Centac at PM-station stops and Cooper starts at AT-station with three other rotary screws work at full load at PM. Pressure rises to critical levels at the station as the discharge is unable to move forward to the network from dryers. A pressure drop of 2.5 bar occurs, and network pressure dips to 4.3 bar. As the pressure is in critical levels on-air production end, the compressors go into off-loading phase. Welding station has extremely low pressure of 3.5 bar, mainly because station compressors are not running at full load. PM-station cannot compensate for the low-pressure level at the welding station as the pipeline between them is too narrow and can only transport 40 cubic meters of air per minute.

Air consumption stays at 140 cubic meters per minute during the second quarter, but the power needed to produce the air lowers to 1.1 megawatts, decreasing the power and output ratio to 7.86.

Both turbo compressors at PM-station and AT-station are running in minimum load in avoidance of pressure discharges as the temperature of the exhaust gases of the compressors would be too high. One to three compressors are operating normally at the welding station, two of them produce air at full-load, and one occasionally starts. Pressure level at welding station sifts between 5 to 6 bar.

During the third quarter of 2011, consumption of air was 150 cubic meters per minute. Power requirement was 1150 kW with the power to air output ratio of 7.67.

During the observation period, there was only one point when pressure levels dropped below the minimum, but generally, pressure levels stayed the same compared to the second quarter. To lower the operating pressure level in welding station would require redoing the connecting pipeline between the welding station and PM-station. Turbo compressor at PM -station, Cooper TA3000, stopped running, maintenance tried to compensate this by turning rotary screw compressor with an inverter on but failing to do so.

Some of the issues resolve during the fourth quarter, as the rotary screw compressors in PM-station are now fully operational and added into Sarlin Balance controlling system. Generally, air consumption and power requirements stay the same compared to the third quarter.

In 2012, there was only one observation period. Air consumption had increased a bit compared to the previous year, 155 cubic meters per minute and power requirement was at 1.2 megawatts, giving an efficiency ratio of 7.74.

Both turbo compressors have increased loading level, but there is still an issue with rotary screw compressors as they tend to work on full-load too easily. Hiross-refrigerator dryer after PM-station has small spikes in its dew points, meaning dew points increase too high during the period of few seconds. At welding station, Tamrock screw compressors 6 and 11 are still the main air producers with compressor eight occasionally starting up and loading.

In 2013, air consumption level increased to 180 cubic meters per minute, power requirement was 1.25 megawatts, an efficiency ratio was at 6.94.

Ingersoll-Rand Centac turbo compressor changed into a newer turbo compressor Samsung SM3000, which runs nearly all the time in full-load. Compressors at welding station run occasionally. Pressure level fluctuated strongly when compressors were running in manual. Balance guides compressors to increase network pressure level to 6.1 bar during web breaks. On 7 December 2013 problems occurred with pressure levels as Sarlin Balance was not functioning normally. 13 December 2013 pressure dropped below a critical level of 4.3 bar, and the compressor moves to manual run.

In the year 2014 average air consumption was 202.3 cubic meters per minute and the power requirement was 1.244 megawatts, giving the efficiency ratio of 6.15.

Cooper TA3000 turbo compressor in station one has been replaced with new Samsung SM3000 compressor. When both SM3000 are running at the same time, the efficiency ratio can be less than 6.0. PM-station is experiencing approximately of 1 bar pressure loss when all the compressors in the station are running, and Hiross-dryer is not in use.

The year 2015 saw continued improvement in energy efficiency as air consumption increased to 229.8 cubic meters per minute, but power requirement decreased to 1.234 megawatts, with an efficiency ratio of 5.76.

Automated guidance was added to the cooling valves of SM3000 turbo compressors as a move to save energy. Hiross-refrigeration dryer changed to FST DTS 720 VH 690V adsorption dryer, which was connected to the Sarlin Balance-system. Pressure difference over after treatment at PM-station is now 0.35 bar.

At the end of the year, pressure levels dropped to 5 bar due to web breaks, which can be seen in Figure 12, in the production as few of the rotary screw compressors were under maintenance and rest of the compressors could not manage with the sudden demand for air.

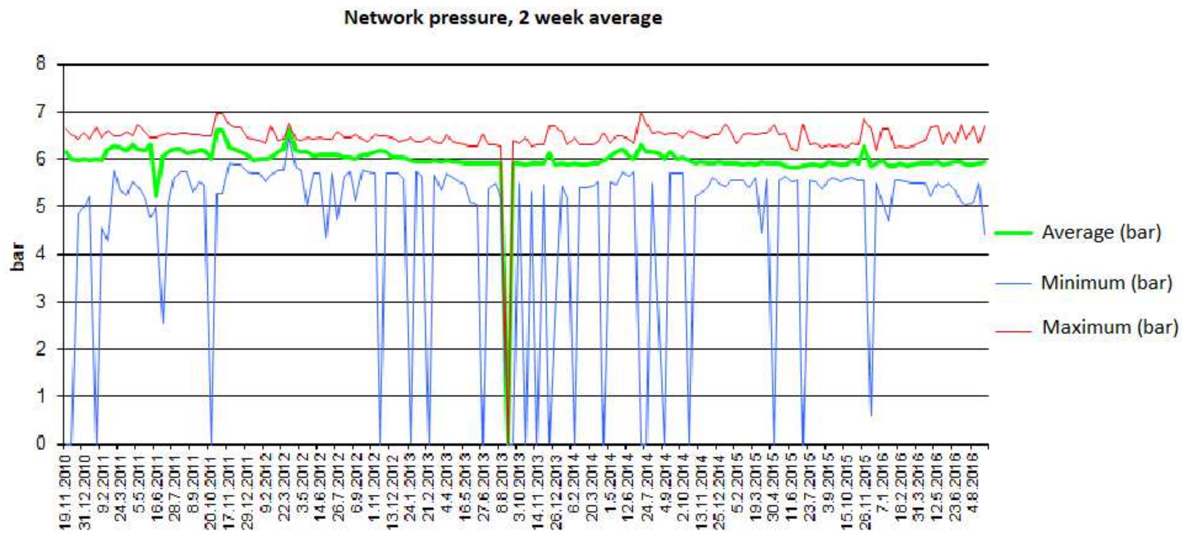


Figure 12. Network pressure changes throughout the period of 2010 – 2016.

During the year 2016 air consumption had risen to an average 256.2 cubic meters per minute with a power requirement of 1.507 megawatts. Specific power was 5.88.

Both Samsung SM3000 turbo compressors were loading at 100 % along with variable speed drive compressor from station one, which supports the turbo's whenever demand for air exceeds 250 cubic meters per minute. Start-ups of rotary screw compressors happened more often due to the increased demand for air, increasing the energy spent as starting the compressors required an increasing amount of energy. Dew points of the dryers were operating on good levels. Rotary screw compressors were running for 2000 hours per month.

In the next observation period, in 2017, air consumption stayed relatively the same, 261.7 cubic meters per second. Power requirement increased a little, to 1.552 megawatts. The efficiency ratio was 5.93, showing that the overall energy efficiency of the pressure system had gone down.

Turbo compressor from Station 3 had its heat exchanger changed for better heat removal from the gas. Another turbo from station one only had its heat exchanger cleaned. Station one compressors are always running except for one screw compressor. Rotary screw compressors at station two “welding station,” has two compressors with malfunctions. Compressor seven had a malfunction in its cooling system, and compressor eight was leaking oil, preventing from using it for extended periods. Compressors nine and ten would not start. Running hours for the screw compressors were the same as in the last observing period, approximately 2000 hours per month.

The year 2018 saw improvements to the overall system due to the addition of a new Samsung SM3000 compressor in Station 1, seen in Figure 13. After the installation of the compressor, air consumption was 258.4 cubic meters per minute, the power requirement was 1.45 megawatts, and the efficiency ratio had dropped to 5.60, showing an improvement of 5.6% to the previous observation period.

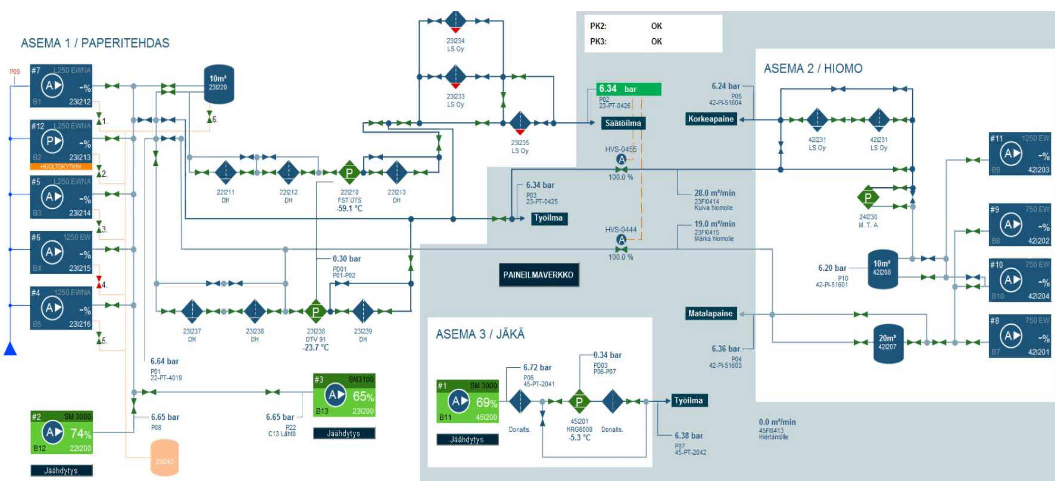


Figure 13. New Sarlin Balance interface showing the updated system layout in 2018.

Pressure fluctuations had settled down due to turbo compressor taking off stress from the older rotary screw compressors — network pressure level now at 6 bar, which is in accordance with the setting in Sarlin Balance guidance system. Turbo compressors had normal loading, generally running between 70 – 100% loading phase. Due to a lower stress on screw compressors, there was no need to run them as much as before; Screw compressors are now running 1600 hours per month. DTV -dryer at Station 1 had malfunctioning blow-off valve, causing to dew point increasing up to -25°C from the normal range of -60°C…-40°C.

## 3.2 Case study B

Case study B is an unnamed sawmill factory in Finland and has been observed through the period of 2005 – 2019. Pressure system layout of the factory is seen in Figure 14.

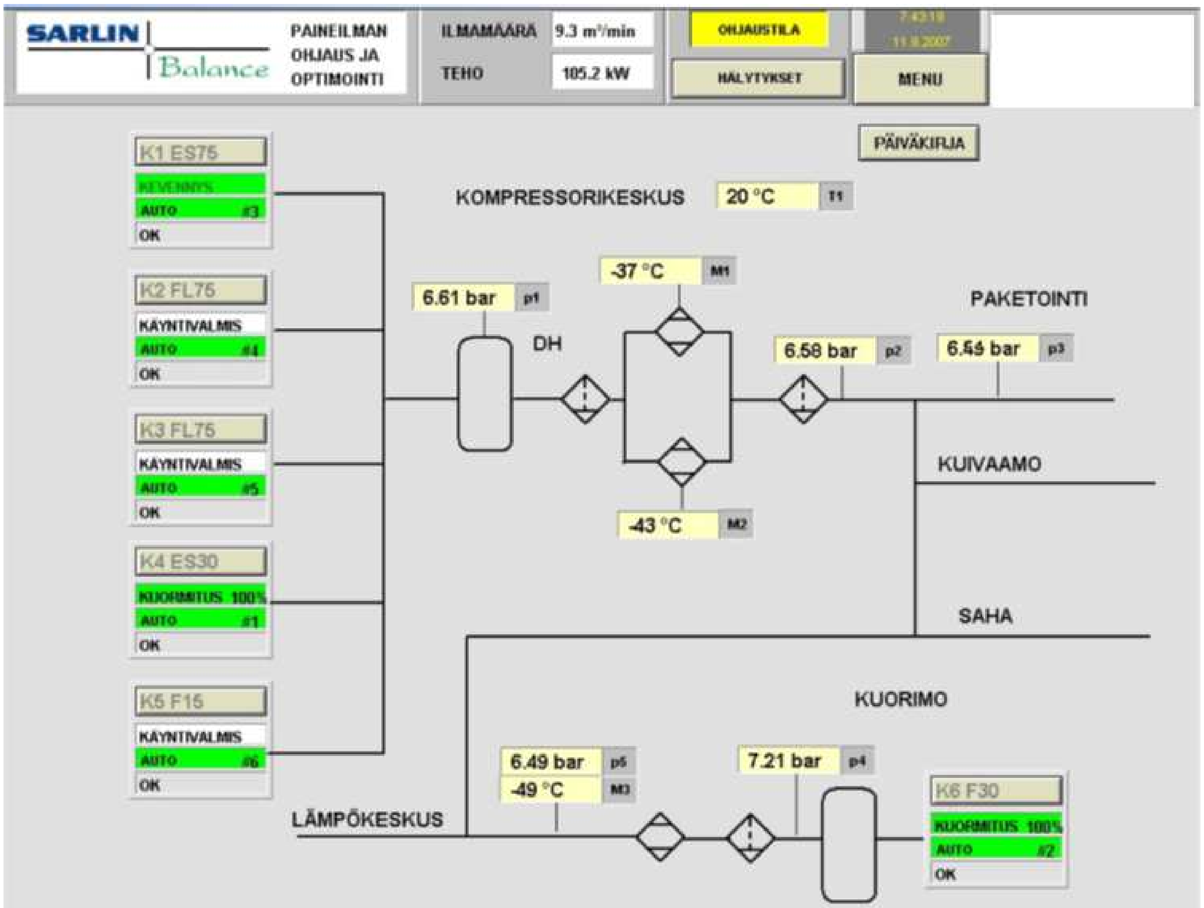


Figure 14. Pressure system layout of the sawmill in 2007.

During the first year, Air consumption was relatively high 23.1 cubic meters per minute with the power required by the compressors was 185.7 kilowatts. Due to this, specific power ratio was 8.04, which shows that the system was not energy efficient.

Sarlin Balance guidance system was installed in 2006. Problem with the guidance system at the beginning of the observation period was that the compressor guidance settings were not optimized, which presented as slow responsiveness to a sudden pressure changes. To prevent pressure fluctuation, compressor guidance settings were re-adjusted in Balance system.

In 2007 air consumption stayed relatively the same, around 23.2 cubic meters per minute with power requirement from the compressors of 189.2 kilowatts. Specific power was 8.16.

Compressor guidance worked better during the observation period of 2007, but there was still some pressure fluctuation present in the network. The issues impact was lessened by decreasing the response delay from the compressor settings. To improve the situation further, network capacity had to be increased. This adjustment also allowed for decreasing the amount of pressure in the network. The critical issue in the network was the pressure loss over the dryers, approximately 0.8 bar. Filter elements were changed in the dryers, which improved the pressure loss by 0.2 bar.

In 2010 air consumption was 22.9 cubic meters per minute, the power required was 185.4 kilowatts and specific power 8.1. There were no changes in the consumption profile compared to the previous year.

Pressure fluctuations were still present in the system. To prevent this, network capacity was increased by 20 cubic meters by adding a receiver to the system. Also, main compressors were instructed to start loading the same time for a faster response for pressure drops in the network.

In 2011 the old compressor system was replaced by a newer one. The new system consists of three Compair L132RS models, which are guided by an updated Sarlin Balance, Figure 15. Pressure settings were lowered to 7.2 bar in small steps. During normal air consumption, using just two compressors at the same time was found to be sufficient, as the pressure fluctuates between 6.2 – 7.2 bar and level did not approach the critical level of 5 bar. Air consumption was 20 cubic meters per minute with a power consumption of 164.8 kilowatts and specific power ratio was 8.24. Another significant change was made to the air suction system for compressors by re-designing the system and improving the air delivery to the compressors.

During 2012 significant improvement happened in the energy efficiency of the system as air consumption decreased to 17 cubic meters per minute, power requirement was 121.1 kilowatts and efficiency ratio was 7.12. This was the first time when the energy efficiency ratio dropped under 7.5.

Compressor guidance was set in such a way, that Balance shuts another compressor when the utilization rate for two compressors is 85% for over one minute. Settings used to be 80% over a minute.

In 2013 air consumption decreased despite that there had been an equipment addition in the system, which required 0.24 cubic meters per minute. In addition, with the new trimmer equipment, two smaller receivers were added to the trimmer station. Pressure network was inspected for leakages and results pointed out that there was 10 kilowatts worth of leakages in the network.

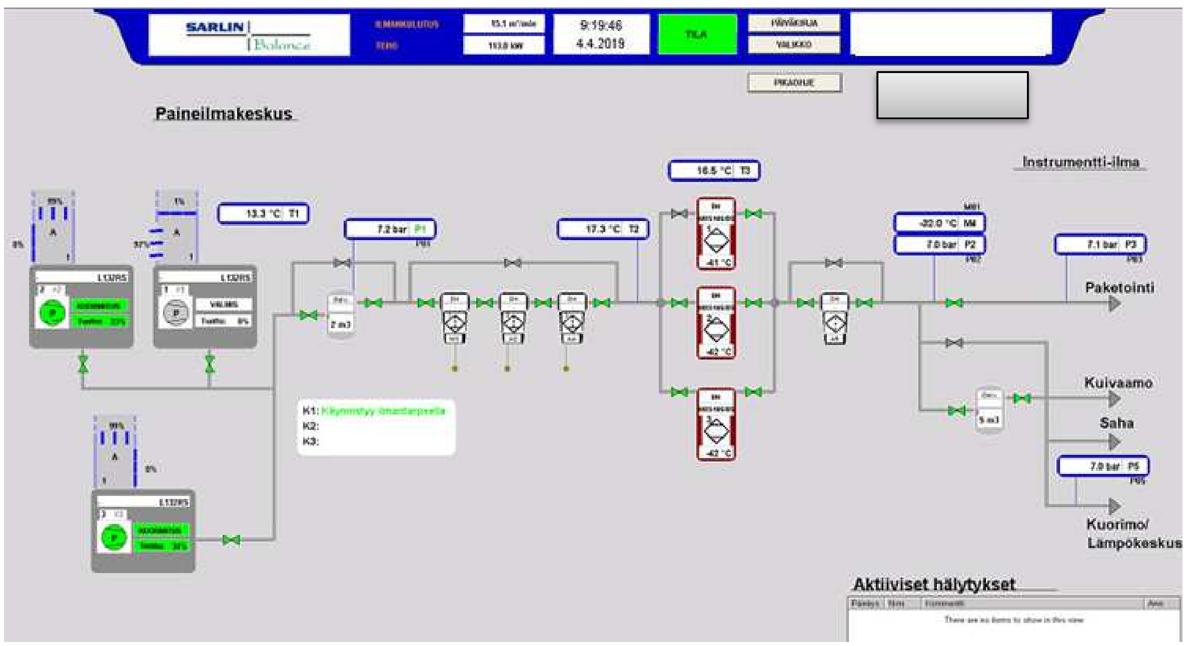


Figure 15. System layout of the sawmill in 2019.

Air consumption kept decreasing as, in 2014, air consumption had reached 15.2 cubic meters per minute, required power of 108.7 kilowatts with a nominal energy of 7.15. Pressure settings had been lowered to 7.1 bar to avoid further air leakages in the network. Compressor K2 was transferred as main air producer, and K1 was pointed as supporting and regulating compressor. K3 worked as a back-up compressor and was started whenever air consumption increased too high for K1 and K2. Pressure difference over the dryers had increased by 0.2 bar up to 0.8 bar.

2016 saw changes in the system as Balance was placed with Compair's Base Load Sequencing (BLS) system. Sarlin Balance could be still used to collect data, but it did not control the compressors anymore. As a result, air consumption increased to 19.4 cubic meters per minute; power required was132.7 kilowatts. Because of the increased air consumption, energy efficiency improved to 6.84. Network pressure was set to 7.2 in the BLS system and it was noticed that pressure increase of 0.1 bar increased air consumption by 1%. The significant difference between Compair's BLS system and Sarlin Balance, is that with BLS the guiding pressure is taken at the air production site, and with Balance it is measured at usage points. Now pressure fluctuated more in the network, approximately between 6.9 – 7.3 bar. Pressure difference over the dryers varied between 0.1 bar and 1 bar.

in 2017 air consumption rose slightly to 20.84 cubic meters per minute and power required 138.1 kilowatts, meaning energy efficiency has improved by 3% and is now 6.63. Air pressure generation was still controlled by Compare's base load sequencing system. Pressure variation at the production site was between 6.4 – 7.7 bar. BLS system keeps switching the two compressors, K1 and K2 as main working compressors every 24 hours. Air consumption was noticed to be on the rise during downtime, insinuating there were leakages in the network.

2018 air consumption decreased back down to 16.5 cubic meters per minute and required power also fell to 114.7 kilowatts. Lower air consumption affects energy efficiency negatively and brings it up to 6.95. The pressure at trimmer station 0.1 lower compared to the general network.

## 3.3 Case study C

In the case of study C, compressor system of a steel mill was examined. It holds three major compressor stations and two smaller stations for rolling mills. Station one consists of four Tamrock 1250ENWA rotary screw compressors and one adsorption dryer. Station two, two screw compressors, two Centac turbo compressors and three adsorption dryers. Station three consists of one Tamrock 1250 screw compressor, two Samsung SM5000, one Centac turbo compressors and two adsorption dryers. Pressure system of the steel mill is seen in Figure 16.

In 2013 the average power required was 4.16 megawatts with 658 cubic meters of air per minute consumption. The specific power of the system varied from 5.5 to 6.5, which was because of the facility's high air consumption.

Screw compressors showed irregular operation, however, when the air consumption was at normal levels, all of the screw compressors were running actively. During one month period, the utilization hours for the screw compressors reached 700 hours.

All of the turbo compressors, except for Centac #2, are being controlled with pressure settings. Discharge from Centac compressors cannot be adequately regulated. Centac #2 was not being regulated by pressure because it was producing a low amount of air which lead to problems with the compressor beginning to surge.

Air production adjustment happened with turbo compressors while running together. Fixed speed compressors were not adjusting.

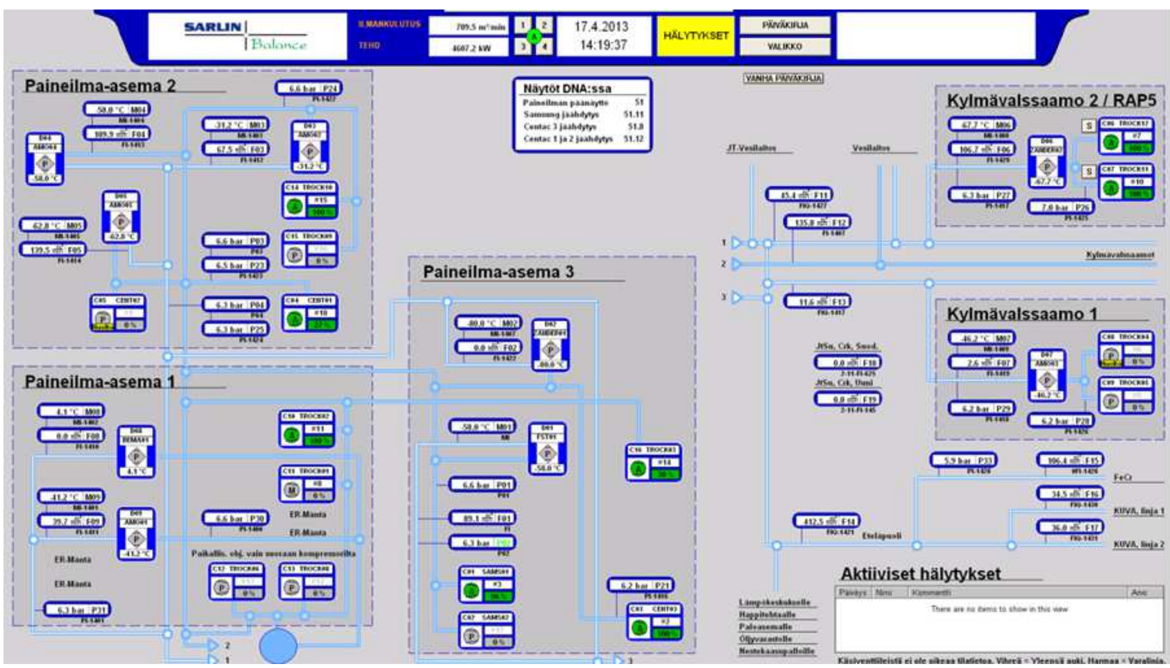


Figure 16. The layout of the pressure system at the steel mill in 2013.

In 2014 air consumption increased by a small amount, to 663 cubic meters per minute and power required by the compressors was 4.06 megawatts. Pressure levels in the network have been decreased to 6.22 bar.

Air is mainly produced with a combination of Samsung SM5000 #1, Centac #3 from station one and station two, Centac #1. Lowering of the network decreased the use of Samsung SM5000 #2. Samsung compressor #1 shows signs of random vibrations, suggesting irregular surging.

Tamrock screw compressors start up for backup every time as air consumption rises briefly above 800 cubic meters per minute. Out of all compressor capacity, 45% is in regular use.

2015 had average air consumption 642.8 cubic meters per minute, and the power required 3.97 megawatts and specific power of 6.18.

From Station 2, Tamrock compressor #10 was stripped down to spare parts for compressor #9. Tamrocks at both rolling mills were starting up several times a day as they were first in line to start up out of all screw compressors. Also, Station 1 Tamrock #2 started up several times a day. The overall loading of the screw compressors had risen because out of all compressor capacity, 43 – 47% are in constant use.

Network pressure settings were at 6.15 bar and pressure dropped at its lowest to 5.8 bar. This was usually just after when Samsung compressor #1 discharged and moved to loading phase. Few screw compressors also started up due to pressure dips.

Samsung compressor #1 still experienced small vibrations, causes were still unknown. Samsung #2 had been loading more than before due to risen air consumption at the end of the year.

In 2016 air consumption increased to 695.2 cubic meters per minute, the power required was 4.38 megawatts. Specific power was 6.3.

Before 2016, the turbo compressors were mainly run three at the same time, but at the beginning of 2016, it was changed to four turbo compressors running at the same time due to increased demand for air. Samsung #1 was still vibrating and was automatically stopped four times due to vibration during the first quarter of 2016. These problems increased throughout the second quarter. The compressor would go under maintenance and vibration testing done by a third party.

Compressor capacity in use out of total capacity was 52 – 54%. This was caused by the fact, that Tamrock screw compressors #3 and #10 were not in use, as #10 was stripped down for parts and #3 was under maintenance. Tamrock #9 was brought back to use at the end of the year.

Pressure in the network fluctuated from 5.8 to 6.5 bar. Pressure in compressor end at Station one occasionally rose to 6.7 bar and pressure difference over the dryers was 0.15 bar, indicating the dryers were working well. Sarlin Balance has a pressure level set to 6.15 bar.

In 2017 air consumption was on the rise as the levels increased to 718 cubic meters per minute at the beginning of the year and power required by the compressed air was 4.45 megawatts with a specific power of 6.19. At the end of the year, the corresponding numbers were 820.3 cubic meters per year, power was 4.91 megawatts and specific power of 5.98.

Three of the turbo compressors, Centac #1, Centac #3 and Samsung #1 were mainly running in full load when pressure was set to 6.5 bar in Sarlin Balance. Fourth turbo compressor, Samsung #2 loading varies between 50 – 80%. The remaining turbo compressor, Centac #2 started momentarily only when air consumption exceeded 1100 cubic meters per minute. After the air consumption set back down to average, both Centac #2 and Samsung #2 would discharge to avoid surging.

Samsung #1 had interference suppression installed to their vibration sensors during November 2016 and the compressor was not shutting down as often as before. Vibration still happened but at a lesser intensity enabling the compressor to stay running.

At the beginning of 2018, air consumption of the facility had gone down to 785.4 cubic meters per minute, the power required to produce the air was 4.74 megawatts and specific power of 6.03.

Four turbo compressors were still running simultaneously. None of the compressors hardly discharged if the air consumption was at normal levels. Both Samsung #1 and #2 had shut down a few times due to vibration alarm. During the second quarter, maintenance was done on both of the Samsung compressors in order to lower the discharge air temperature. Cooling water valves were now 60% open.

Tamrock screw compressors were kept as supporting compressors. The order in which they start up is switched around between compressors from station one and rolling mills compressors. Compressors which were next in line for loading after the turbo compressors, started up several times a day. Screw compressors only produced 1.6 – 3.3% out of all air produced. Rest of the air was produced by the turbo compressors.

Average network pressure set at 6.34 bar, due to adjustment for higher pressure limit in Balance at the start of the year. The pressure difference between all of the stations was less than 0.1 bar.

# 4 Observations

## 4.1 Case study A

By the first year 2011, changes were made quarterly and onwards from 2012 Sarlin Oy would go back to the client every half a year to make changes based on the data that in 2011 installed Sarlin Balance -unit would give.

Initially, the issue was clearly with the older equipment and lack of guidance system the factory used to produce the pressurized air. Both of the primary air producers, Cooper TA3000 and Ingersoll-Rand Centac, could not run in full load because the air would get too hot and blow-off valve would discharge the gas. This had to be fixed by adjusting cooling waters flow to more suitable volume flow. Screw compressors at the welding stations could not take enough of electricity to produce air at full load, giving exceeding low-pressure levels of 3.5 bar at the station. Compressors were fixed which showed as increased pressure levels during the next observation period. To prevent further malfunctioning, the compressors were to be run more frequently. The pressure drop of 2.5 bar from after treatment and overpressure at production side hints at that the dryer was not functioning properly. Hiross-refrigerating dryer was added to the guidance system, which seemed to help with the issue as did the new pipeline between station one and two.

While fixing turbo compressors proved to be very effective, they were not yet under the control of Sarlin Balance, which showed as an ineffective operation. Turbos were added to the guidance system to fix this. Screw compressors also had an issue after the original maintenance as they moved to full load too easily. The issue was resolved by lowering the full load pressure level from the settings and adjusting their response delay from 15 seconds to 20 seconds. After the adjustments, the compressors were more effective at responding to the decreasing pressure levels.

As seen in Figure 17, gradual changes worked exceptionally well. However, the first major effective action was to replace the Ingersoll-Rands Centac turbo compressor with newer Samsung SM3000 model. Moreover, soon after replacing of the other older turbo, Cooper TA3000, with another SM3000 compressor. This is seen in the graph as the second significant drop in the green line. As the demand for air increases, the two SM3000 are running at full load and older rotary screw compressors have to start supporting the compressors more as their capacity alone were not enough.

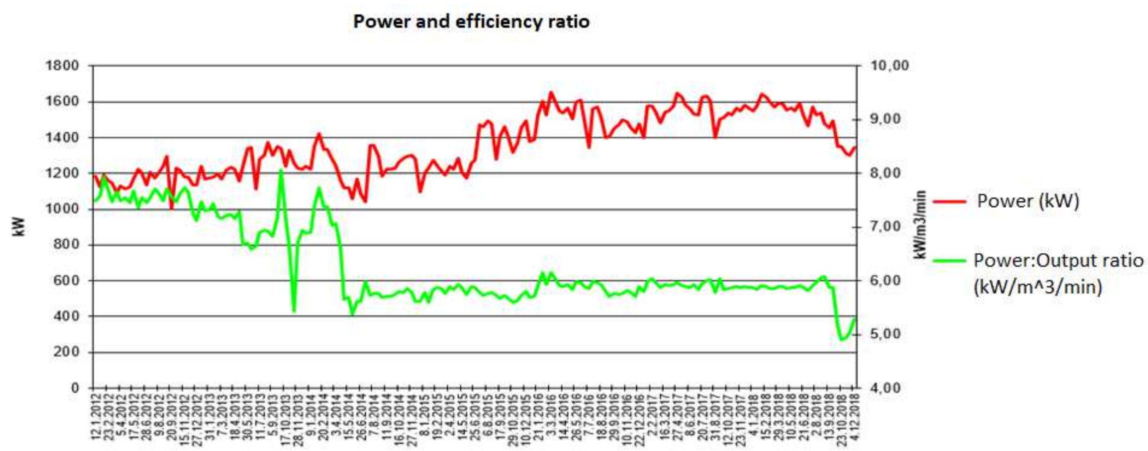


Figure 17. Timeline showing improvement in energy efficiency.

Balance succeeded at keeping the specific power close to 6.0 even as the air consumption and power requirements increase steadily from 2014 to 2017 by keeping the large capacity compressors as main air producers and switched backing compressors starting order after certain periods, assuring their reliability.

As the air consumption started to increase in 2014 and as the capacities of then existing turbo compressors were starting to approach their limits, the system had to start relying on the screw compressors to be able to keep up with the air demand. As many of the screw compressors were fixed speed compressors, this leads to pressure fluctuation in the network. The issue was corrected in 2017 when the new turbo was installed and compressors were able to again provide steadier flow.

The system started in 2011 at a specific power of 8.57, indicating very poor performance overall. Air consumption was 140 cubic meters per minute and power needed 1.2 megawatts. At the end of 2018, the specific power had dropped down to 5.88 with nearly doubled air consumption of 258.4 cubic meters per minute and power of 1.45 megawatts. Since the installation of Balance, the pressurized air system has improved by 31.4%.

## 4.2 Case study B

The challenge with facility B at the beginning was the older equipment used for producing the compressed air and relatively low air consumption levels which affected the energy efficiency of the system.

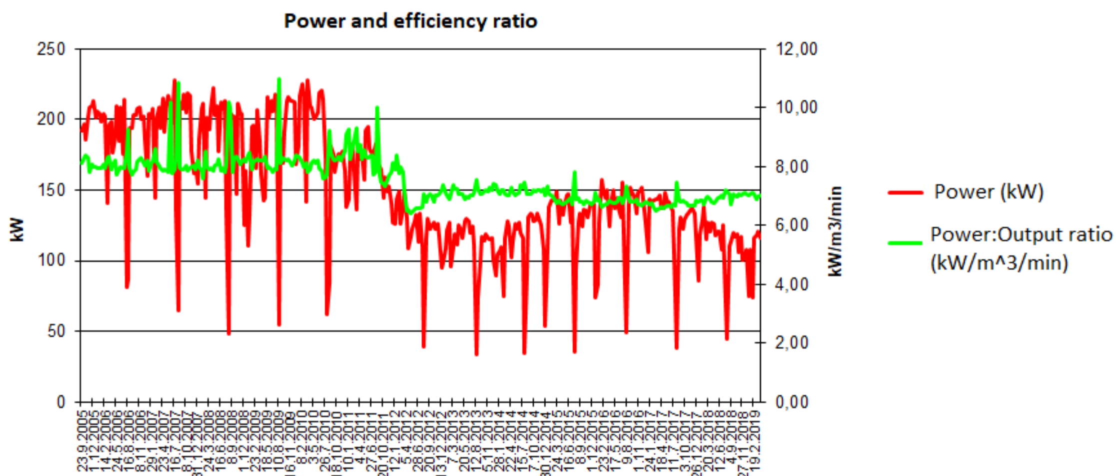


Figure 18. Energy efficiency improvement throughout 23.92005 – 19.2.2019.

The largest issue was the older compressors used in the factory. System was comprised of five different compressors going up to a maximum of 75-kilowatt motors and the smallest being just 15-kilowatt compressor. As all of the compressors were fixed speed compressors and, therefore, are either loading air at full capacity or unloading and not producing any air. This shows as a lack of efficiency in regulating the pressure levels as some of the compressors would have to constantly shut down and start up for compressors to be able to do any adjusting for the pressure, causing the loss of energy during the power up. Improvement is seen during 2011 when all of the older compressors are exchanged with three newer Compair L132RS variable screw compressors. As L132RS are variable speed compressors and have higher capacity, they are able to bring down the energy costs by having one of the compressors regularly run at higher outputs as primary air producer and the second compressor would regulate the output pressure to the needs of the network. The last compressor can be used as a backup compressor if something unexpected happens.

The second more significant issue was with the high-pressure level. High pressure in the network increases the risks for network leakages considerably and if the end usage does not require higher pressure, it is unnecessary energy cost to bring to air up to 7.5 bar in the saw mill’s case. In case B, the pressure was eventually brought down to the level of 7.1 bar which helped to eliminate constant pipeline leaks worth of 10 kilowatts in 2014.

Pressure fluctuation posed another problem as it leads to unstable use of air at the end-points and might cause unwanted irregularities in how the compressors run; thus, causing energy losses. The issue was gradually solved at the start by adding more capacity to the network. This was done by adding multiple receivers, which help to keep the pressure levels steadier. The first receiver added had the capability hold 20 cubic meters of air per minute and later two smaller less than one cubic meter receivers were added to the trimming station. Another correcting measure was to guide the main compressors to respond at the same time to decreasing pressure level.

Improvements made in the system eventually brought the systems specific power from 8.04 to 6.95, seeing improvement of 13.6% from the beginning of 2007 to the beginning of 2019.

## 4.3 Case study C

Case C shows an example, where every main component of the system is working as intended. The pressure systems specific power stays relatively the same throughout the period Sarlin Balance has been in use even if the air consumption and power increased from 658 cubic meters per minute, 4.16 megawatts to 785.4 cubic meters per minute and 4.74 megawatts. The increase for air consumption is 16.2% and for power requirement 12.2%.

The steady specific power is achieved through utilizing the turbo compressors ability to output massive amounts of pressurized air and using the rotary screw compressors as backing compressors. The increases of specific power in Figure 19 are caused by the air consumption increasing well above the average and screw compressors start up, requiring more power to generate the pressurized air.

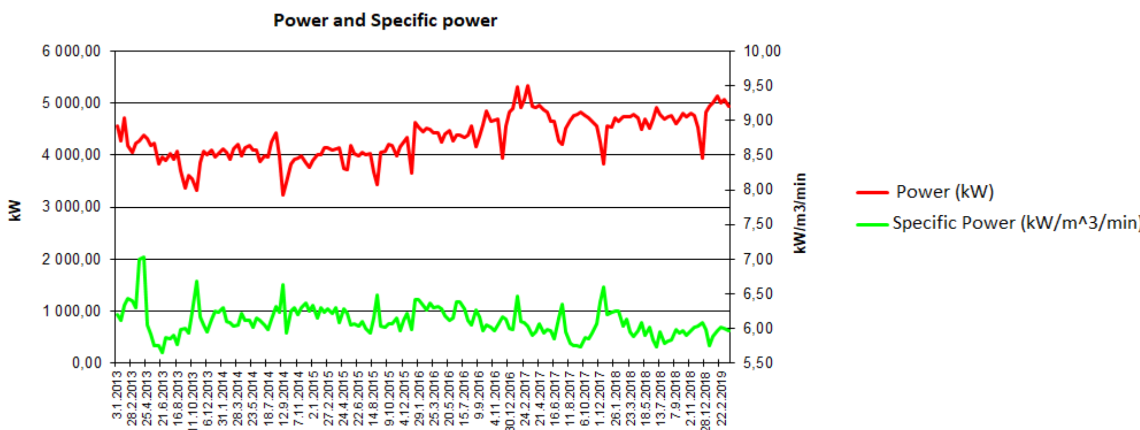


Figure 19. Energy efficiency of the system throughout 3.1.2013 -22.2.2019.

Because the capacity in the network is sufficient and the system is controlled by Sarlin Balance, this seen as steady pressure on the trend in Figure 20.

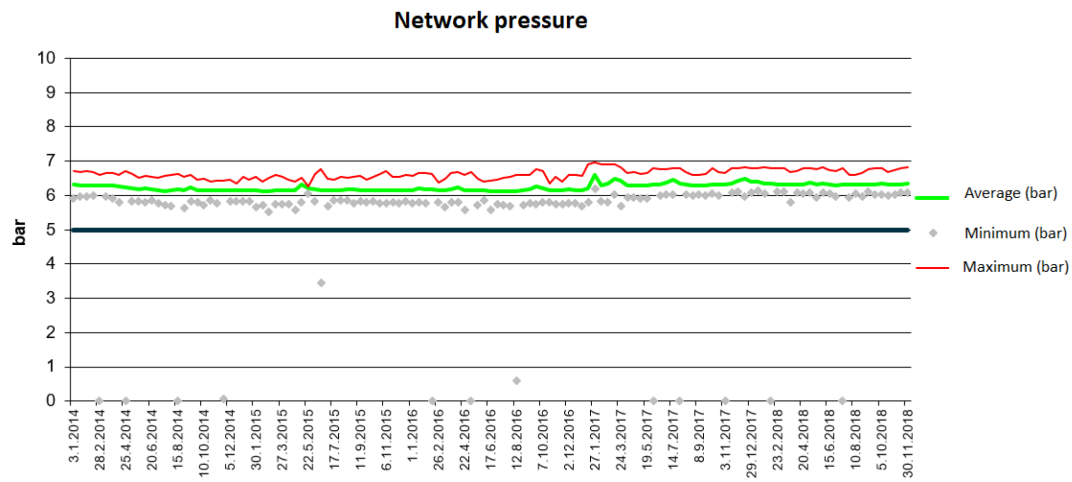


Figure 20. Network pressure of the steel mill from 3.1.2014 to 30.11.2018.

However, there were minor issues with the Samsung turbo compressors due to them experiencing vibration above the alarm limit, which caused the compressors to shut down in order to protect the equipment. The ultimate reason for, why the compressors experienced vibration, was left unknown. But maintenance was able to diminish the symptoms to the extent that the vibrations were not as severe as before and the compressors were able to be kept running.

## 5 Conclusions

The meaning of this thesis was to find and identify the means for energy efficient changes in compressed air systems. Another aim was to produce training material for international subcontractors or clients for Sarlin Oy Ab.

The theoretical part of the thesis examined the basics of compressed air, ISO -regulations of air quality, and common air compressor equipment from different types of compressors to air purification equipment.

The thesis was able to identify the most common problems in pressurized air systems that were caused by either older machinery in use, too high of pressure in the network which leads to unnecessary pressure losses through leakages in the pipelines. Case A also illustrated the effects of not having a guidance system in the start as the pressure fluctuated in the system quite much. This is normally caused by the fact that the compressors do not understand the need for air in the system and only react once the pressure drops below the set limit at their end and by that time the pressure is much lower at the endpoint of the network. Sarlin Balance solves the issue by installing pressure sensors near the usage points, which then relay the information faster back to the compressors; thus, enabling the compressors to react faster to pressure changes than they normally would.

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