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Analysis and Benchmark of two Compressor Production Systems using a new setting of Key Performance Indicators

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AFFIDAVIT

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Note of thanks

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Abstract

Energy efficient machines have become extremely important in the western society. The refrigerator of a household accounts for 10 % of the energy consumption in a modern world household. A compressor is an essential component of a refrigerator that is demanded at low price with high-quality standards. Compressors with a high efficiency are greatly valued and due to their complexity are usually outsourced from the refrigerator OEMs. The low-price high-quality problem was investigated in a compressor manufacturing company and showed room for improvement in operations as well as in manufacturing technologies. The goal of the study was to analyze and benchmark manufacturing technologies in conjunction with the production operations to understand which area is accountable for more costs. Models were developed to measure and compare the operations related costs and the manufacturing quality related costs. Machining variability is a big contributor for efficiency losses that directly influence the final price of a compressor. The compressor's parts were this variability is especially harmful are the piston and the rotor; their quality greatly depends on the centerless finish grinding and the pressure die casting processes, for these two processes an experimentation procedure using controllable machine parameters was proposed.

Kurzfassung

Energieeffiziente Maschinen sind in der westlichen Gesellschaft extrem wichtig geworden. Der Kühlschrank eines Haushalts macht 10% des Energieverbrauchs in einem Haushalt der modernen Welt aus. Ein Kompressor ist ein wesentlicher Bestandteil eines Kühlschranks, der zu einem niedrigen Preis mit hohen Qualitätsstandards nachgefragt wird. Kompressoren mit hohem Wirkungsgrad werden sehr geschätzt und aufgrund ihrer Komplexität in der Regel von den Kühlschrankherstellern ausgelagert. Das Niedrigpreis-Qualitätsproblem wurde in einem Kompressorhersteller untersucht und zeigte Verbesserungspotenzial im Bereich der Betriebsabläufe und Fertigungstechnologien auf. Ziel der Studie war es, Fertigungstechnologien in Verbindung mit den Produktionsabläufen zu analysieren und zu bewerten, um niedrigere Teilekosten bei gleich bleibenden Qualitätsstandards zu erzielen. Es wurde festgestellt, dass Qualitätssicherungssysteme und korrekte Toleranzen eine wichtige Rolle bei den Herstellungskosten spielen. Die Variabilität der Bearbeitung ist auch eine Ursache für Effizienzverluste, die sich direkt auf den Endpreis eines Kompressors auswirken. Die Teile des Kompressors, an denen diese Variabilität besonders schädlich ist, sind der Kolben und der Rotor. Ihre Qualität hängt stark vom spitzenlosen Schliff und den Druckgussverfahren ab. Für diese beiden Verfahren wird als zukünftige Studie ein Versuchsverfahren mit steuerbaren Maschinenparametern vorgeschlagen.

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List of Abbreviations

ABB	Axial Ball Bearing
AGV	Automated Guided Vehicle
CB	Conveyor Belt
COP	Coefficient of Performance
cpk	Process Capability Index
CTQ	Critical to Quality
DFM	Design for Manufacturing
DoA	Degree of Automation
DOE	Design of Experiments
HRC	Hermetic Reciprocating Compressor
KPI	Key Performance Indicator
LSL	Lower Specification Limit
NGAA	Nidec Global Appliance Austria GmbH
OEM	Original Equipment Manufacturer
PSM	Production Science and Management
ROI	Return on Investment
SPC	Statistical Process Control
TDC	Top Dead Center
USL	Upper Specification Limit
WIP	Work In Process
WPC	Work Piece Carrier

List of units

Abbreviation	Name	Units
μ	Arithmetic Mean	----
θ	Blade angle	°
c_L	Component Labor Cost	€/#
d_s	Centerless Grinding Wheel Diameter	mm
a_e	Depth of Cut	mm, µm
α	Efficiency (COP) Influence factor	ΔCOP%/µm
v_s	Grinding Wheel Speed	m/s
p	Productivity	$\#/h_w$
d_c	Regulating Wheel Diameter	mm
Q_w	Removal Rate	mm^3/s
rpm	Revolutions Per Minute	min^{-1}
Q'_w	Specific Removal Rate	mm^2/s
σ	Standard Deviation	----
γ_s	Tangent Angle	°
h	Work height	mm
v_w	Work speed	m/s
d_w	Workpiece diameter	mm

1 Introduction

This master thesis was a cooperation between TU Graz's Institute of Production Engineering and Nidec Global Appliance Austria GmbH.

1.1 Nidec Global Appliance Austria GmbH

Figure 1.1: The NGAA plant facilities in Fürstenfeld (Austria), Source: www.secop.com

Nidec Global Appliance Austria GmbH (NGAA) with the headquarters situated in Fürstenfeld, Austria; is a manufacturer of hermetic reciprocating compressors for refrigerators. Formerly known as Secop, was now recently acquired by Nidec Corporation, a Japanese enterprise manufacturer of electric motors with more than 100.000 employees worldwide. NGAA was founded in 1982 as "Verdichter Oe", and since then has developed extensive experience in developing and manufacturing high performance cooling compressor solutions, mainly for household refrigeration appliances. In 2013 NGAA has breached the 100 million compressors sold milestone and counts presently with over 400 employees in Fürstenfeld.

1.2 The Hermetic Reciprocating Compressor

A hermetic reciprocating compressor (HRC) main task (as a part of a refrigerator) is to bring a refrigerant gas from a low/suction pressure to a high/discharge pressure. HRCs are different structurally to other open compressors based on the perfectly sealed design (hermetic), which means there is no refrigerant gas leakage possible. The reciprocating motion of compression is also a differentiating design aspect; there are for example screw compressors, turbocompressors, rotary compressors which have a different machine design[1]. HRCs are usually operating with asynchronous (or induction) motors, which is the case for NGAA's compressors. A typical design of a HRC is presented in figure 1.2. (The example design is not from NGAA).

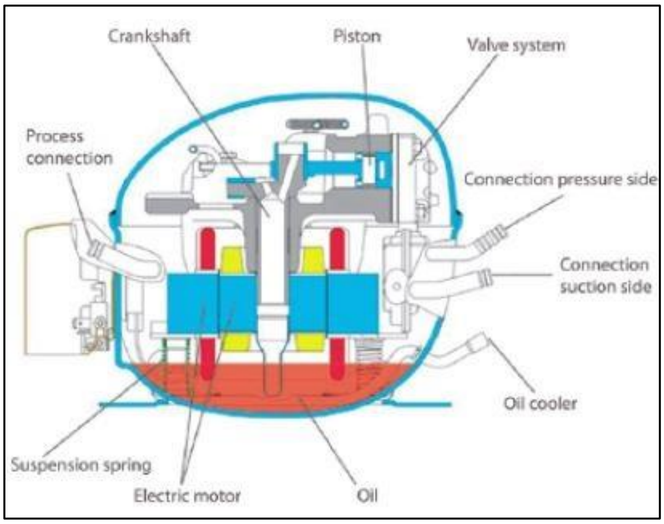

Figure 1.2:Reciprocating Hermetic Compressor, cf. Bachmann (2008), p.1

HRCs are the heart of a refrigerator, and therefore, an important component of the thermodynamic refrigeration cycle, which consists of 4 main steps (Figure 1.3):

1st step: Compression of the refrigeration gas, (done in the compressor) increasing the refrigeration gas pressure from 0,6 bars to 8 bars as well as the temperature up to 100°C, entering a superheated vapor phase.

2nd step: Condensation of the refrigeration gas, the refrigeration gas enters the condenser unit behind the refrigerator releasing heat to the room but maintaining pressure, at this moment the gas is at a pressure of 8 bar and a temperature of roughly 55°C in a saturated liquid phase.

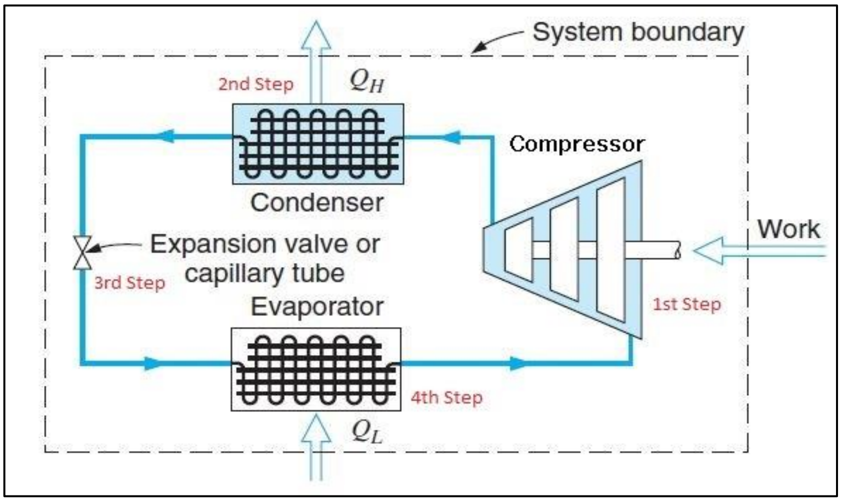

Figure 1.3: A simple vapor-compression refrigeration cycle, cf. Borgnakke/Sonntag (2013), p. 220

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[1] Cf. Bachmann (2008), pp. 1-3

3rd step: Expansion of the refrigeration gas, done usually in a capillary tube or expansion valve, where the refrigeration gas will lose pressure, this changes its boiling point to roughly -23°C, at this point the refrigeration gas is at 0,6 bars and -23°C, in a liquid-vapor mixture phase.

4th step: Evaporation of the refrigeration liquid-vapor mixture, the refrigeration mixture enters the refrigerator at a low temperature of -23°C, lower than the inside of a refrigerator (usually around 5°C) and therefore removing heat from the inside of the refrigerator as well as fully transitioning to a vapor phase. At the end the refrigeration gas is at 0,6 bars in a saturated/subcooled vapor phase. The refrigeration gas is then sucked into the compressor and the cycle starts again[2].

1.3 Compressor's Coefficient of Performance (COP, β)

To understand how the quality of a hermetic reciprocating compressor is measured, there is a concept that must be introduced: The Coefficient of Performance (COP or β).

The efficiency of a refrigerator is expressed in terms of coefficient of performance (COP), which for a household refrigerator is usually between 1,5 and 2,5[3]. As depicted in Figure 1.3, a refrigeration cycle requires work to remove heat from a specified volume. The COP or β is then calculated as:

$$COP,\beta = \frac{Q_L(Energy\ sought)}{Work(Energy\ that\ costs)} = \frac{Q_L}{Q_H - Q_L} \tag{1.1}$$

In the compressor case, work would stand for electrical power input, this work is done by the compressor on the refrigerant gas by means of an electrical powered motor (the asynchronous motor).

Based on these facts, NGAA, as a supplier of compressors for refrigerator OEMs, has a direct influence on the final efficiency of the refrigerator. Usually, a fixed COP is demanded from the customer. The task of NGAA is then to deliver a compressor to fulfill these demands.

A hermetic reciprocating compressor is a motor, and as every motor it has losses. Specifically, the electrical power input is not 100% converted to enthalpic energy (compression of the refrigeration gas) so the compressor itself has also an efficiency. The efficiency of a HRC can be expressed, as a function of ten parameters representing various kinds of the main losses in the compressor[4], such as:

- Frictional losses: Piston, main and crank pin journal bearings.
- Pressure losses at the suction and discharge valves.

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[2] Cf. Nidec-Secop, Online Source [28.02.2019].
[3] Cf. Borgnakke/Sonntag (2013), pp. 216-222.
[4] Cf. Yang/Ziviani/Groll (2017), pp. 1-2.

- Leakage loss of refrigerant gas between piston and cylinder.
- Motor losses such as: Eddy Current losses, losses due to stator and rotor impedance, magnetic losses, hysteresis losses.[5]

To reduce as much as possible these losses, NGAA has developed a optimized product portfolio over the last 40 years. Finally, a important role for the commercialization of efficient compressors, is played by the manufacturing processes, which will be one of the scopes of this thesis.

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[5] Cf. Yang/Ziviani/Groll (2017), pp. 1-2.

1.4 Problem proposal

This master thesis, as a final project of the TU Graz's master program Production Science and Management focuses in two fields of study: *Manufacturing technologies*, the field that investigates different techniques to produce a desired product in the most efficient way. And, *Industrial Operations and Management*, whose purpose is to correctly manage, support and control industrial activities to fully use their capacities and thereby increase profitability.

The course of action was to fully analyze and then evaluate, based on a new setting of KPIs, the manufacturing processes within NGAA with both the objectives of reducing manufacturing costs and increasing quality.

The first stage of the project focused on a thoroughly As-Is analysis and documentation of the whole manufacturing and logistic chain, with the intention of pin-pointing the weaker or fragile knots in the production chain as well as giving a deep understanding of the manufacturing flow of a refrigeration compressor.

The second stage was to create a list of possible KPIs that could effectively measure the manufacturing capacities in terms of cost, quality and speed. Internal meetings with the relevant departments took place, to decide which of the KPIs in the list should be finally measured. Parallelly, it was discussed with the internal product engineering experts which product features had the highest influence on the final quality of the product (the features were defined as Critical to Quality or CTQ), these CTQ features were then quantified in the form of percentage loss of COP per unit out the nominal value. The COP of a compressor is directly related to the selling price of a compressor, therefore quantifying the CTQs assists the decision-making of which manufacturing process should be improved.

The third phase was to organize and merge the manufacturing operations KPIs together with the CTQs to understand which manufacturing processes show a bigger potential for improvement and then studying the respective manufacturing processes or comparing them to other more viable state-of-the-art technologies.

The study allowed an identification of the most fragile and critical areas of the manufacturing plant, which are: the pairing of the piston with the cylinder, and the rotor-stator assembly. Other findings included a lack of appropriate quality KPIs such as scrap rate, which are required to better control and manage each production line. Additionally, potential out of scope improvement opportunities were found, these include: Introducing automated control systems and developing digital interfaces between the manufacturing floor and the production managers.

In sum, NGAA has achieved over long years of experience, a solid manufacturing technology know-how, therefore can count with a robust and reliable production chain. On the other hand, with a fast-paced market that every year demands higher quality standards at a lower price and with a constant increasing competition, innovation is a success key factor, specially, manufacturing processes innovation. These processes, if used as components of a Computer Integrated Manufacturing System, can successfully set a company ahead in the market position.

2 Literature Review

To better solve the problem, a literature review is required to get in touch with the State-Of-The-Art in operations and manufacturing technologies.

2.1 Manufacturing Operations

When dealing with manufacturing operations one must have in mind that measuring the performance of these operations is essential to achieve good control and long-term improvement[6]. The constant measurement of robust, meaningful and controllable KPIs will put a stress on an organization if these measurements are doing poor. Conversely, it will motivate and compensate the organization if the measurements show good results.

The critical aspect to success in choosing the correct manufacturing process to improve, will always be choosing the right KPI's. A good criterion to use on the decision making of choosing a good KPI is suggested in (F. Franceschini, M. Galetto, D. Maisano, 2007) as follows:

- The first important design concept is keeping the number of KPI's to a minimum level, this will force that the KPIs to be chosen are only the critical ones.
- The cost of obtaining a specific KPI should never surpass the gain or value that it can bring. Many KPIs require extensive work to be measured and obtained and bring no valuable insight over a manufacturing process.
- The measurement to be extracted must be clear and understandable, the units of the measurement should bring as much information as possible.
- The KPIs should be aligned with what the organization is pursuing. For example, if a high-quality car OEM such as Ferrari or Lamborghini would want to launch a new car model, a very exclusive limited edition, measuring the cycle time of the piston production line could be a hazardous measure. It could be in fact a negative measure, if it stresses operators to work faster and then compromise on quality.
- Consider that some measurements might conflict with others: Productivity measurements will probably clash with quality measurements.

Based on these criteria a set of possible KPIs can be developed. Once they are chosen a simple test can be performed on them:

The SMART test (University of California 1998)

S (Specific). The KPI should have a clear unit. Like number of process steps in a production line.

M (Measurable). The KPI must be quantifiable.

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[6] Cf. Franceschini/Galetto/Maisano (2007), *p. 109*.

A (Attainable). Is it possible to measure this KPI? If the energy consumption of a specific production line in a big manufacturing plant is to be measured, it might be in practice hard to attain.

R (Realistic). Is the KPI aligned with the objectives, is it cost-effective?

T (Timely). The time given to extract measurements is always limited, so the time frame should be considered[7].

A similar test can also be made on the KPIs to be measured, a method used by the U.S. Department of the Treasury, also cited in (F. Franceschini, M. Galetto, D. Maisano, 2007):[8]

Availability: Is the data currently available?

Accuracy: Is the data reliable?

Timeliness: Will the data acquisition be timely with the evaluation deadline? How frequently is it measured (constantly, weekly, monthly)?

Security: Are there privacy/confidentiality issues that could block the retrieval of the data?

Costs of data collection: Are there automatic data collection systems, is there a responsible for data collection and treatment?[9]

2.1.1 Manufacturing Operations KPIs

The current relevant measurement metrics will be briefly introduced. When starting a performance overview of various manufacturing systems there is one concept that never gets outdated; simplicity: "*A practical measure is a simple measure which is easy for data collection and informative, for instance, stock turnover, throughput time"* [10].

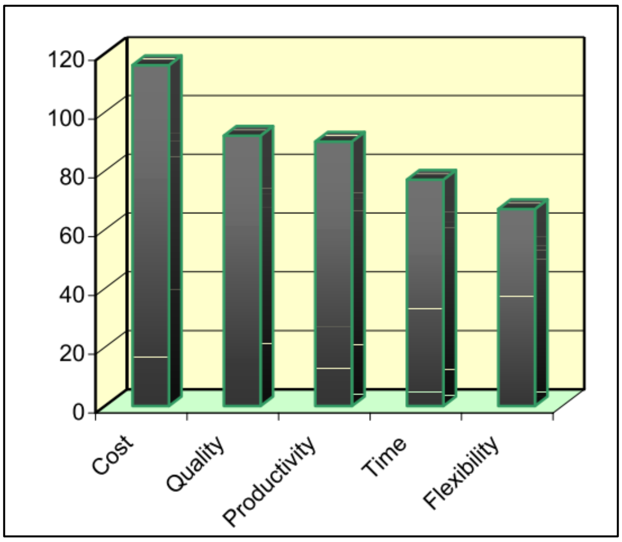

Figure 2.1: Number of Manufacturing system measures, Hon (2005), p.143

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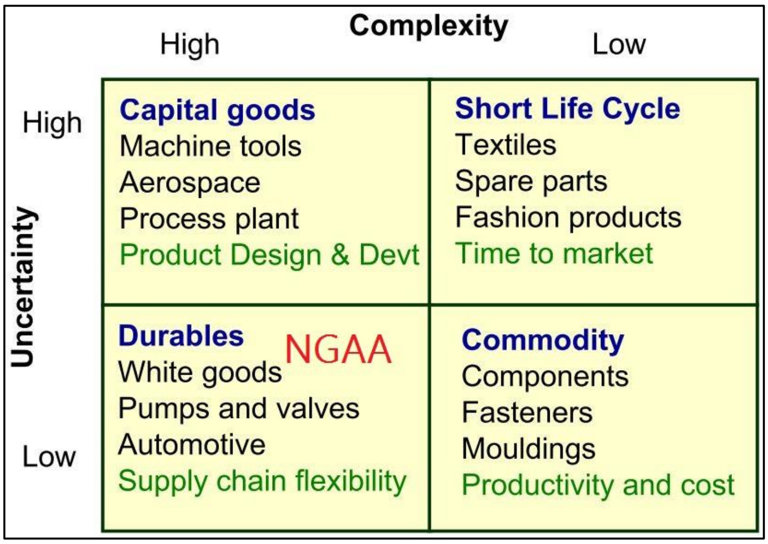
[7] Cf. Franceschini/Galetto/Maisano (2007), *p. 168*.
[8] Cf. U.S. DEPARTMENT OF THE TREASURY (1994), Online Source [10.04.2019] .
[9] Cf. Franceschini/Galetto/Maisano (2007), *p. 169*.
[10] Cf. Hon (2005), p. 140.

Now when it comes to the choice of good manufacture measures a vast array of possible KPIs comes immediately out of the industrial literature, and of different categories: Cost, quality, productivity, time or flexibility[11]. Figure 2.1 exhibits the amount of measures that can fall to each category.

One more aspect to aid performance measurement is to understand what is the nature of the product being manufactured. Based in the complexity and uncertainty, a good approach is represented in Figure 2.2.



		Complexity	
		High	Low
Uncertainty	High	**Capital goods** Machine tools Aerospace Process plant Product Design & Devt	**Short Life Cycle** Textiles Spare parts Fashion products Time to market
	Low	**Durables** NGAA White goods Pumps and valves Automotive Supply chain flexibility	**Commodity** Components Fasteners Mouldings Productivity and cost

Figure 2.2: Classification of Manufacturing Activities, cf. Hon (2005), p. 144 (slightly modified)

As illustrated in Figure 2.2 supply chain flexibility is of vital importance for NGAA product portfolio. When the subject of observation is a single manufacturing plant, a relevant measure will be Process Flexibility, which directly contributes to Supply Chain Flexibility.

There is also a simple approach which is the cost-quality-speed triangle of production (Figure 2.3) which basically defines that cost, quality and speed (also commonly called Output) of production are closely related to each other[12]. They strongly constrain each other in a way that a production manager will always have to negotiate between the three of them. In NGAA case, sales are the bottleneck, for this reason the manufacturing plant is not working on 100% capacity as it was in the past (in the past it was running on a 20 8-hour shift per week basis, and the 1 remaining weekly shift was left for maintenance). As the market looks, this condition will not change so soon. For this reason, realizing that the plant has over-capacity, the speed vertex will be the vertex which will be given less importance during this study. The KPIs chosen will have the scope more on the quality and cost vertexes.

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[11] Cf. Hon (2005), pp. 144-145.

[12] Cf. Rowe (2014), p. 3.

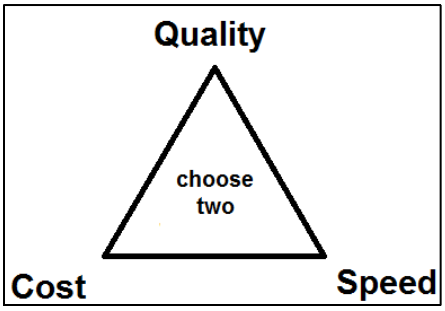

Figure 2.3: Triangle of Production, cf. Rowe (2014), p.160 (slightly modified)

Production Capacity

In manufacturing operations, a critical measure to be able to correctly plan manufacturing and deliver products on time is production capacity, it also ensures that a manufacturer is aware of and utilizes correctly his internal capabilities[13]. It might seem contradictory to introduce this KPI right after defining that speed will not be the scope of this study, but it was included because as already mentioned before, it is a cornerstone of manufacturing operations; plus, it also indirectly influences cost. Theoretically this measure indicates the amount of parts a specific manufacturing unit (production line, machine, factory) can produce over a specific time interval considering perfect conditions: No breaks, no planned or unplanned maintenances, no setup times, no waiting times, etc. In complex systems such as compressor manufacturing activities, it is often a measure that shows deviations from theoretical to actual point of views. For this reason, a slightly different approach is used in this study. The production capacity will instead include all possible production stops above mentioned, this is done by dividing the total amount of produced parts in a specific line in a bigger time interval (such as one month or more) by the total amount of manufacturing hours during that interval. The final units will be #(parts)/h(hour).

There are dangers attached to this approach that must be kept in mind: The specific manufacturing unit will have a different capacity in real time, sometimes higher, sometimes lower, which is much more complex to calculate. Not considering this can lead to over-production or not fulfilling orders on time.

On the other hand, this metric is easy and fast to obtain as well as robust, giving a quick overview about the capabilities of a specific manufacturing unit or line.

Number of required workers

One of the major cost components in manufacturing activities is labor cost. Also, it is a variable cost, which makes it adjustable to the firm's needs[14]. In this analysis it will be applied to all levels of a manufacturing plant (plant, production line and process step). The unit of the metric will be number of workers required. Here, it is important to note that this metric can be a decimal

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[13] Cf. Sabet et al. (2019), pp. 1-2.
[14] Cf. Wang/Li (2017), pp. 23-25.

number, this is because some activities do not require a worker 100% of the time, but, for example, 50% of the time, in this case the number of required workers for this activity would be 0,5.

Productivity

Taking into consideration that merely measuring the labor costs via headcount is not a sufficiently accurate cost measure, productivity is added and is defined as illustrated in equation 2.1. This KPI will measure the labor efficiency of a plant, production line, process step, etc. in a discrete time interval, usually hours, the final unit is parts produced per worker-hour (#/h_w).

This KPI can be easily reverted to an interesting €-measure which is defined as: component labor cost c_L, which is simply the amount of labor costs that each manufactured component contains, it could also be interesting to use this measure in conjunction with the component material cost to define if the component is material intensive or labor intensive. This measure is calculated as illustrated in equation 2.2. The units would be euros of labor per part produced (€/#).

$$p, Productivity = \frac{Parts\ Produced}{Number\ of\ Worker.Hours\ Required} \qquad 2.1$$

$$c_L, Component\ Labor\ Cost = \frac{Worker.Hour\ Cost\ in\ Austria}{Productivity} \qquad 2.2$$

Energy costs

Together with labor costs, energy consumption of the manufacturing activities is nowadays a main contributor for production costs[15], the problem with this KPI is that it is only measurable in a macroscopic view (whole plant energy consumption). It is very time intensive to retrieve the energy consumption of each manufacturing machine in a plant, for that reason and considering the study time-frame this KPI will only be regarded qualitatively. Nonetheless it is mentioned because of its high relevance in cost analysis.

Cost of Scrap and Scrap Rate

This KPI was chosen due to its versatility in exposing manufacturing fragilities. It is like an iceberg tip; if a manufacturing activity is having too high scrap costs it will be a good warning to check the manufacturing process appropriateness, the reasons can be numerous: Incorrect tolerances; a common cause of excessive manufacturing cost is the specification by designers

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[15] Cf. Wang/Li (2017), pp. 23-25.

of too many tolerances or tolerances that are tighter than necessary[16]. Other possibility of too high scrap costs is of course a machine that is not capable of a specific tolerance (in case the tolerance is correct), this is then a good indicator for a manufacturing process improvement by equipment substitution. Or for example, a supplier is not delivering reliably.

One way to measure this KPI is accounting the amount of scraped parts produced and then multiplying it by the material costs (this is the modus operandi in NGAA). Even though it is a cost measure, it can be used as a scope on quality (triangle of production). It is effective not only on detecting processes that point to poor quality, but it can also reveal processes that might have over-quality or over-processing (in case scrap cost is too low). There is one danger in this KPI which is: A high scrap cost doesn't always mean poor process quality, it might be because the raw material is too expensive making one manufacturing error costlier (but the process is still capable and appropriate).

There is other similar KPI that could substitute the cost of scrap which is scrap rate: Two values are used to calculate this KPI: (1) the number of units that are scrapped during the production process, and (2) the total number of units produced during the same period. Scrapped units are defined as any units of the production output that are not in conformity and thus wasted, or parts that require rework. Scrap rate is then (1) divided by (2), in percentage (multiplied by 100). Good units, reworked units and scrapped units are all included in the denominator of this calculation[17].

WIP costs

Work in Process (WIP) costs will be a concept KPI that will be regarded throughout this thesis. There are many definitions of WIP, in this thesis it will be defined as: Amount of goods that are being processed or waiting to be further processed inside the production chain, these don't include raw inventories neither do include finished-goods inventories[18].

For the quantitative analysis it will not be measured, but it is important that this concept is regarded throughout the manufacturing process analysis. In our case it will be especially relevant in the piston-cylinder pairing, the reason is that the tolerance range of the piston diameter can be further divided into smaller categories or intervals to have better clearances. This requires a higher amount of piston inventories, which deteriorate fast, thus increasing the WIP costs.

In Figure 2.4 this concept is illustrated, the longer a component is in the grey region the higher the WIP costs will be.

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[16] Cf. Poli (2001), *p. 14*.
[17] Cf. OpsDog, Online Source [20.03.2019].
[18] Cf. Hopp/Spearman (2011), pp. 616-621.

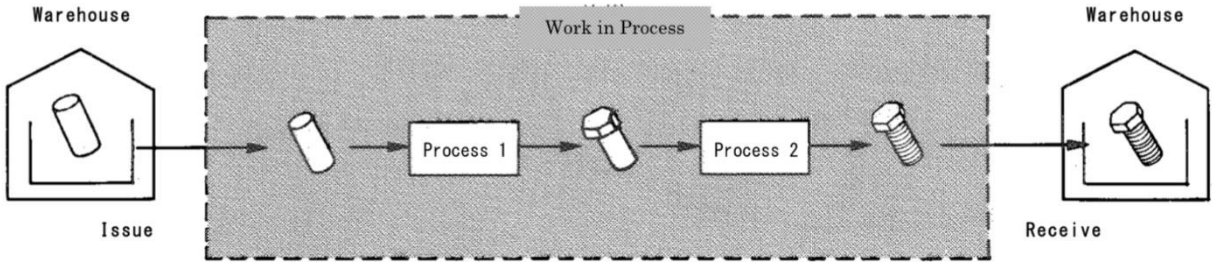

Figure 2.4: Work in Process description, Online source: www.asprova.com [18.03.2019]

Degree of Automation

Industrial automation of a plant or process is the appliance of information systems to control a desired process flow. Nowadays, automation goes as far as being a requirement from the costumer of the costumer, therefore standard and immediate products are the minimum that an end-customer expects.[19]

It is an aspect that goes together with labor costs and due to its rapid growth in the last four decades it gained a considerable hype, therefore many theories appeared on how to measure its ROI, savings on labor costs, throughput, etc. and still no real method has been found that robustly measures automation effects on operations and finance areas, mainly on labor areas.[20] This means that measuring automation alone will not say much about a specific process, it still requires interpretation along with other metrics.

A robust metric to gather information with regards to automation in the shortest amount of time is the Degree of Automation DoA defined as follows (for a specific production line):

$$DoA = 1 - \frac{Number\ of\ working\ places\ in\ Production\ Line\ i}{Number\ of\ processing\ steps\ in\ Production\ Line\ i} \qquad 2.3$$

The number of required workers has already been defined and the number of processing steps is the sum of all the different processes a production line contains (logistic processes like moving or storing are not included). In Figure 2.5 the process flow of a production line is given to exemplify this calculation. For the given example only five process steps would be counted, as the automated palletizer is a logistic step. Note that some steps contain various actions, this is because the same workstation is responsible for more than one task.

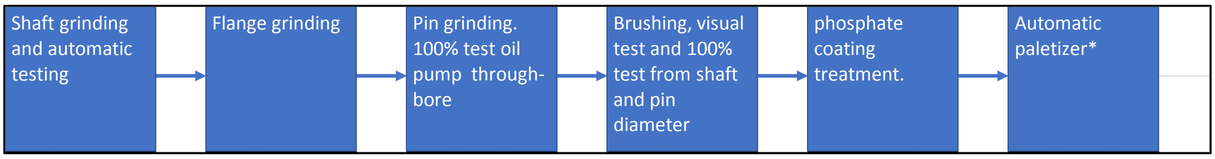

Figure 2.5: Number of processing steps example, Source: Own Illustration

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[19] Cf. Mehta/Reddy (2015), p. 1.

[20] Cf. Kessler (2017), Online Source [15.04.2019].

Bottlenecks Identification

This last KPI is not strictly a performance measurement, it is rather a describing KPI. Even though it comes in the last position of this study, it should never be underestimated. In theory of constraints all the management activities should focus the bottleneck operation, which is also designated as the “drum”, because it sets the beat of production, this is usually one machine or person through which the produced goods must always go through, though it can also be a short supply of materials or too low sales[21]. Strictly speaking there is only one bottleneck at a time in a production operation, though it is not always the same bottleneck. In connected line flow production systems such as the compressor manufacturing, it can be helpful to identify more than one bottleneck, a good approach is to identify the bottleneck of each production line.

Under the Theory of Constraints all the effort should be focused on the bottleneck of a company, by focusing more resources on the bottleneck and making it more efficient the company will maximize its profits[22]. This approach is of significant aid in very complex systems because it focuses the “few” critical, instead of trying to make *all* operations more efficient, this way resources are not invested in operations that cannot increase overall throughput. Therefore, the first thing is to locate the constraint/bottleneck, this can be done by asking some of the following questions: *Where are large quantities of inventory piled up? Which operations do constantly show problems? Which operations show high utilization?*[23] When the identification of the bottlenecks is finished, they can be properly managed to achieve higher throughput, via simple techniques such as: *Covering the break-times*: During break-times keep the bottleneck operation running, this will allow that posterior work stations do not wait after breaks. *Offload incidental work*: This is useful for operators that work on the bottleneck processes, if they are both responsible for productive and maintenance/cleaning tasks it might be useful to offload the maintenance/cleaning tasks to a second operator to keep the throughput at maximum efficiency. *Quality reviews done before the bottleneck operation:* This will avoid unnecessary processing of parts that are out of conformity before coming to the bottleneck operation. *Backup staff and increased payment at bottleneck:* This measure is useful for bottleneck operations that are monotonous, which usual have higher absenteeism. Either having backup trained employees or increasing motivation with higher payment can be a solution.[24]

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[21] Cf. Bragg (2007), pp. 1-3.
[22] Cf. Bragg (2007), p. 3.
[23] Cf. Bragg (2007), pp. 15-17.
[24] Cf. Bragg (2007), pp. 18-21.

2.2 Manufacturing process organization

Now that relevant KPIs have been introduced, it will be also described how to measure and approach the manufacturing activities.

2.2.1 Types of Manufacturing units

A quick overview of manufacturing unit types will be helpful for a more comprehensive appliance of performance metrics which are defined as follows:

Single Machine: The most basic form of a manufacturing system is a single machine or workstation. The Peklenik model describes a single machine as something containing: A sub-system for positioning, n sub-systems for kinematics and one sub-system for the transmission of energy (material removal, material forming, material joining, etc.).

Manufacturing Cell: A group of single machines that operate together to achieve more complex geometrical features. This type of system is not always present in a manufacturing plant, in NGAA it will be presented a couple of systems falling in this category.

Flow Line: For high volume production especially for consumer goods, a tightly coupled and finely balanced production line based on Henry Ford’s principle is the best choice when minimum cycle time is the key objective.

Factory: Containing all the phases and cycles of a product, from design to planning, programming, manufacturing, controlling up to dispatching are key activities nowadays.

Production Network: A global view of an enterprise, containing not only factories but also first and second tier suppliers and contributors for the supply chain.

The described manufacturing unit division is based on Hon (2005) approach.[25]

2.2.2 Main groups of manufacturing technology

Following the DIN 8580 norm, the manufacturing processes can be divided in six main groups:

1. Molding or Primary shaping, which is manufacturing a component out of formless material, like metal powder or liquid melted metal. Examples: Casting, sintering, also many of the recent additive manufacturing technologies (3D printing) such as Selective Laser Melting can fall to this category.

2. Material Forming, in its more basic definition is deforming a material to a desired geometry without removing any material, heat is usually also added to improve workability of the part. Examples: Forging, rolling, cold or hot extrusion.

3. Material Removing, which includes any manufacturing process that changes the geometry of a part by means of material cutting or removal. The most significant sub-group here would

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[25] Cf. Hon (2005), p. 141.

be machining (such as milling, grinding, turning, etc.), other examples are die cutting or shearing, laser cutting, etc.

4. Joining, which includes all processes that set two parts together for long-term conditions. Examples are: welding, soldering, screwing, stitching, etc.

5. Coating, includes all processes that change the surface of a part by addition of an adhering layer of formless material (e.g. liquids, powders), examples are: Painting, galvanization, phosphate coating treatment, etc.

6. Modifying material properties, any process that changes the physical properties of a material fall to this category. Examples are tempering, annealing, hardening, etc.

Now that the types manufacturing units and the main groups of technology have been defined, [26] it will be discussed in the next chapter some important manufacturing processes relevant for the manufacturing of a HRC.

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[26] Cf. Koether/Sauer (2016), pp. 18-19.

2.3 Statistical Process Control

It is also important, when dealing with manufacturing activities, to deliver quality to the customer confidently and reliably. Now quality is a broad field, one of its tools is the Statistic Process Control SPC, which deals a lot with statistics and control, it has nevertheless the purpose of serving quality, which plays a big role on the competitiveness of the company[27].

In SPC studies processes are continuously monitored in terms of an average value or mean, and in terms of variability. It is also a real time activity that requires constant quality control. Which enables a better grasping of the controllable variables (SPC generally starts with a measurable quality attribute such as Piston roundness). And no matter how accurate a machine can produce within a tolerance, there will always be a variability. An important concept in SPC is understanding if a process is *capable*, a very simple definition of capability (of a process): A capable process meets product specifications *regularly*. Now, the word "*regularly*" must be statistically defined.[28]

2.3.1 Process Capability, the Cpk index

In SPC two important measures are *accuracy* (hitting the target) and *precision* (achieving low spread). These two concepts can be calculated using two simple statistical functions: The arithmetic mean μ and the standard deviation σ, respectively, and defined as:[29]

Arithmetic Mean

μ

$$\mu = \sum_{i=1}^{n} \frac{x_i}{n} \quad (2.4)$$

Standard Deviation

σ

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n-1}} \quad (2.5)$$

Where x_i is the measured value within a set of n trials, like for example diameter of a cylinder bore. Note that in the σ calculation, which is a measure of "average deviation from μ", the number of samples n is subtracted by one, this compensates biases in small sized samples[30].

In SPC, an assumption needs to be made, and this is that a process is completely random, this means that all samples in an arbitrary set are independent from each other.

This is a dangerous assumption because it might hide a non-random cause, but it is often a good approximation due to a surprising result known as the central limit theorem. This theorem states that the mean of any set of variates with any distribution having a finite mean and

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[27] Cf. Oakland (2007), p. 3.
[28] Cf. Hopp/Spearman (2011), *pp. 404-405.*
[29] Cf. Oakland (2007), p. 83.
[30] Cf. Oakland (2007), pp. 88-89.

variance tends to the normal distribution. Many common attributes such as test scores, height, etc., follow roughly normal distributions, with few members at the high and low ends and many in the middle.[31] An illustration of a normal distribution can be better understood in Figure 2.6.

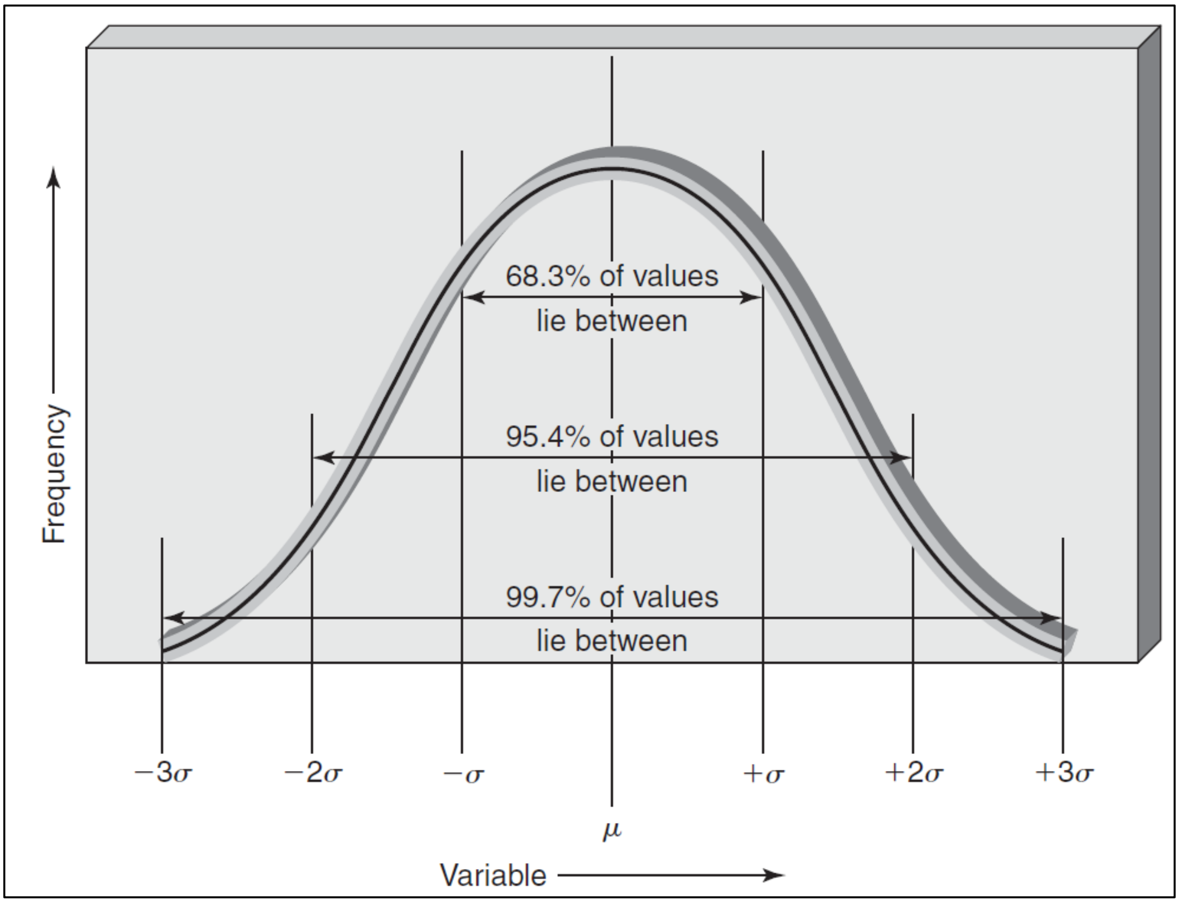

Figure 2.6: A Normal Distributed curve, Oakland (2007), p. 90

Now, to communicate if a specific process (with a defined target T, an Upper Specification Limit USL, and a Lower Specification Limit LSL) is capable, a SPC tool is introduced; the process capability index *cpk.* It is defined as:

$$cpk = min\left\{\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\right\} \qquad 2.6$$

The *cpk* index is basically a ratio between the specification limits of a desired product feature, and the variance of the process used to manufacture the desired product feature. It could also be the ratio of USL-LSL divided by 6σ, but this way it would not be considering centering between the target specification and the μ. *cpk* = 1 is usually the minimum required out of common industry processes[32], this means that the ratio is 1, so it can be assured that the process will be in conformity 99,7% of the times, this is also known as the sigma level 3.

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[31] Weisstein, Online Source [16.05.2019].

[32] Cf. Hopp/Spearman (2011), p.408.

2.4 Relevant manufacturing technologies for a HRC

Now some relevant process technologies will be reviewed to be able to compare NGAA processes to the state-of-the-art.

2.4.1 Rotor construction of an induction motor

Induction motor energy losses can be categorized in five groups: 1. Stator losses, 2. Rotor conductor losses (I^2R), 3. Core losses, 4. Mechanical (such as friction) losses, 5. Stray load losses[33]. In this thesis it will be taken a closer look at rotor conductor losses, which are also influenced by its manufacturing process. As already introduced, motor losses also account for COP losses, which is nowadays a main quality factor of a refrigerator.

One must also note that when dealing with induction motors, there are 4 important rotor design types: aluminum die cast, copper die cast, fabricated aluminum bars, and fabricated copper bars. Currently the most common process is aluminum die cast[34].

The Die Casting process

Die casting is a permanent-mold casting process (mold is not lost after every casting cycle) in which the molten metal is injected into the mold cavity under high pressure. Typical injection pressures range from 14 to 140 MPa, though, for special applications with high accuracy requirements, they can reach values up to 370 MPa. The pressure is maintained during solidification, after which the mold is opened, and the part is removed. Molds in this casting operation are called dies; hence the name die casting. The use of high pressure to force the metal into the die cavity is the most notable feature that distinguishes this process from others in the permanent-mold category.[35]

For an induction motor rotor, as already mentioned, the two most common materials to be die casted are aluminum and copper due to their good electrical conductivity properties.[36] When die casted, both materials will be more correctly manufactured using the *cold-chamber die casting* process (Figure 2.7) due to either higher liquid phase reactiveness with the steel tooling (aluminum) or higher melting temperature (copper, 1084°C[37]), both attributes would quickly wear out the tooling. In cold-chamber die casting machines, molten metal is poured into an unheated chamber from an external melting container (injection system is not submerged in the metal liquid bath), and a piston is used to inject the metal under high pressure into the die cavity.

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[33] Cf. Yun/Lee (2018), p. 2.
[34] Cf. Finley/Hodowanec (2001), p. 1563.
[35] Cf. Groover (2010), p. 241.
[36] Helmenstine (2018), Online Source [30.05.2019].
[37] Engineering ToolBox (2005), Online Source [30.05.2019].

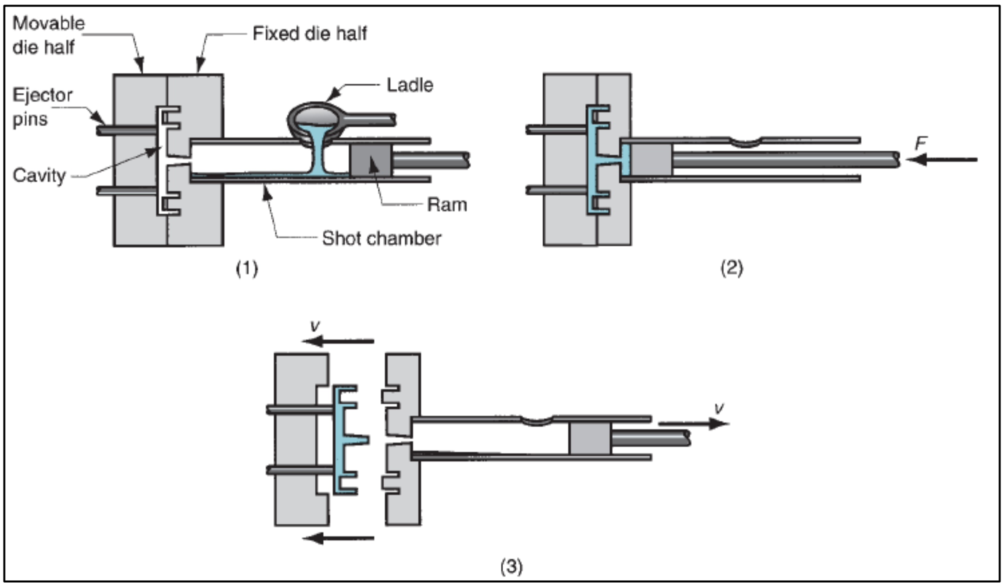

Figure 2.7: Cold-chamber die casting, Mikell P. Groover (2010), p. 241

When dealing with aluminum die casting processes, there are many parameters within the process that can be configurated to achieve better quality, some of the most relevant/critical include: Cooling system of the die, lubricant of the die, pouring temperature, filling time, die temperature, injection pressure, between others. Important is to define which of these parameters have a higher in influence in the final quality of the rotor, and then correctly control them.[38]

For HRC applications with induction motors, a critical to quality feature is the porosity of the aluminum die casted rotor (the air retained in the inside pores greatly disturbs the electrical conductivity inside the rotor, increasing losses) and even though porosity cannot be completely avoided, as aluminum shrinks 7% in volume during solidification[39], it can be reduced by

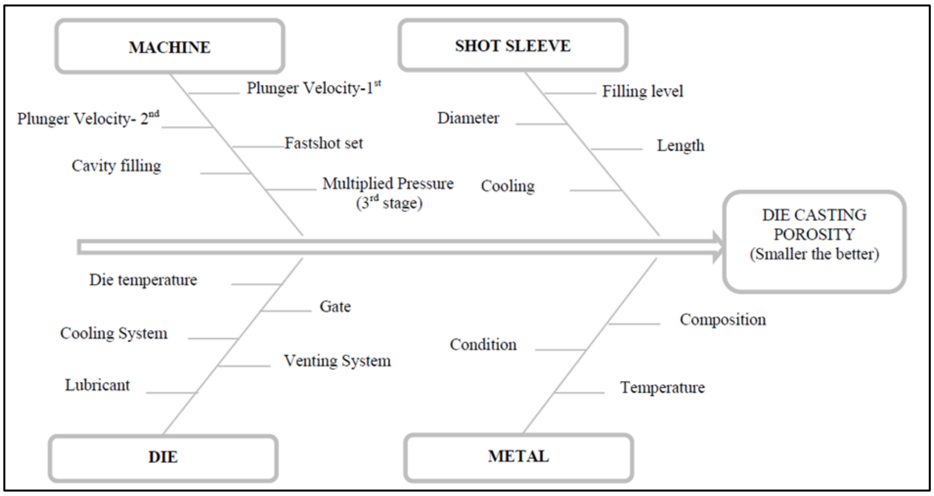

Figure 2.8: Ishikawa diagram of the die casting porosity, Apparao/Birru (2017), p. 1854

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[38] Cf. Apparao/Birru (2017), p. 1853.

[39] Cf. Yun/Lee (2018), p. 1.

improving its manufacturing process. Figure 2.8 depicts an Ishikawa Diagram of the process parameters in the die casting manufacturing and their influences on porosity[40]:

The four process parameters (pouring temperature, filling time, die temperature and injection pressure) relationship with porosity, based on the Taguchi approach studies, are proposed in Figure 2.9[41]. In Apparao and Birru (2017) the experimental results show that the injection pressure has the biggest influence on porosity, which in die casting machines can be configurated by means of a pressure regulating valve.

Parameter destination	Process parameters	Range	Level 1	Level 2	Level 3
A	Pouring temperature(^{0}C)	650 - 750	650	700	750
B	Filling time (ms)	40 - 130	40	85	130
C	Die temperature(^{0}C)	180 - 260	180	220	260
D	Injection pressure(bar)	120 - 240	120	180	240

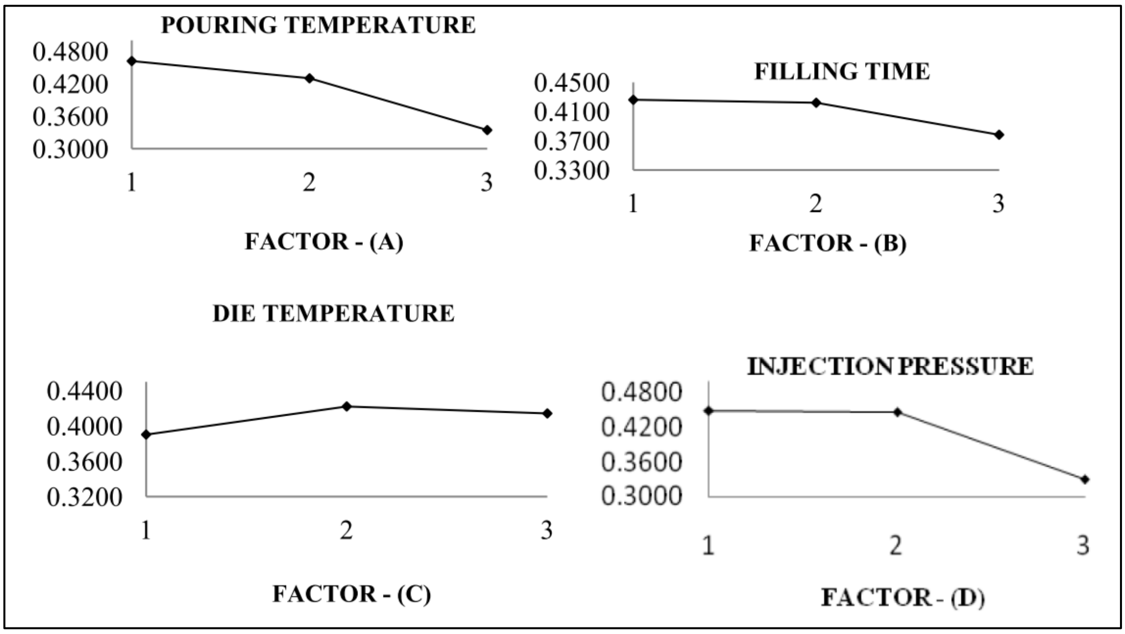

Figure 2.9: Porosity function of different die casting process parameters, Apparao/Birru (2017), pp. 1854-1856

2.4.2 Piston-Cylinder pairing manufacturing

It will now be described in more depth manufacturing technologies, that are of special relevance to produce a HRC's piston. As it will be later proposed, two critical processes that have a high influence on the final efficiency (or COP) of the compressor are the finish grinding of the piston and the honing of the cylinder, which then are paired with clearances with an order of magnitude of 1µm. Some grinding principles are described in the next sections.

The Grinding Process

Following the DIN 8580 norm, grinding is a machining process belonging to the group: Material Removal. Within this group it belongs to the sub-group: machining with an undefined cutting

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[40] Cf. Apparao/Birru (2017), p. 1854.
[41] Cf. Apparao/Birru (2017), p. 1853.

edge[42]. It is an abrasive machining technology that has been rapidly developing since the 20th century and it still is a critical process to achieve competitive success, it is regarded as a crucial strategic process in many industries such as fine mechanics, aero-engines or missile guided systems[43].

Grinding is a process usually found at the end of a production line, where the WIP costs have considerably stacked up, it is therefore critical that the grinding process doesn't produce out of conformity parts (at the end of the production line the losses are higher), additionally the value added after grinding is also very high, this is due to its high accuracy with regards to tolerances and surface finishing[44].

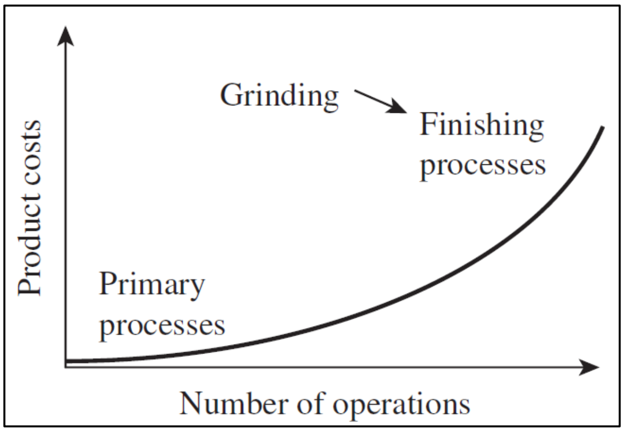

Figure 2.10: Grinding process costs, Rowe (2014), p. 5

The usual strategy nowadays to achieve less costs, is to either avoid grinding, in case the product specifications can be handled by prior machining stations, or remove as much material as possible in the grinding operation and thus substituting prior rougher operations.

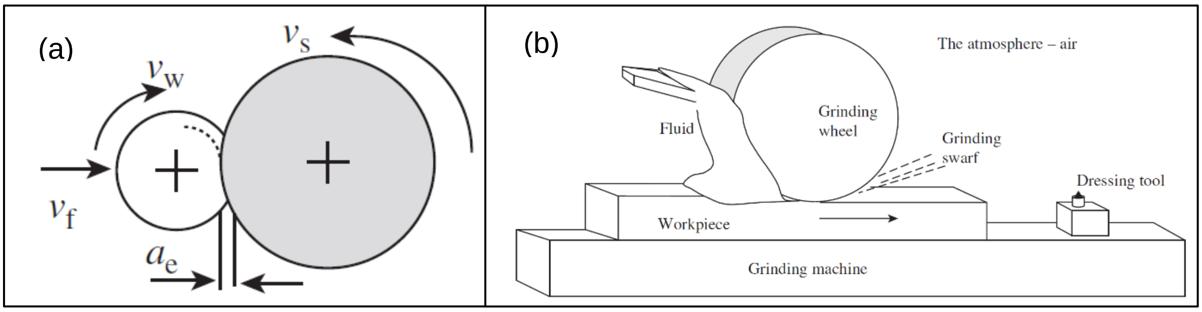

Figure 2.11: a) Peripheral cylindrical grinding, Rowe (2014), p. 18;
b) Basic elements of a grinding process, Rowe (2014), p. 8

There are various types of grinding processes, for the piston grinding a very relevant grinding process is the peripheral cylindrical grinding, illustrated in Figure 2.11.(a). The basic elements to be considered in the grinding process include: Grinding machine, grinding wheel, workpiece (piston in this case), grinding fluid, atmosphere and the grinding swarf, (the dressing tool is

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[42] Cf. Fritz/Schulze (2013), p. 2.
[43] Cf. Rowe (2014), pp. 2-3.
[44] Cf. Rowe (2014), p. 5.

also included for the maintenance of the grinding wheel). These elements must be designed in a way that they work optimally together[45], see Figure 2.11.(b).

Now, as illustrated in Figure 2.11.(a), some important grinding parameters must be defined: a_e is the depth of cut, v_s is the grinding wheel speed, v_w is the work speed (in this case, of the piston) and v_f is the infeed rate.

Also, the rate at which material is removed Q_w from a part is very relevant for machines forces, deflections, and power consumption; measured as volume removed per time unit. For this reason, an additional important parameter to be introduced is the specific removal rate Q'_w, which is removal rate of material per unit of width, which is measured in mm^2/s, given by[46]:

$$\text{Removal Rate} \qquad Q_w = a_e \cdot v_w \cdot b_w \qquad 2.7$$

$$\text{Specific Removal Rate} \qquad Q'_w = \frac{Q_w}{b_w} \qquad 2.8$$

$$\text{Specific Removal Rate} \qquad Q'_w = a_e \cdot v_w \qquad 2.9$$

The removal rate is extremely important when it comes to abrasive behavior of the grinding wheel, it is a good effectiveness measure to compare different grinding grains, and it will also reduce the number of variables required to compare different grinding wheels[47].

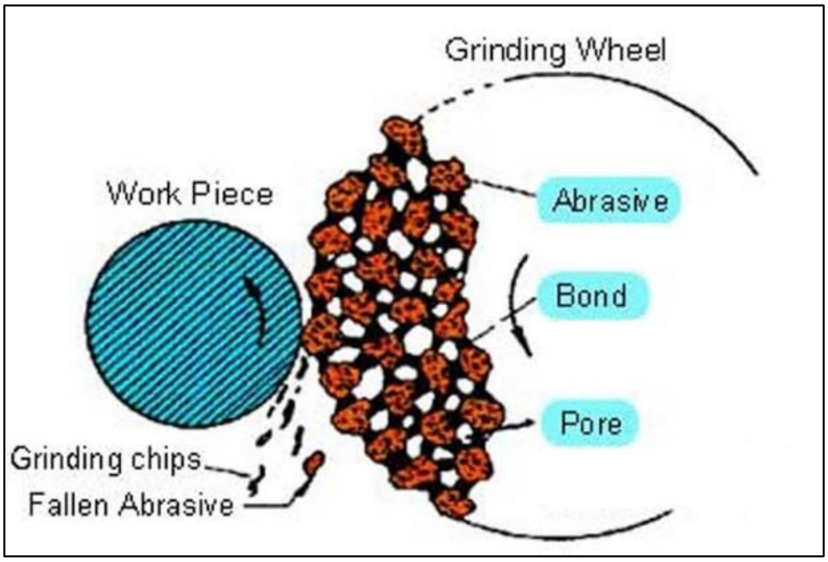

Figure 2.12: Components of a grinding wheel, online source: www.forturetools.com [11.03.2019], slightly modified

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[45] Cf. Rowe (2014), pp. 8-9.
[46] Cf. Fritz/Schulze (2008), p. 302.
[47] Cf. Rowe (2014), pp. 22-23.

The grinding wheels, as already briefly mentioned, as basic grinding elements, have seen a considerable growth in the last decades. They are material compounds containing high strength abrasive grains which do the cutting job, bond material which is responsible for maintaining the grains bonded together and reducing vibrations transmitted to the workpiece, and pores to help expelling the workpiece cut chips and releasing heat from the grinding wheel[48]. As illustrated in Figure 2.12.

When it comes to abrasive grains, as the cutting compound of the grinding wheel, a very important property is hardness, usually measured in GPa, additionally, because almost every grinding wheel loses hardness with increased temperature, other important properties are thermal conductivity and thermal diffusivity. A sub-field of study within the abrasive grain, that is gaining economic importance, are the superabrasive grains. They used to be too expensive to be economically viable in manufacturing operations, but due to economies of scale and increasing high quality demands they are gaining relevance in the markets. One superabrasive of special importance for the steel and casted iron machining is the crystalline Cubic Boron Nitride (CBD) and conventional abrasives for the same materials include the Aluminum Oxide (Al_2O_3) or the Silicon Carbide (SiC, high hardness but high wear rate with irons and steels due to carbon affinity)[49].

Bonding material is also a vast study topic as well as an important influence factor. The three main classes of bonding material are: 1. Organic or resin bonds, 2. Vitrified bond wheels, 3. Metal bond types[50]. Within these three classes there is a vast variety of different bond materials supply each with very specific characteristics.

With regards to the scope of this study, it is important to design the grinding process in a way that costs are minimized, and quality requirements are met. As exhibited in Figure 2.13 many factors come into play when designing the grinding process for cost reduction.

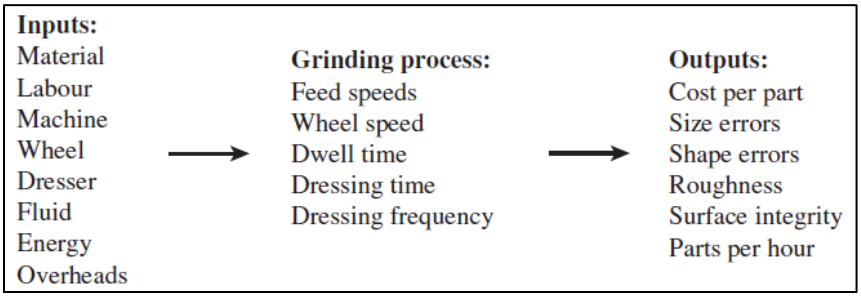

Figure 2.13: Grinding process design factors, Rowe (2014), p. 160

A calculation method will be proposed to estimate the cost per part, which should be regularly applied. First, the costs must be divided into three main groups[51]: Machine, Labor, and

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[48] Cf. Cheil Grinding Wheel Ind. Co., Online Source [10.04.2019].
[49] Cf. Rowe (2014), pp. 35-40.
[50] Cf. Rowe (2014), p. 46.
[51] Cf. Rowe (2014), p. 161.

Grinding Wheel costs. Secondly, total cycle time t_t must also be defined to have a per part cost estimation. Total cycle time is composed of two terms, grinding cycle time t_s and dressing cycle time t_d (dressing is the basic maintenance operation of the grinding wheel). Number of parts ground before dressing or dressing frequency N_d is also required (highly influenced by the hardness of the abrasive chosen). The total cycle time will then be:

$$t_t = t_s + \frac{t_d}{N_d} \tag{2.10}$$

Now the *total variable cost per part* c_t, as already mentioned, can be based in three main groups. *Machine Cost per part,* c_m: Which is given by the total cost of the grinding machine C_m, total cycle time t_t, and the required payback time y_t.

$$c_m = C_m \times \frac{t_t}{y_t} \tag{2.11}$$

Labor cost per part, c_L: Given by the cost of labor per time unit, C_L (which depends on the country and company policies), and the total cycle time t_t.

$$c_L = C_L \times t_t \tag{2.12}$$

And finally, *grinding wheel costs per part,* c_w: Based on the grinding wheel cost C_w, and the number of ground parts before the wheel is reduced to a minimum safe size, N_w.

$$c_w = \frac{C_w}{N_w} \tag{2.13}$$

Setting all the equations together the total variable cost per part c_t can be calculated as:

$$c_t = c_m + c_L + c_w \tag{2.14}$$

An interest conclusion taking out of this model is the importance of the factor N_d (dressing frequency), this is because dressing frequency directly contributes for the total cycle time (**2.10**), which in turn directly influences the labor cost per part c_L and the machine cost per part c_m. Additionally, the factor N_w is greatly influenced by dressing frequency N_d; this is because higher dressing frequencies increase consumption rate of the grinding wheel. So, the dressing frequency N_d influences all the right-hand factors in **2.14**, making it an important parameter when optimizing grinding processes[52].

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[52] Cf. Rowe (2014), p. 166.

Centerless grinding

Centerless grinding is a special kind of grinding process, it is highly appropriate for mass production operations and precision batch processes. It appeared in 1917 due to an increasing need in the automotive industry of higher accuracy as well as higher productivity. With the appearing of centerless grinding the nominal value accuracy improved by one forth and the throughput time was reduced to one-tenth of what was the standards during that time.[53]

Compared to grinding between centers, the main advantages of centerless grinding are: high specific removal rate Q' due to wider grinding wheels, reduced shape errors related to positioning/centering of the part (process requires no centering operation inside the grinding machine), it is a highly automated production process that requires low supervision, wheels have lower wear and thus dressing time productivity losses are reduced. Additionally, conventional abrasives are usually a good choice for this process (though superabrasives are starting to gain importance in very high wheel speed application which can achieve even tighter tolerances).[54]

The centerless grinding process or more specifically the external centerless grinding process has three main components: A regulating wheel (also called control wheel) and a slightly tilted blade to support the workpiece which act together to push the workpiece against the grinding wheel (third component) which does the material removal. Figure 2.14 and Figure 2.15 illustrate the process:

Figure 2.14: Centreless grinding machine,
Online source: www.mikrosa.com [26.04.2019]

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[53] Cf. Hashimoto et al. (2012), p. 747.
[54] Cf. Rowe (2014), p. 264.

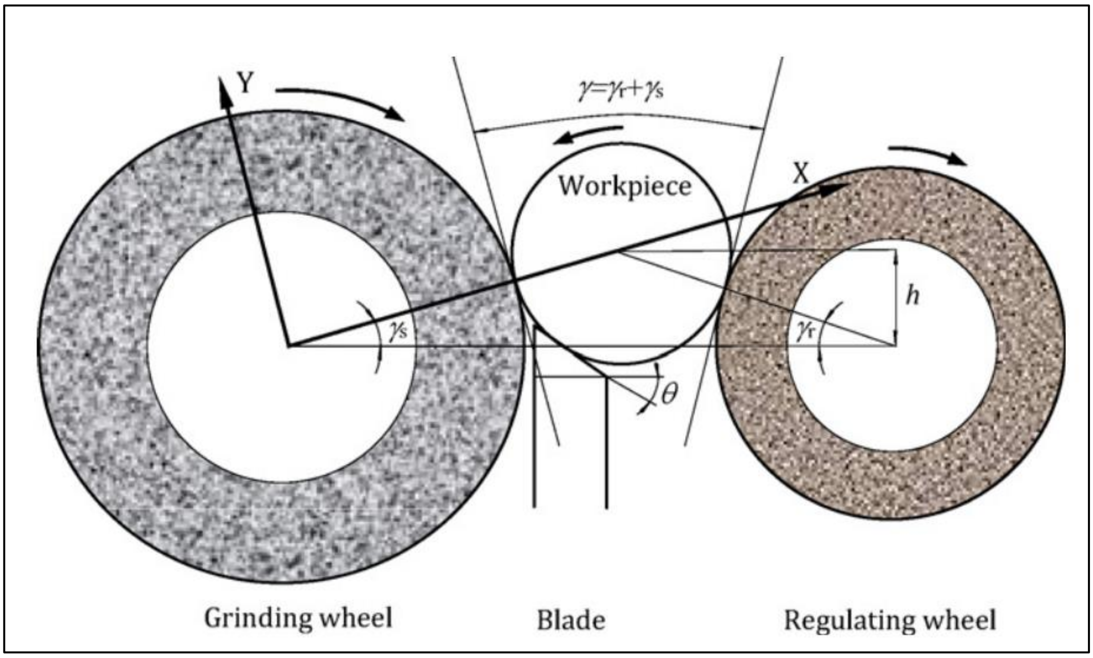

Figure 2.15: Geometric description of centerless grinding, Hashimoto et al. (2012), p. 750

As illustrated in Figure 2.15, important parameters include blade angle θ, work height h which is configurated or set to give the most appropriate tangent angle γ_s. The tangent angle is a critical parameter in centerless grinding to achieve low roundness errors, its optimal region for the finish grinding is between 6° to 8°. Additionally, it has been suggested (in processes where two grinding operations are required, e.g. rough grinding followed by finish grinding), that using two different heights for each centerless grinding operation reduces roundness errors; for example, using a tangent angle γ_s of 4° for the rough grinding and 7° for the finish grinding[55]. Now an important expression to relate work height h with the tangent angle γ_s is given as[56]:

$$h = \frac{\gamma_s/2}{\frac{1}{d_s + d_w} + \frac{1}{d_c + d_w}} \qquad 2.15$$

Where d_s is the grinding wheel diameter, d_w is the workpiece diameter and d_c is the regulating wheel diameter. In the previous section, removal rate Q_w was introduced for conventional center-type cylindrical grinding (note the centering in Figure 2.11.(a)), in centerless grinding the material is grinded from the diameter of the workpiece instead of the radius, for this reason depth of cut a_e calculation method is slightly altered (a factor of 2 needs to be added):

Depth of cut

$$a_e = \frac{1}{2} \cdot \pi \cdot d_w \cdot \frac{v_f}{v_w} \qquad 2.16$$

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[55] Cf. Harrison/Pearce (2004), pp. 159-164.
[56] Cf. Rowe (2014), p. 269.

An important aspect in centerless grinding is the machine design, this will affect the productivity and accuracy of the grinding process. Other important design aspect is the machine stiffness, with higher machine stiffness it is possible to achieve higher removal rate, and at the same time, better roundness. This is due to a higher natural frequency range as well as higher damping which reduces vibrations.[57]

A very common phenomenon in machining processes is the *regenerative chatter* which introduces instability in the process causing high vibrations (workpiece tolerances are affected: Reduced surface smoothness and roundness). Chatter also increases tool wear rate.[58]

Studies have shown that it is possible to improve the centerless grinding capabilities without buying new machines which is an expensive investment:

One example has shown that by adding two inertial active dampers in the centerless grinding machine it is possible to reduce chatter in the machine, through that, productivity was increased while maintaining the same work speed. Additionally, better roundness values were achieved.[59] This application is shown in Figure 2.16.

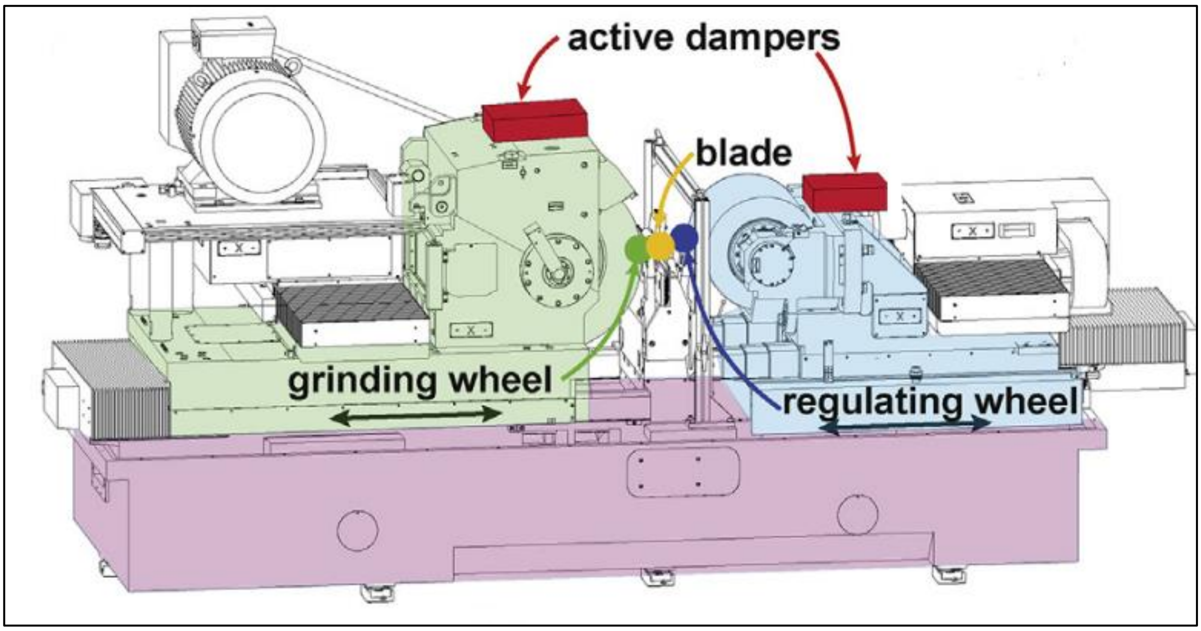

Figure 2.16: Inertial Active Dampers, Barrenetxea et al. (2018) p. 338

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[57] Cf. Rowe (2014), pp. 275-276.

[58] Cf. Faassen/Wouw/Oosterling/Nijmeijer (2003), p. 1437.

[59] Cf. Barrenetxea/Mancisidor/Beudaert/Munoa (2018), pp. 337-340.

3 Analysis

3.1 A Top-Down Analysis Approach

A manufacturing plant is a very complex system, in this specific case, a manufacturing plant with over 40 production lines (and each line with, sometimes, more than 40 single processes as in the assembly lines), these lines have very distinct manufacturing process, some are mainly doing metal machining processes such as milling or grinding, other lines are pure assembly lines, other lines are doing aluminum pressure die casting and the list and diversity goes on. It still applies for NGAA manufacturing plant what Aristotle said for more than 2000 years ago, “The whole is greater than the sum of the parts”, but it is also true, as suggested by newer chains of thought such as Theory of Constraints by Mr. Eliyahu M. Goldratt, that improving the weakest parts (E.g. bottlenecks or constraints) will lead to a better performance of the whole.

For this reason, to find the weakest parts of the production chain and improve the whole, the plant was subdivided into three different levels of production depth: 1st Level: Platforms, 2nd Level: Production Lines and 3rd Level: Process Steps.

3.1.1 Platforms

Platforms are the different compressors currently being produced at NGAA plant. Currently two: Kappa and Delta (Figure 3.1). The platforms are composed of all the production lines that are required to produce each compressor (Kappa or Delta). The analysis was made with the vision of adding future platforms (such as the new compressor in development stage: Delta-VSD), to compare manufacturing performance quantitatively, and to set standards of comparison.

Figure 3.1: Kappa and Delta Platforms, source: NGAA internal documents

3.1.2 Production Lines

Production lines are the second level of observation, one degree deeper than the platforms. This causes an increase in complexity. For each platform a production flow diagram was designed in Excel as follows (figure 3.2):

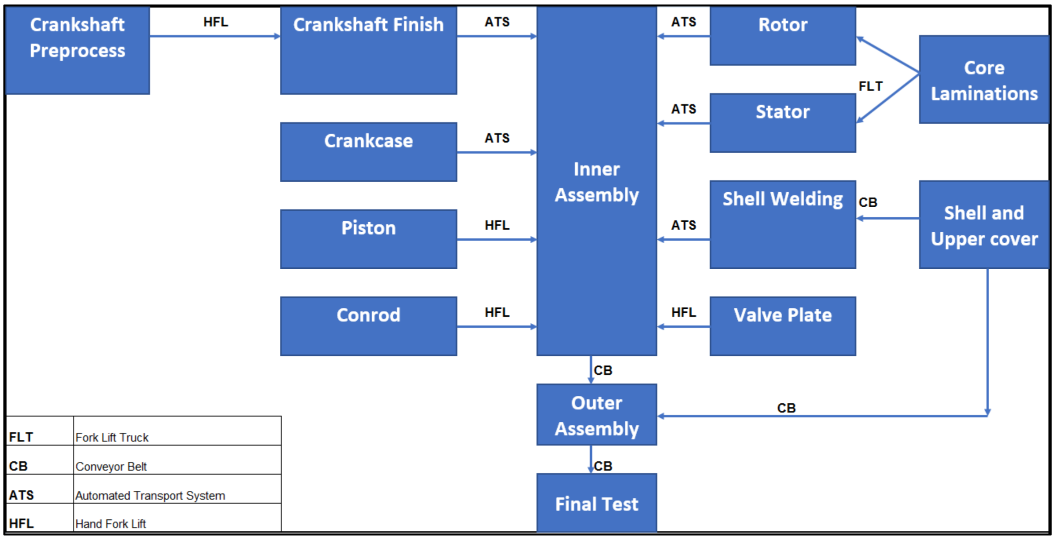


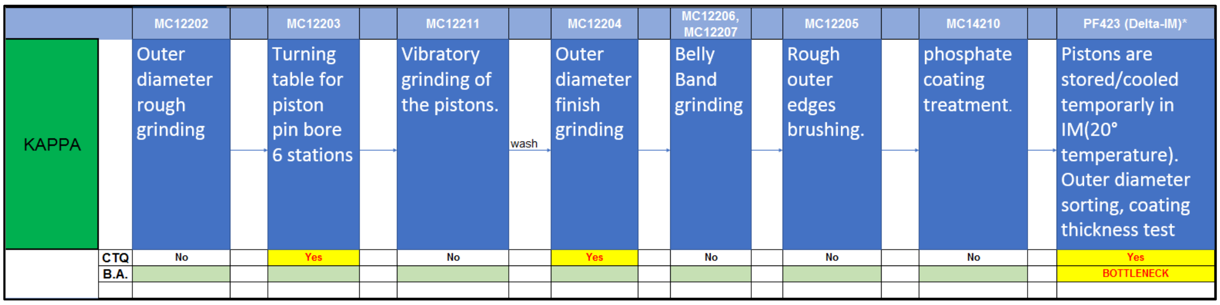
Figure 3.2: Production Flow of the Kappa platform, Source: Own illustration

The blue squares represent each production line, which will be individually described. The production flow of the Kappa and Delta compressors is practically identical, the only main difference is the outsourcing of the Crankshaft preprocess in the Delta platform.

3.1.3 Process Steps

The third level is the analysis of each process step belonging to a single production line, where each process step is described and evaluated for process and financial capability. It will be the most extensive level, as each production line unfolds into many process steps. Figure 3.3 illustrates a production flow chart for the piston production, which is an example of a production line with a high amount of machining processes.

Just at this production line there are over 10 manufacturing process stations (some are counted twice because of a double identical process step). It is also important to define what is a process step, and there are many approaches on this problem, it was decided in this case to use an approach suggested in (Manufacturing Process Selection Handbook, 2013).



		MC12202		MC12203		MC12211		MC12204		MC12206, MC12207		MC12205		MC14210		PF423 (Delta-IM)*
KAPPA		Outer diameter rough grinding		Turning table for piston pin bore 6 stations		Vibratory grinding of the pistons.	wash	Outer diameter finish grinding		Belly Band grinding		Rough outer edges brushing.		phosphate coating treatment.		Pistons are stored/cooled temporarly in IM(20° temperature). Outer diameter sorting, coating thickness test
	CTQ	No		Yes		No		Yes		No		No		No		Yes
	B.A.															BOTTLENECK

Figure 3.3: Process steps of the Kappa piston, Source: Own illustration

The process steps can be of three categories: First, primary shaping processes; such as casting, forming, molding, powder sintering. Second, secondary shaping processes; such as bulk heat treatment processes, material removal processes (machining for example), surface treatment processes. And finally, Assembly/Test processes; such as joining processes (bolting, welding, adhesive bonding, etc.), assembly system processes (component feeding, orientation, robotics, placement, insertion) and Test processes (measurement, inspections, functional testing).[60]

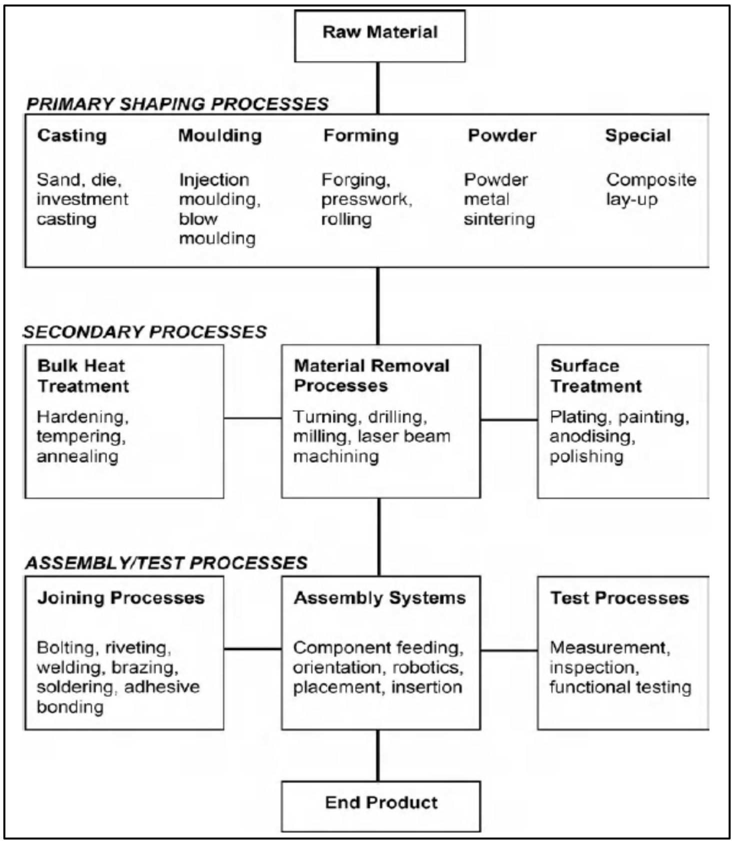


Figure 3.4: Process Step Definition and Categories, Swift/Booker (2013), pp. 10

Most of processes in NGAA will fall to the Secondary and Assembly/Test Process categories. And, because the scope of the study is set on the analysis and benchmark of the manufacturing systems, all logistic processes will not be measured. They were nonetheless qualitatively analyzed and all logistic flows for each production line can be found in the Appendixes A & B, this was done also because logistics have an important influence in WIP costs, which must be taken in to consideration.

The platform, production line, process step concept is illustrated in Figure 3.5.

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[60] Cf. Swift/Booker (2013), p. 10.

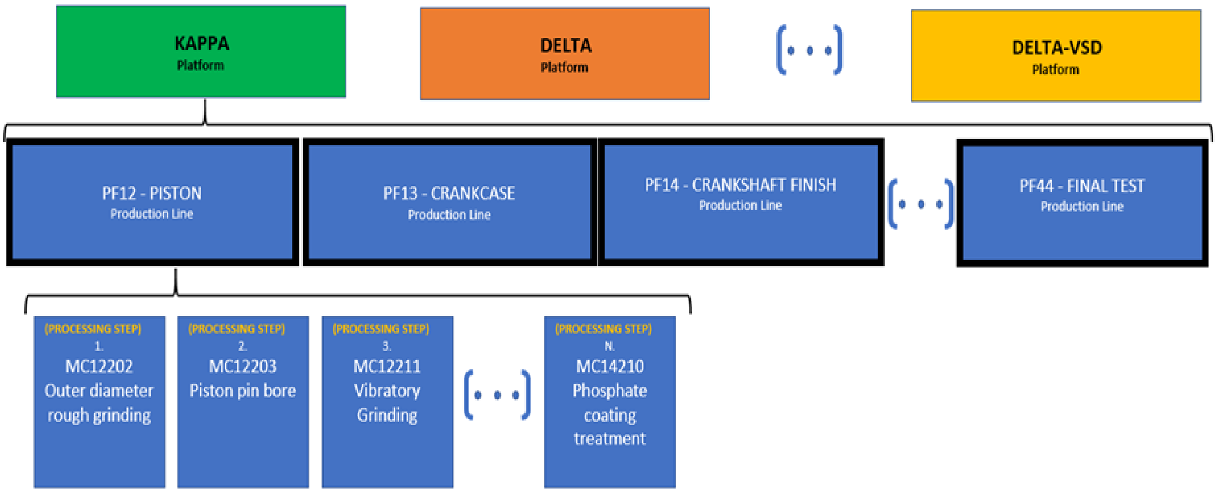


Figure 3.5: Platform, production line, process step, source: Own illustration

3.2 Plant analysis and description

As represented in Figure 3.2 each platform is composed of 15 production lines (Delta only 14 lines due to outsource of PF18), it will now be given an overview of each production line, dividing into Kappa and Delta description. The inner assembly will be the first to be described, as it is the critical line in the manufacturing plant.

Table 3.1: Nomenclature of each Production Line

PF12	Piston
PF13	Crankcase
PF14	Crankshaft Finish
PF15	Conrod
PF18	Crankshaft Preprocess
PF21.1	Shell
PF21.2	Upper cover
PF22	Rotor
PF23	Core Laminations
PF26	Shell welding
PF31	Stator
PF41	Valve Plate
PF42	Inner Assembly
PF43	Outer Assembly
PF44	Final Test

3.2.1 Inner Assembly

The inner assembly (PF42) is where all the produced and outsourced components of the compressor are assembled, the only part left out is the cover, which is assembled (welded) in the next line, PF43 Outer Assembly. PF42 is the production line that marks the rhythm of the whole production. It is also the most labor intensive one. Many critical quality aspects will be dictated in this line: The clearance between piston and cylinder assembly and the air gap between the rotor and the stator, these are not the only ones as it will be seen. A full description of the process flow can be found in the Appendix A.

Table 3.2: Inner Assembly Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity* *#/h* $_w$	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF42**	**Inner Assembly**	**280**	**9**	**31,6**	**0,055**	**68%**	**stator mounting**	**28**
KAPPA	**PF42**	**Inner Assembly**	**490**	**10**	**44,5**	**0,016**	**74%**	**stator mounting**	**39**

- **Kappa:**

For the Kappa line there is 39 processing steps (most of them assemble processes). To better understand the inner assembly line an exploded view of the Kappa compressor is provided in Figure 3.6. Additionally, a flow chart was created to expose the stations that require more attention which can be seen in Figure 3.7, the red marked stations are critical to quality stations. As it possible to interpret, the most labor-intensive operations are the crank train assembly and the stator correct alignment with the rotor, these are also the most influential geometrical aspects on the final COP of the compressor as it will be seen later in this chapter.

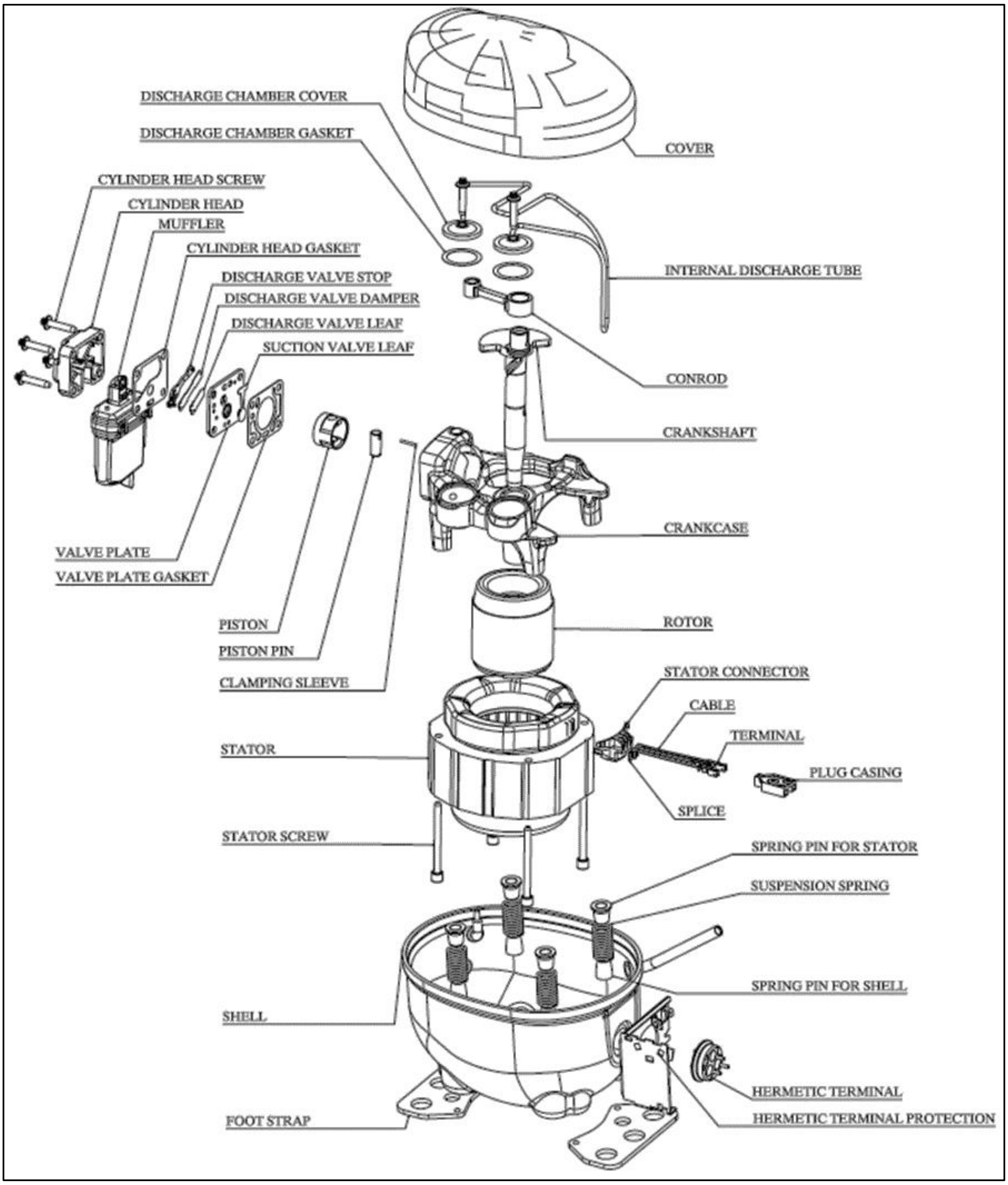


Figure 3.6: Kappa exploded View, Source: NGAA internal documents

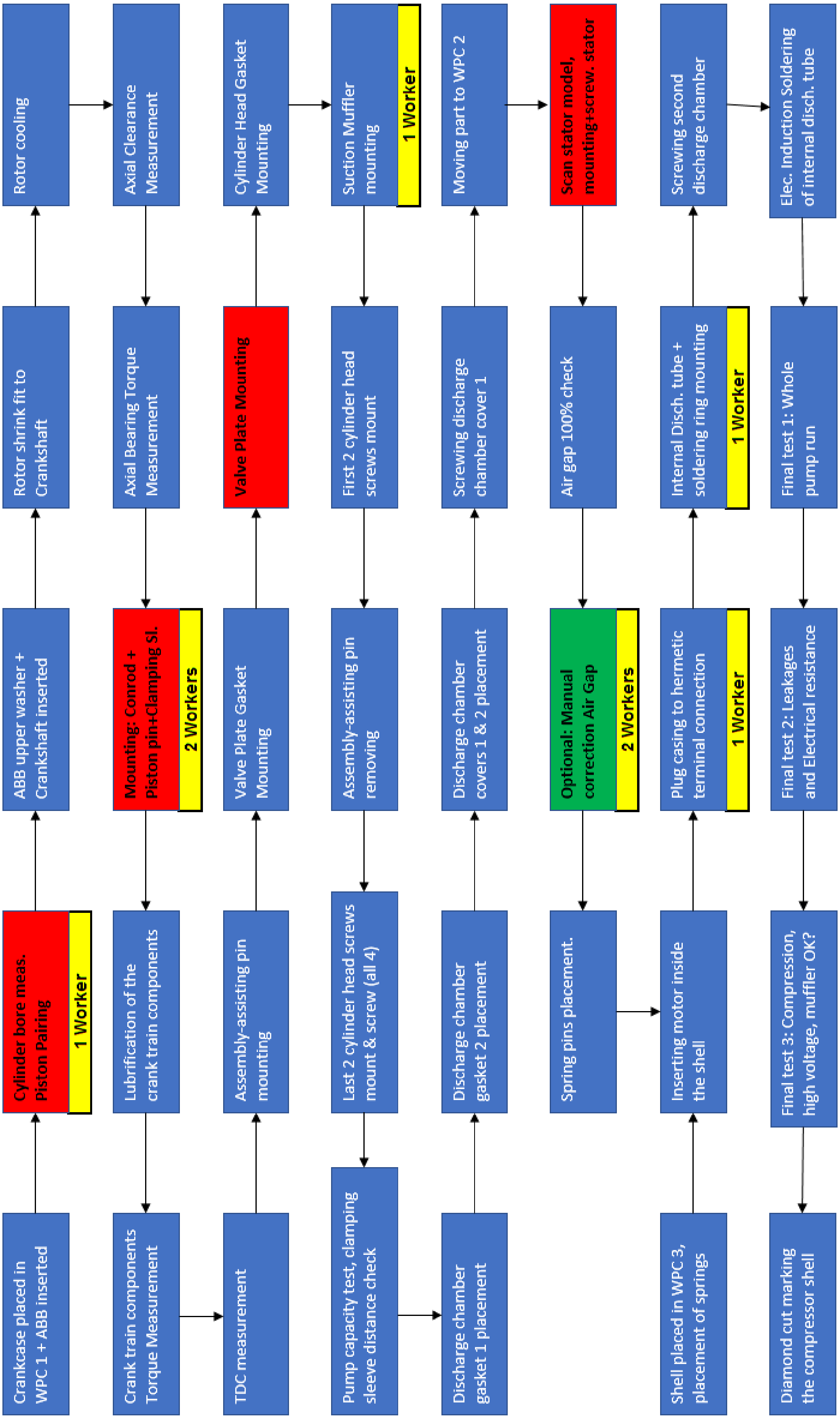


Figure 3.7: Kappa Inner Assembly process flow, Source: Own Illustration

- **Delta**

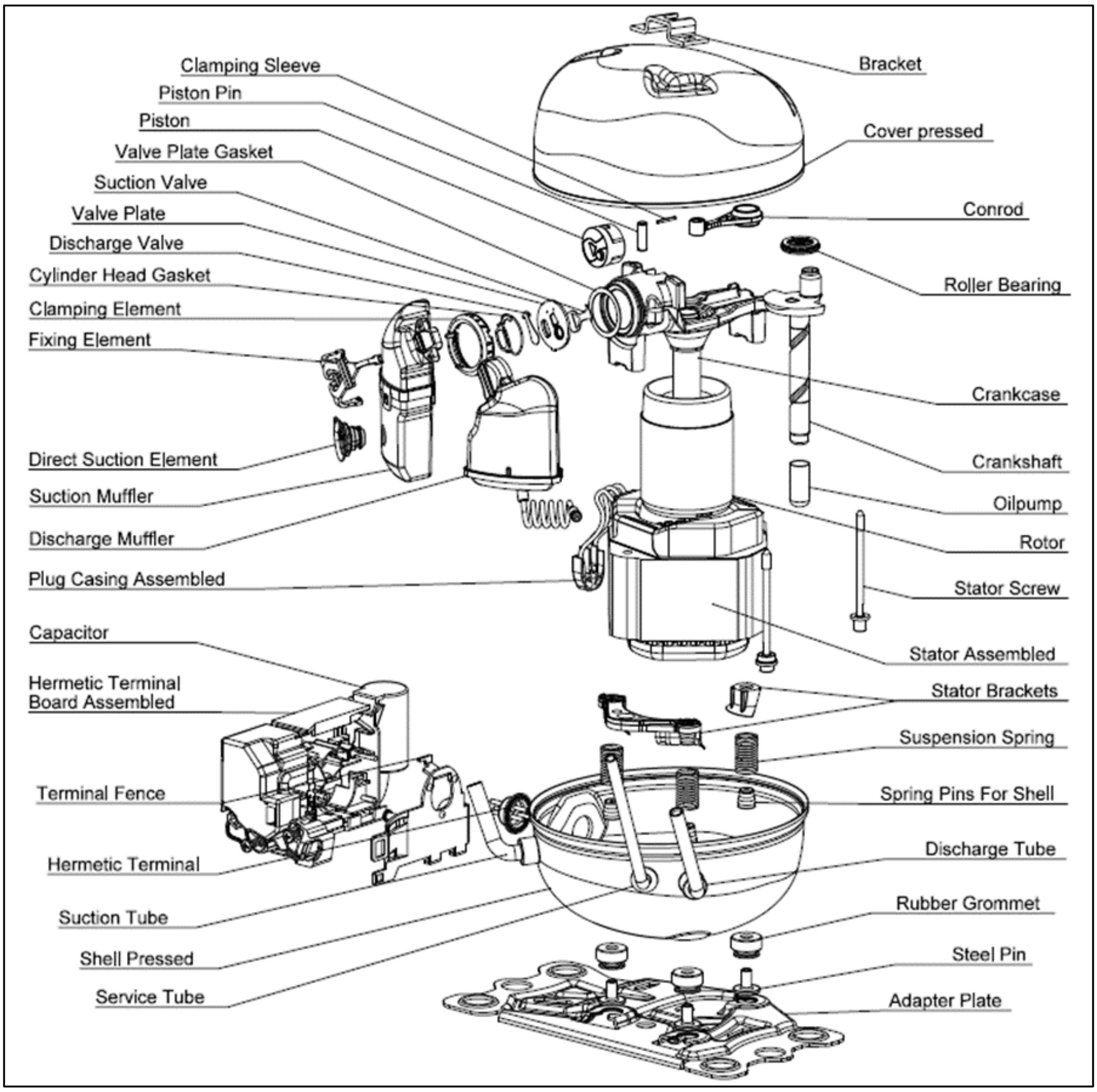


Figure 3.8: Delta exploded view, source: NGAA internal documents

For the Delta line there are 29 processing steps (most of them assemble processes). A schematic description of this line is illustrated in Figure 3.9. Comparing to the Kappa the line, this line shows a considerate room for improvement with regards to automatization; certain analogous automated steps in the Kappa line are manually done in the Delta line, for example: The shell placement in the WPC. This would increase the DoA and the productivity of the line, which additionally has workers doing more than one station, which interrupts the flow of the assembly.

As for the Kappa example, the red marked steps are critical to quality. A full description of the assembly process flow can be found in the Appendix B.

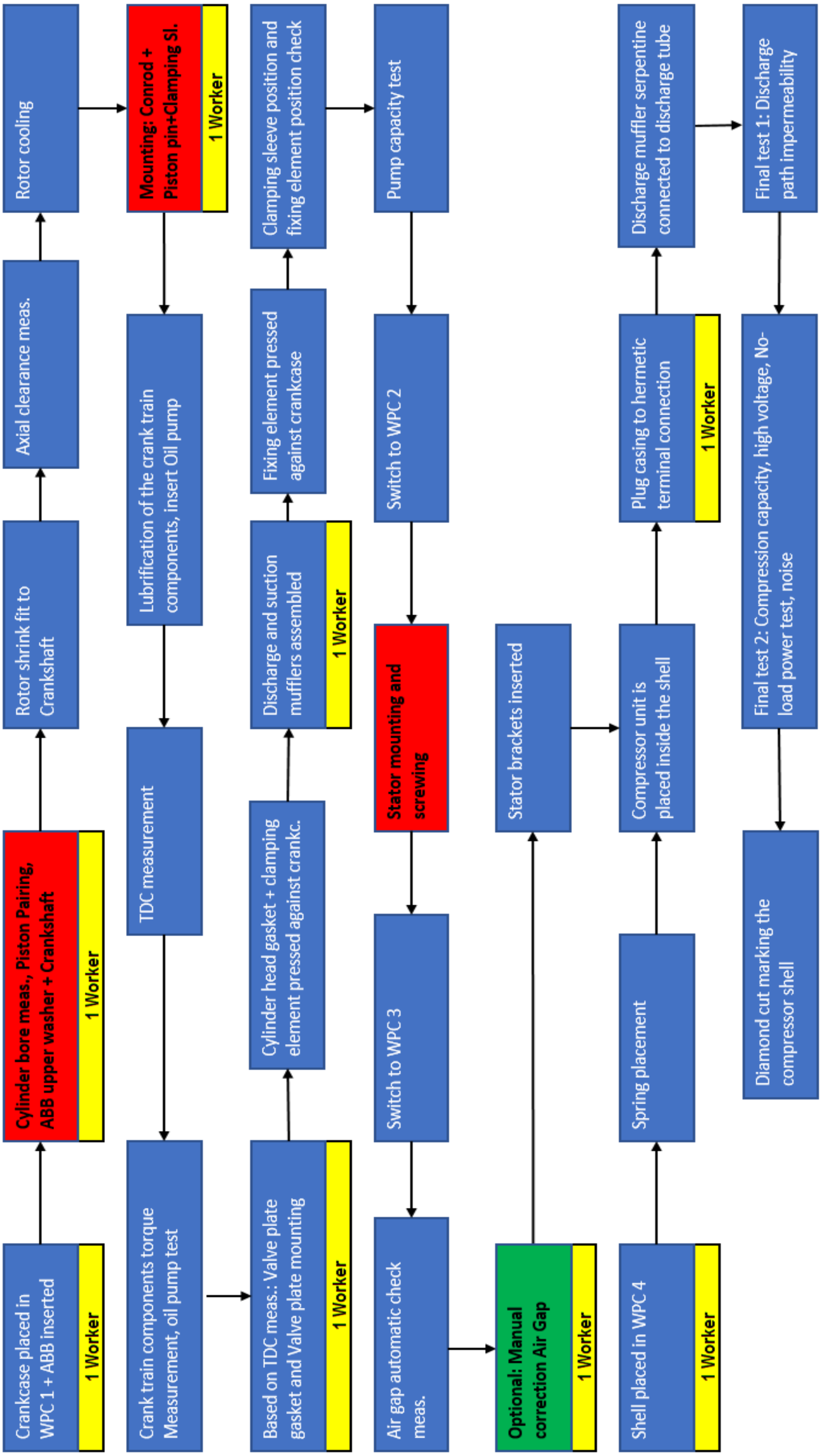


Figure 3.9: Delta Inner Assembly process flow, Source: Own Illustration

3.2.2 Crank train components

The process flow of the parts that compose the crank train will now be described. For these components the processes are mostly machining processes. The components are: piston, crankcase (where the cylinder is), crankshaft and conrod.

PF12 - Piston

The piston is a critical part of a compressor, minor deviations in this production operation can severely reduce the COP of a refrigerator, either by refrigerant gas leakages, or by increased frictional losses.

Table 3.3: Piston Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of working places	*Productivity #/h $_w$*	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	PF12	**Piston**	**400**	**4**	**105**	**0,008**	**67%**	**Sorting**	**12**
KAPPA	PF12	**Piston**	**490**	**4,5**	**150**	**0,004**	**50%**	**Sorting**	**9**

- **Kappa:**

This production line is composed of eight main processes. First, the raw pistons are manually loaded to the first machine, this machine is responsible for a first rough grinding removing most of the outer diameter material, this operation is needed for the afterward processing.

Then comes the piston pin bore drilling, this machining step is critical because it will dictate the perpendicularity between the piston axis and the piston-pin bore axis, this geometric feature influence on the refrigerator COP is high. This machining step is a turning table with incremental material removal steps: drilling, counter-boring, boring, reaming. The pistons are brought manually in small boxes to this station.

Next, is the vibratory grinding to eliminate all rough edges and burrs, pistons are also brought manually to this machine. The pistons are then washed in the washing line (which is in a considerable distance away from PF12) and brought back again to the line. Now comes a very critical process step, the finish grinding, it is critical due to its direct influence in the piston diameter and roundness which are also critical to quality features.

Following, there is the belly band grinding (material removal from the side of the piston to reduce friction losses inside the cylinder), done by two parallel machining centers, followed by a brushing of the burrs left by the belly band grind. Then a phosphate coating treatment of the piston is required, which adds 2 to 3 microns to the outer diameter, fact that is important for the piston to cylinder clearance.

Finally, a critical measurement and the bottleneck operation of the line: the pistons are stored in the Inner Assembly room of the Delta compressor, this room is kept at 20°C, after some hours the pistons will shrink due to temperature gradient. They will then be measured: Perpendicularity of the two axes, outer diameter and circularity and the coating will be tested. After the measurement the pistons are sorted by diameter categories or ranges, that will be later paired with the respective cylinder diameter category.

- **Delta:**

The Delta piston manufacturing has some differences to the Kappa, but the critical to quality features of the component are the same. The first step is the same (rough grinding), and done in the same machine as in Kappa. Then the pistons are manually transported to the bore turning table where the piston pin bore is done.

Analogously, the pistons undergo vibratory grinding (same machine as for Kappa). After this special grinding process, they also must be washed. They are then brought back to the piston line to be finish grinded (again the same machine as Kappa).

The main difference to the Kappa piston is the belly band machining, in this case the belly band is milled instead of grinded. After the belly band milling, the resulting rough edges are brushed. Then again comes the phosphate coating treatment of the piston. Afterwards there is an additional step in the Delta piston: Honing the piston-pin bore manually, this additional step will require a posterior washing of the piston. After being washed the pistons are stored in the inner assembly room, where they will be finally measured (perpendicularity, roundness and diameter) and sorted (by diameter class).

PF13 - Crankcase

The crankcase is also a critical part of the compressor, it can be viewed as the “skeleton” of the whole motor, it supports the weight of the crank train components. The cylinder bore also belongs to the crankcase, making the crankcase an important “multi-task” part. The crankcase has four legs (or two legs if the Delta platform is considered), which subsequently deliver the weight to the outer shell of the compressor. For both platforms, four critical geometric features have been agreed upon: 1. Perpendicularity between the shaft axis and the cylinder axis; 2. Cylinder diameter; 3. Cylinder roundness, 4. Main bearing diameter.

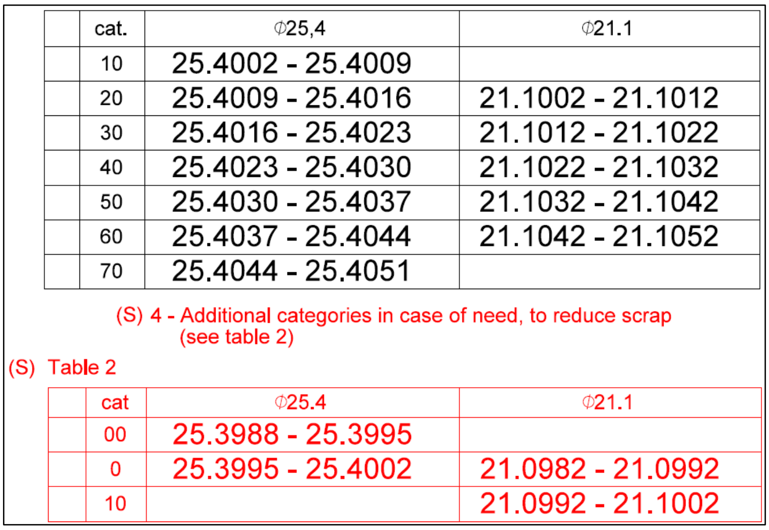
Table 3.4: Crankcase Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h* $_{w}$	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	PF13	**Crankcase**	**220**	**3**	**87**	**0,011**	**50%**	**Honing**	**6**
KAPPA	PF13	**Crankcase**	**450**	**4**	**125**	**0,022**	**20%**	**Honing**	**5**

- **Kappa:**

This production line is fully interlinked, requiring no human hand on its transportation (up to the Inner Assembly room). First an operator is required to put the casted crankcase on the conveyor belt which brings the crankcases to the first process step, a machining center with five machining units, also identified as OP10. This five machining units will do several rough machining operations like drilling the cylinder bore, drilling the crankshaft bore, milling the cylinder head, doing the cylinder head threads and their pre-required drills, etc. (all minor operations will not be described to remain inside our problem boundaries), the OP10 hook takes/returns 3 crankcases at a time from/to the CB.

After this first rough machining center there is a second rough machining center, OP20; with some additional higher precision steps: pre- and finish-turning the cylinder and crankshaft bores; finish-milling the cylinder head, milling the suction valve leaf groove, etc. Also, in OP20 three crankcases are taken/returned from/to the CB. The next step is the honing and brushing of the cylinder, a critical to quality feature. This process is done through a progressive honing and brushing machine, the diameter of the cylinder is measured at the end; the number of successive honing steps is dictated by the Piston diameter categories, (the piston grinding has a bigger tolerance spread, for this reason, if, for example, in a time interval many finished pistons fall in the category 50, the honing machine will only hone the cylinder bore five times). Afterwards there is the honing and brushing of the shaft bore (or main bearing), also in a progressive honing station; the machining processes are now over. The crankcases are further transported (still via CB), to the in-line washing station, and finally they are automatically palletized and picked up by the automated guided vehicle (AGV) that delivers the pallets to the Inner Assembly line.



	cat.	Φ25,4	Φ21.1
	10	25.4002 - 25.4009	
	20	25.4009 - 25.4016	21.1002 - 21.1012
	30	25.4016 - 25.4023	21.1012 - 21.1022
	40	25.4023 - 25.4030	21.1022 - 21.1032
	50	25.4030 - 25.4037	21.1032 - 21.1042
	60	25.4037 - 25.4044	21.1042 - 21.1052
	70	25.4044 - 25.4051	

(S) 4 - Additional categories in case of need, to reduce scrap
(see table 2)

(S) Table 2

	cat	Φ25.4	Φ21.1
	00	25.3988 - 25.3995	
	0	25.3995 - 25.4002	21.0982 - 21.0992
	10		21.0992 - 21.1002

Figure 3.10: Kappa piston categories, source: NGAA internal documentation

- **Delta:**

The Delta crankcase has a very different design in comparison with the Kappa crankcase, more than just the common size differences. It has two legs instead of four, it has no discharge chambers incorporated, it has no threads on the cylinder head; despite these differences the manufacturing chain is very similar: First, the raw crankcases are picked up by a magnetic picker that places the crankcases in the CB, afterwards they are demagnetized and brought to the first machining center, with seven stations, also called OP10 where the first rough machining is done (cylinder and shaft boring and turning, milling the feet, turning the head surface, making the threads, etc.). They are then conducted to the second machining center, OP20, where a more precise machining is done, as well as pre-diameter measurements, with a total of six stations. After this second machining center the crankcase needs a final machining, done in the progressive honing centers, one for the cylinder bore and other for the crankshaft bore. After these final machining operations comes the first differences; The production flow is broken: The crankcases are picked up one-by-one and are placed in trays (an operator does this manually), these trays are manually transported to a washing station incorporated in the line, they are then manually removed from the washing station, they are 100% visually inspected and the perpendicularity is also 100% checked (these two inspections are man-made). They are then manually palletized and transported to the inner assembly via forklift driver. There are ongoing projects to have the delta line fully interlinked, but as of now, the Delta line has less automated flow capacity than the Kappa line. In the Kappa line the crankcases are also not 100% manually checked, which means minus one worker in the line, on the other hand the Delta line has an automated magnetic picker which also reliefs one worker in the line.

PF14 – Crankshaft finish

The crankshaft is the compressor mechanical part that transforms the electrical power into mechanic power (in connection with the Rotor). The crankshaft has also an oil pumping feature; an elliptical groove around the shaft that serves as a pumping device through the whole compressor. This line is called “crankshaft finish” because there is other crankshaft line that is responsible for the pre-machining. The two lines are not connected (and for the Delta crankshafts they are outsourced). The design of the two crankshafts is very similar, the only big difference is in size. In this case it will be seen an example of two almost identical parts with identical manufacturing process, but with a quite different line layout.

Table 3.5: Crankshaft Finish Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h*$_{w}$	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	PF14	**Crankshaft Finish**	**300**	**2**	**135**	**0,007**	**67%**	**Brushing**	**6**
KAPPA	PF14	**Crankshaft Finish**	**470**	**3,5**	**105**	**0,009**	**30%**	**Pin grinding**	**5**

- **Kappa:**

The Kappa line has complex U shape and is fully linked up to the coating process, the phosphate coating. It starts with an operator feeding a container of preprocessed crankshafts to the line, then with the use of a long fork he pulls the crankshafts, which fall to a CB turning pot. The crankshafts are then automatically guided and correctly positioned in the CB by this turning pot. The first machining operation is the shaft grinding, in this step there are two parallel grinding machines, all crankshafts are automatically proofed. Afterwards there is the flange grinding again split between two parallel grinding machines. Then there is the pin grinding also done by two parallel grinding machines, the piston grind is a critical process step since it was defined that the crankshaft pin diameter and roundness are critical to quality features.

Now comes the tests-phase, which includes: Oil transportation capacity through the oil groove (automated); shaft and pin diameter measurement; parallelism between pin and axis; conicity of the main shaft; concentricity etc. (requires one operator to pick the crankshafts and put them in the measuring machine). The crankshafts are then placed in small trays that are manually brought to the phosphate coating station. After the coating treatment they are stored in racks and will wait there until the AGV picks them up and delivers them to the inner assembly.

- **Delta:**

Analyzing the Delta crankshaft line, overall it has a better disposition, it has a simple linear shape, it has also a good degree of automation and continuity. Like the Kappa line, this line is fully linked up to the phosphate coating. The first step is unpacking the outsourced pre-machined crankshafts and feeding them to the CB. They then follow a similar process flow as the Kappa crankshafts, first going through the shaft grinding operation, but this time only one station is running. Then comes the flange grinding, like the Kappa line also containing two parallel machining stations, immediately afterwards comes the pin grinding which is also done by two parallel machining stations, this last step is responsible for two critical features: The roundness and the diameter of the pin. The main machining steps are finished, now comes the visual inspection of the shaft and pin diameter done on all crankshafts. They are finally manually palletized, they take the phosphate coating and are sent to the Inner Assembly room.

PF15-Conrod

The conrod, or connection rod, is also a vital part of the compressor, it is the link between the crankshaft (which together with the rotor is rotating over itself) and the piston (which has a linear motion, back and forth). It can be seen as a “motion type converter” (rotatory to linear). In Table 3.6 it can be observed the more process intensive Kappa conrod, which has 3 more process steps.

Table 3.6: Conrod Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	Productivity #/h_w	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
KAPPA	PF15	**Conrod**	**500**	**3**	**170**	**0**	**63%**	**Manual Twist/Bend**	**8**
DELTA	PF15	**Conrod**	**300**	**2**	**150**	**0,002**	**60%**	**Manual Twist/Bend**	**5**

- **Kappa**

The Kappa raw conrods come slightly rougher than the Delta ones, for this reason they will require more machining. The process starts with a sandblasting operation to smooth the rough edges, this step requires an operator to feed the raw parts to the sandblaster and to start the process. Then the operator will feed the conrods to the reaming machine (enlarge a bore without leaving rough edges, done on both eyes), this machine has four stations; three do progressive bigger bores on both eyes, and the last station will check the quality of the bores (diameter, roundness, cylindricity, etc.). After the reaming comes a more precise bore enlargement via progressive honing, this time there are two parallel machines, the first for the big eye and the second for the small eye, in this progressive honing process it is also required a tool at the end of the processing which brushes the conrods.

The machining of the conrods is now finished. The conrods are then manually brought to the washing station to remove the impurities and oil. After being washed they are again manually brought back to the line. They undergo manual quality checks and manual bending corrections: parallelism between the two eyes (CTQ feature) and distance between the axes. Afterwards they are brought manually to the phosphate coating treatment station, when the treatment is done, they need again to be brought back to the manual quality check station to be brushed (also manually). They are now ready to be assembled and are transported to the assembly via tray wagon. This line is quite labor intensive (requires an operator in almost every processing step), additionally its logistics are sub-optimal: it has many production chain breaks and long transportation distances between the different processing steps, as well as many buffers between the processing steps increasing WIP costs.

- **Delta**

The Delta conrods require significantly less processing, due to more outsourced machining. This line is also completely unlinked. First the conrods are manually transported to the honing machine and the operator loads the honing machine. After being honed (both big and small eye) the conrods must be transported to the washing station. After being washed they need to come back to the quality check and manual bending station: Parallelism of the two axes (CTQ feature) and the distance between the axes. After the quality check and bending, the conrods undergo phosphate coating treatment, once coated they are sent to the Delta inner assembly room where they will be brushed manually and visually checked (most important check will be the diameter of the bores). The conrods are now ready for assembly. The Delta conrods also have high transportation losses.

PF18-Crankshaft Preprocess

This line is only existing now for Kappa crankshafts, the Delta crankshaft preprocess is outsourced. It is a rough machining line, the raw parts come sand casted from the supplier. The line is fully linked with conveyer belts or similar automated transport systems. In Table 3.7 Delta will has no entries.

Table 3.7: Crankshaft Preprocess Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h* $_{w}$	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF18**	**Crankshaft Preprocess**	**0**	**0**	**0**	**0**	**0%**	**--**	**0**
KAPPA	**PF18**	**Crankshaft Preprocess**	**460**	**2**	**260**	**0,003**	**33%**	**--**	**3**

The first step is feeding the raw parts to the machine with aid of a forklift truck, the crankshafts are then picked up by a conveyor belt with hooks that drops them afterwards at the first machining operation: the shaft turning, which is a rough removal of material from the flange and shaft. The crankshafts are then further transported (automatically) to the pin machining operation: Turning the pin and making the oil exit bore drill on top of the pin. Then the final machining operation comes, which is drilling the oil pump in the crankshaft bottom face (the bore axis is eccentric to the shaft axis in order to force the oil via centrifugal force). In this machining step the oil-pumping groove milling also takes place, which is an elliptic curve around the upper side of the crankshaft, responsible for the crank train lubrification. The crankshafts are now ready for the finish machining, they fall in a container which will be further transported to PF14 line.

3.2.3 Electric Motor components

Now the processes of the motor will be described and analyzed, that is basically the construction of the rotor and the stator.

PF23-Core Laminations

This line is the antecessor of the stator and rotor line, here the core laminations are die cut and stacked up (stacking and interlocking only for the rotor cores), these stacks will be both the core of the rotor and the stator. Both cores are done with laminated silicon-content steel sheets (which present enhanced electromagnetic properties) mainly to reduce the Eddy current losses and Hysteresis losses. It is interesting to note here, as a side observation, other core design possibilities such as the solid rotor core (relevant for variable medium and high-speed induction motors), which has tremendous advantages over traditional cage induction motor regarding simplicity and mechanical strength[61]. Other design possibilities include having thinner laminations (presently the sheets have 0,5 mm thickness) to further reduce Eddy current losses and achieve a more precise die cutting. The steel sheets would be then more expensive from the suppliers, due to a costlier manufacturability. This line is composed of two die cutting machines, one heat treatment station for the stator laminations and one oil burning station for the already interlinked rotor cores. Table 3.8 gives an overview comparison.

Table 3.8: Core Laminations Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h $_{w}$*	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF18**	**Core Laminations**	**220**	**1,5**	**260**	**0,008**	**25%**	**Blanking**	**2**
KAPPA	**PF18**	**Core Laminations**	**470**	**3**	**250**	**0,026**	**-50%**	**Blanking**	**2**

- **Kappa and Delta**

The process flow in this line is identical for both platforms. First the steel sheet rolls that are fed to the machine with the aid of a ceiling bridge crane. They are inserted in an unfolder machine, which feeds the sheet metal to the line, this unfolder machine also stretches the sheet to increase its flatness, which is a critical geometrical feature for the rotor and stator cores (the air between laminations greatly increases electromagnetic torque loss). Once the sheet is inside the die cutting machine two components will be manufactured:

1. The stator laminations: First, an incremental high-speed die cutting is done, which then outputs the laminations already in the correct stack position. Afterwards, an operator picks them up and drops them in a tray, which he will then bring to the heat treatment station. The heat treatment includes: Oil burning between the stator laminations, tempering the electrical steel, annealing and finally cooling the stator laminations. This heat treatment will enhance the stator electrical efficiency and further reduce the Eddy current losses, this is because the heat treatment oxidizes the lamination's layer improving isolation between laminations. Once the heat treatment is finished the laminations are ready to be transported to the stator assembly line (done by a forklift truck driver).

2. The rotor stacks: This component is also composed of die cut laminations (blanked), which is then stacked in an angle (Squirrel-cage rotor). The machine will also join the laminations together, using an interlocking system, making a rotor stack. Once the rotor stack comes out of the die cutting station, it requires an extra processing step, the burning oil between the laminations (oil from the die cutting operation), this is done in a nearby hoven which burns gradually the oil content in the rotor stacks (the operator must bring the stacks in trays to the

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[61] Cf. Khanduri/Kalra/Agrawal (2014), p. 1.

hoven with the aid of a hand forklift). Once this operation is done the rotor stacks are ready to be sent to the rotor casting line, via forklift truck driver. The rotor core laminations don't need to be as thin as the stator laminations (the Eddy current losses on the rotor are small compared to the stator) but they are the same thickness because the die cutting machine is regulated for that specific thickness (0,5 mm). A future possible measure is to make thicker rotor laminations (the sheet metal would be cheaper to buy).

PF22-Rotor

The rotor is also a vital part of the compressor, it absorbs the magnetic field generated by the stator, and in conjunction with the crankshaft it spins over itself transforming the electrical power into mechanical power. The critical part features of the rotor are: Air bubbles inside the casted aluminum, or porosity, the target is to reduce porosity and make it as homogenously distributed as possible. Other critical quality feature will be the outer circular runout due to its influence in the air gap between stator and rotor (critical feature in the inner assembly PF42), this runout will be only measured after the rotor shrinkage on the crankshaft. The cores to be die casted are supplied by the line PF23. Both lines are utilizing cold-chamber die casting technology. The delta rotor has lower capacity due to an additional centerless grinding operation as illustrated in Table 3.9.

Table 3.9: Rotor Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h* $_{w}$	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF22**	**Rotor**	**350**	**1,5**	**250**	**0,014**	**70%**	**Centerless Grinding**	**5**
KAPPA	**PF22**	**Rotor**	**480**	**1,2**	**440**	**0,014**	**60%**	**Die Casting**	**3**

- **Kappa:**

The first step is inserting the bars of aluminum in the hoven, which melts the aluminum bars, this melting hoven is shared by the kappa and delta line. The operator then moves a sliding viaduct which will make the melted aluminum flow to either the kappa or delta die casting machines (these containers are also heated to keep the aluminum liquid). Then a dosage of aluminum is poured to the shot chamber (injection of aluminum in the rotor stacks), the molds cavity design allows five rotor production per cycle, this machining step can run faster but this may be at a cost of final product quality (more porosity inside the rotor) and an increase in tooling wear (more costs), this is a good practical example where the quality, cost, speed triangle can help in the decision making process. After the die casting comes the heat treatment to further improve electrical and magnetic properties of the rotor. Next comes the electrical test on all the rotors (they are paired with a stator and the angular speed is measured). Finally, the rotors are automatically picked by a robot arm and placed in trays which will be further transported to the Inner Assembly with the ADV. As expected from a cold-chamber die casting process, this line is not labor intensive as all the machining steps are automated and every machine is linked with a CB. A further optimization could be automating the sliding viaduct of the aluminum melting hoven.

- **Delta:**

The delta line is very similar to the kappa line, there are some differences though, after the die casting step the rotors undergo cooling off and then go to a centerless grinding machine, which allows a tighter tolerance on the air gap between stator and rotor (which has a high influence in the COP). This grinding step will require an afterward washing of the rotor. Therefore, there is a washing station integrated in the line to maintain the process flow. After being washed the rotors are also heat treated. They are then cooled off, and 100% electrically tested the same way the Kappa rotors do. Finally, an operator manually buffers the rotors in trays which will later be transported to the Inner Assembly. Labor costs are also mainly logistic operations.

PF31-Stator

The stator is a vital part of the compressor motor, design deviations in this part will greatly influence the final compressor COP, for example the winding's material choice (copper or aluminum). Regarding materials and processing costs this is a very cost intensive component (copper windings, processing of the stator core laminations, labor and process intensive, etc.) It is also important to mention that here there will be multiple stator models for each platform (more than 20 models for each platform, these models differentiate themselves mainly by the windings setup: material and quantity), which deliver different efficiency and COP. This line is usually where the quality compensations are made: The amount of copper inserted in the stator can always balance the over quality or lack of quality in the other components.

Table 3.10: Stator Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h* $_{w}$	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF31**	**Stator**	**200**	**3,5**	**62**	**0,051**	**71%**	**Winding**	**12**
KAPPA	**PF31**	**Stator**	**500**	**11**	**47,5**	**0,023**	**-22%**	**Interlacing**	**9**

- **Kappa:**

The Kappa stator line is composed of two parallel identical lines (to achieve double capacity). It starts by receiving the stator core laminations from the forklift truck. An operator must manually insert the laminations in the machine. Then the first processing step is stacking the laminations in the right amount to reach a specific stator core height (CTQ). Afterwards the core slots are insulated with a plastic foil (the windings cannot contact the core directly). Then comes the bottleneck process, the winding of the stator, winding is inserting the conductive filaments that will conduct electrical current through the stator core slots, generating a magnetic field that is absorbed by the rotor. There are two fields of filaments; the auxiliary (for starting operation of the compressor) and the main field (for normal run after start of the compressor). Once the winding is done, an identification code must be given to each stator, this code is indented in the upper lamination. Then there is the mounting of the plug casing and cabling (after the winding process 3 to 6 windings are left loose, these windings will be connected to a cable which is fixed by a plug casing, this plug will then be connected to the hermetic terminal); this mounting process is composed of four stations, each with one person that manually mounts the plug casing, making a total of four operators.

The stator requires some final “tune ups”, the first one is a winding overhead press or forming (compacting the stator windings), which is required for the next step: Bandaging (or interlacing) the stator windings, there are 2 fully automated bandaging machine units per line (4 in total). Once the bandaging is done, there is an operator that visually checks every stator and reworks (or reshapes) them if needed. Finally, a press machine presses the stator overhang to a final optimal form. The stator is now finished, it goes through a final electrical test, is automatically palletized and transported via ADV.

- **Delta:**

The Delta Stator assembly is slightly more complex, as the stator itself is different. It is a single line. The first step is the loading of the machine with the core laminations, which is man-made. Then, the first machine chooses the right number of laminations to make a stator core with the correct height (CTQ), afterwards comes the slot insulation placement which is divided between four stations (in Kappa is done by only two). Then is required a placement of an isolation cap on top of the stator which is warm shaped together with the slot isolations. Then comes the bottleneck, the winding of the stator, here instead of five linear stations, a circular layout of five winding stations with a robotic arm in the middle is applied. Then every stator is awarded an identification code. Afterwards, there is the first cable assembly operation which is connecting the windings to the cables, crimping three splices to the windings (in this operation the stator connector is also mounted). The second cable assembly operation is connecting the terminal of the cable to the plug casing. Both stations are operated by one man, but there is not always a man at each station (it would be over capacitated). There is then the preforming of the winding overhang, which needs to be compacted (avoid loose windings). Then the major difference to the Kappa stator comes, the windings instead of being interlaced are bonded together with a heating of the overhang, this is thanks to a special coating of the windings, this coating when submitted to higher temperatures activates a gluing compound and the windings are stuck together. After the bonding operation, which is at a temperature of up to 200 °C. The stator must be then cooled.

Now is reached the end of the line where the stators are 100% electrically tested, and then manually test the flatness of the stator core, if it isn't flat enough the operator coins the stator core. The stator is finally manually palletized and brought to the inner assembly via forklift truck.

To this line one appointment is left: The Kappa line bonding operation is the bottleneck of the line and it is a complex sewing operation, which after interview the operators, is constantly having breaks. A possible solution to avoid this could be integrating the coated filaments with glue as in the Delta line.

3.2.4 Other components

This sub-section includes the cover and shell of the HRC. It includes the copper tubes welding line (see Figure 3.1). It also includes the valve plate assembly, a critical component of the HRC which is the interface between the cylinder head and the suction and discharge mufflers.

PF21-Cover and Shell

Together, the cover and shell, form the compressor housing, the cover is the upper housing being slightly shorter and the shell is the lower housing where all the tubes (discharge, suction and service) and hermetic terminal ("fusite") pass through. The shell will also have the feet of the compressor attached. This line though, is only responsible for the pressing of these two parts, made of steel.

Table 3.11: Shell and Cover Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h $_{w}$*	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF21.1**	**Shell**	**680**	**0,6**	**580**	**0,001**	**40%**	**Cutting & Deep Drawing**	**1**
DELTA	**PF21.2**	**Upper cover**	**780**	**0,4**	**765**	**0,001**	**60%**	**Cutting & Deep Drawing**	**1**
KAPPA	**PF21.1**	**Shell**	**680**	**0,6**	**580**	**0,003**	**40%**	**Cutting & Deep Drawing**	**1**
KAPPA	**PF21.2**	**Upper cover**	**780**	**0,4**	**765**	**0,003**	**60%**	**Cutting & Deep Drawing**	**1**

- **Kappa and Delta**

Both cover and shell, of the Kappa and Delta platforms respectively, are done in the same line, this line is composed of two parallel hydraulic press machines, with deep drawing and die cutting tools integrated. The first step would be bringing the steel sheet rolls, which is done with an operator controlling an overhead crane, or bridge crane, that carries the steel sheet rolls to the production line. The line's first machine automatically unfolds the steel rolls, and stretches them out to make the blanks flat. Once the steel blank is flat, it is fed to the hydraulic press machine. The first step is a cut process (die cutting), which has a different geometry depending on which part is being produced (cover or shell; Delta or Kappa), both have a circle geometry cut, but, for the shell, the punch also cuts the tube holes. Additionally, for the Kappa shell, the tool also cuts the discharge chamber covers and the compressor foot straps (as additional minor parts of the compressor; it is an example of good design for manufacturability, maximizing the material utilization). Once the cutting is done, the scrap falls to an underground conveyor belt that transports the scrap to be posteriorly sold; the minor parts fall to a container and wait for transportation. To be further processes are the circular shaped steel sheets, that are gradually punched (deep drawing) into the housing shape (see Figure 3.1). For the covers they require 4/3 punches, for Kappa/Delta respectively. Due to the more complex shape of the shell it requires 6/8 punching steps, for Kappa/Delta respectively. To avoid overheating of the tool, the punching speed is set to 15 strokes/min, which is not the full capacity of the machine. Once the shells and covers are formed they fall in other container and they are ready to be washed before their respective welding lines. A fragile operation in this deep drawing line is changing the cutting and forming tool (it must be frequently changed because each design requires a different tool). The tool has a substantial size and weight, for this reason it takes roughly 4 hours to change the tool, the criticality is timing the periodicity of tool change to avoid interruptions in the downstream production lines.

PF26-Shell Welding

This production line is responsible for the welding of all the components that connect the inside of a compressor to the outside (such as refrigeration gas in & outlet, electrical power input, feet of the compressor). As the subject of the study is a hermetic compressor, the weld seams must be completely sealed, mainly to avoid refrigeration gas leakages, but also to avoid infiltration of small particles into the compressor. The Kappa and Delta lines, have a high automation potential, this is because all manufacturing steps in both lines use mainly spot welding which is a highly automatable manufacturing technology (as illustrated in Table 3.12 the degree of automation in the Kappa line shows good improvement potential).

Table 3.12: Shell Welding Line KPIs, source: own internal NGAA data retrieval

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h $_w$*	cost of scrap €/#	degree of automation	bottleneck analysis	Number of processing steps
DELTA	**PF26**	**Shell welding**	**400**	**1**	**284**	**0,015**	**88%**	**Weld pin/fusite**	**8**
KAPPA	**PF26**	**Shell welding**	**520**	**3**	**158**	**0,005**	**67%**	**Weld discharge tube**	**9**

- **Kappa:**

In this line the parts flow continuously through a conveyor belt and every processing step is automated. The first process is an alkaline wash of the shell which is covered in oil after the deep drawing process. Once the washing is finished, comes the first weld operation, the spot weld of the four spring pins inside the shell, the spring pins must be washed before this operation. Afterwards the shell is conveyed to the next welding machine, the spot weld of the two foot-straps. The foot straps are die cut in the line PF21, vibratory grinded and washed before coming to this line. Then the spot weld of the hermetic terminal (the electrical interface to the outside of the compressor) is done. Right after, the terminal fence is spot welded, which is required for the mounting of the compressor to the refrigerator. Finally, the following spot welds are done in the following order: the suction tube, discharge tube and service tube (these copper tubes are all outsourced). At the end of the line the discharge tube must be bended in the inside of the shell. The finish welded shells are then automatically palletized and automatically transported (via AGV) to the inner assembly. Even though all machines are automated and the transport within the line is fully automated (CB), this line requires three operators which in comparison to other less automated lines is a relative high number.

- **Delta:**

The Delta line is also fully interlinked with a conveyor belt, with only one non-automated processing step at the end. It starts with an alkaline wash like Kappa. Next, the spring pins are spot welded (on the inside, they support the suspension springs). The Delta compressor doesn’t have foot straps, it is attached to a refrigerator by means of an adapter plate. This adapter plate is fixed to three steel pins (done by the customer). These steel pins are spot welded together with rubber grommets. Afterwards the hermetic terminal and the terminal fence are spot welded, the same as in Kappa. And finally, as in Kappa, the three tubes are spot welded. The discharge tube, then the service tube and lastly the suction tube. In the Delta line there is one operator at the end which does a visual inspection and manually palletizes the welded shells. This line, in comparison to the Kappa line, has a better degree of automation, with only one operator required.

3.3 Critical to Quality features

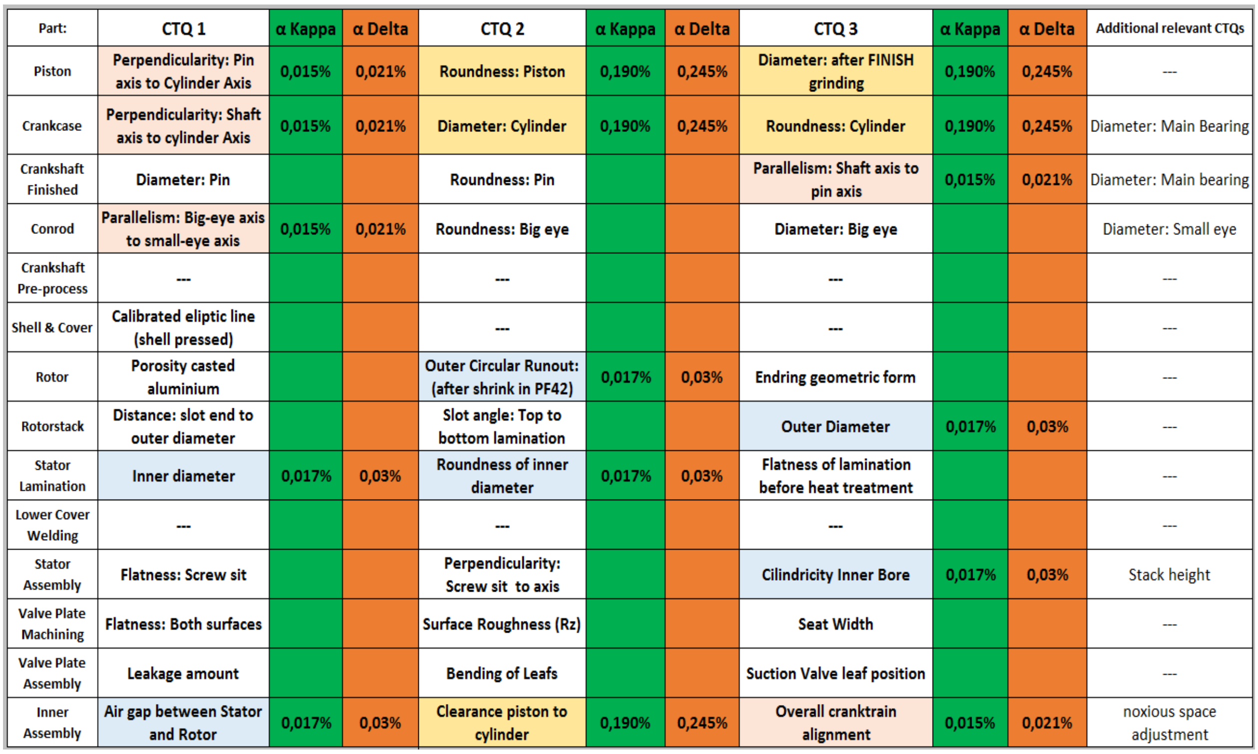
After analyzing the different production lines and their respective main manufacturing technologies, the analysis scope was turned to the product specifications and its respective components. To achieve a more efficient manufacturing, one must also have a deep understanding of the product, (the opposite is also true). The course of action here was to discuss with the different product experts within NGAA R&D department what are the component’s features that matter the most for the achievement of a high-performance compressor (the measure of performance chosen was the COP). These meetings involved three teams within the R&D department, which represent the three main fields of efficiency losses in a compressor: The crank train team, mainly mechanical losses, such as friction. The electric motor team, representing the losses in the induction motor. The gas-line team, responsible for all the components in which the refrigeration gas flows, representing mainly the enthalpy losses.

The jack of all trades in NGAA's manufacturing plant is the amount of copper or aluminum windings introduced in the motor, this amount counts as the top most expensive raw materials in the production chain. The amount of winding material in the stator directly influences the power output capacity of a HRC, for this reason, one can decide, for example, to have a less precise piston grinding process at the expense of introducing more winding material in the stator, which will directly compensate the power losses due to increased friction losses (pistons have a rougher surface). This is a short-term oriented decision; the firm will be more dependent on the winding's suppliers and their prices. A more long-term oriented strategy is to develop a better compressor quality (through more precise manufacturing) that enables less copper or aluminum content, by enhancing the compressor efficiency.

For this reason, this study focused in pin-pointing each component feature that has a higher impact on the COP. Also known as critical to quality (CTQ) features (all determined CTQs can be seen in Figure 3.11). It was decided, to keep the problem confined to an appropriate level of depth, to only define three CTQ features per compressor component.

To make the problem quantitative, it was also required to have a value that could numerically measure this influence. This measure was called: *COP influence factor of a component's geometric feature* (α), the values were inserted in Figure 3.11. Some values are still to be calculated in future studies, others might be unpractical to calculate, the target was to develop a course of action method to be further applied in the future.

The α is measured in % of COP lost per µm out of the nominal value. The α calculation method will be demonstrated by exemplifying two CTQ features cases: One belonging to the piston line: Perpendicularity of the piston main axis to the pin axis; the other belonging to the inner assembly line: Air Gap between stator and rotor. As it will be seen the COP will vary depending on the nominal values' deviation.



Part:	CTQ 1	α Kappa	α Delta	CTQ 2	α Kappa	α Delta	CTQ 3	α Kappa	α Delta	Additional relevant CTQs
Piston	Perpendicularity: Pin axis to Cylinder Axis	0,015%	0,021%	Roundness: Piston	0,190%	0,245%	Diameter: after FINISH grinding	0,190%	0,245%	---
Crankcase	Perpendicularity: Shaft axis to cylinder Axis	0,015%	0,021%	Diameter: Cylinder	0,190%	0,245%	Roundness: Cylinder	0,190%	0,245%	Diameter: Main Bearing
Crankshaft Finished	Diameter: Pin			Roundness: Pin			Parallelism: Shaft axis to pin axis	0,015%	0,021%	Diameter: Main bearing
Conrod	Parallelism: Big-eye axis to small-eye axis	0,015%	0,021%	Roundness: Big eye			Diameter: Big eye			Diameter: Small eye
Crankshaft Pre-process	---			---			---			---
Shell & Cover	Calibrated eliptic line (shell pressed)			---			---			---
Rotor	Porosity casted aluminium			Outer Circular Runout: (after shrink in PF42)	0,017%	0,03%	Endring geometric form			---
Rotorstack	Distance: slot end to outer diameter			Slot angle: Top to bottom lamination			Outer Diameter	0,017%	0,03%	---
Stator Lamination	Inner diameter	0,017%	0,03%	Roundness of inner diameter	0,017%	0,03%	Flatness of lamination before heat treatment			---
Lower Cover Welding	---			---			---			---
Stator Assembly	Flatness: Screw sit			Perpendicularity: Screw sit to axis			Cilindricity Inner Bore	0,017%	0,03%	Stack height
Valve Plate Machining	Flatness: Both surfaces			Surface Roughness (Rz)			Seat Width			---
Valve Plate Assembly	Leakage amount			Bending of Leafs			Suction Valve leaf position			---
Inner Assembly	Air gap between Stator and Rotor	0,017%	0,03%	Clearance piston to cylinder	0,190%	0,245%	Overall cranktrain alignment	0,015%	0,021%	noxious space adjustment

Figure 3.11: CTQs features and their α value, source: Own illustration

3.3.1 Example 1: Perpendicularity influence on compressor efficiency (COP)

For this specific CTQ (Figure 3.12, marked in yellow dimension) it is important to understand that this geometric dimension influences the overall crank train alignment: if the piston pin bore is not perpendicular, then the piston pin will not stand 90° upright inside the piston-pin bore,

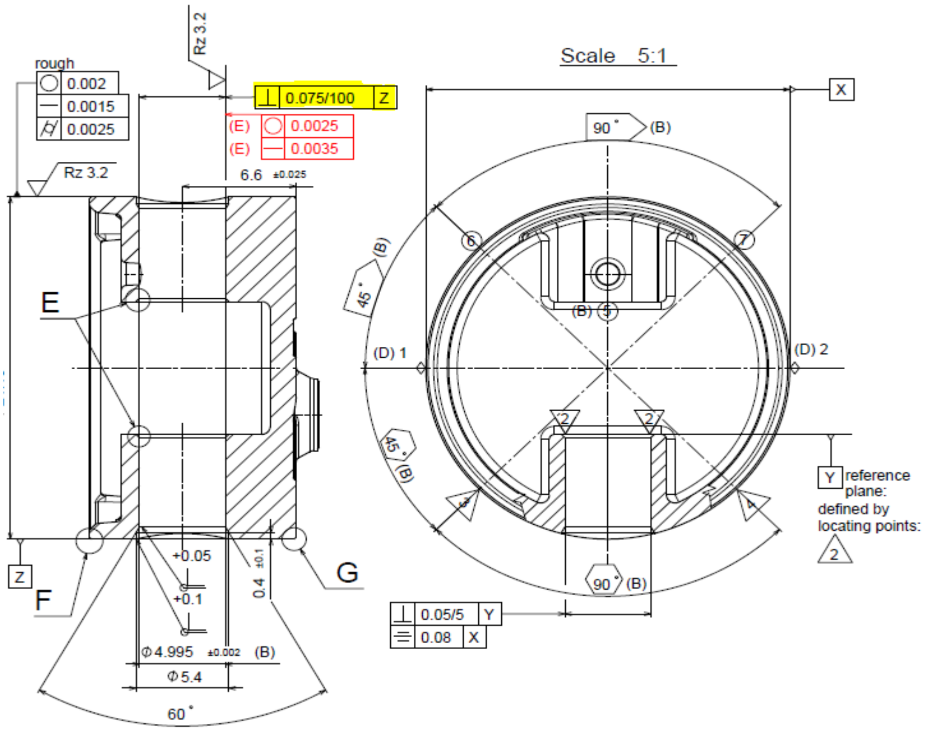


Figure 3.12: Kappa pin-bore perpendicularity (marked in yellow), source: NGAA internal documents (slightly modified)

which then will also misalign the conrod small eye and thus making the whole conrod not to be horizontal, which in its turn is connected to the crankshaft pin.

Now, assuming that the crankshaft pin is perfectly parallel to the crankshaft main bearing, and that the crankshaft is pressed inside the rotor, two things can happened: The crankshaft pin bends, making the crankshaft rotate in an unbalanced form and thus greatly augmenting wear (clearances for the oil are lost), or, in an even worst case scenario the bending moment (or tilt forces) are absorbed by the rotor reducing/eliminating the stator-rotor air gap which could have the disastrous impact of the induction motor not even being able to start.

For this reason, it was decided that this geometrical feature should be included for every crank train component that has a direct influence on alignment, for example: Parallelism between the two conrod's eyes, crankshaft main bearing parallelism to the crankshaft pin, crankcase's cylinder bore perpendicularity to the main bearing (light orange CTQs marked on Figure 3.11).

For the quantification of these tilt forces and their influence on the COP, the efficiency of the same compressor was measured several times, changing only the piston-pin bore perpendicularity to the piston main axis (again, Figure 3.12, marked in yellow dimension). The following plot was then made based on the data given by the respective crank train product expert:

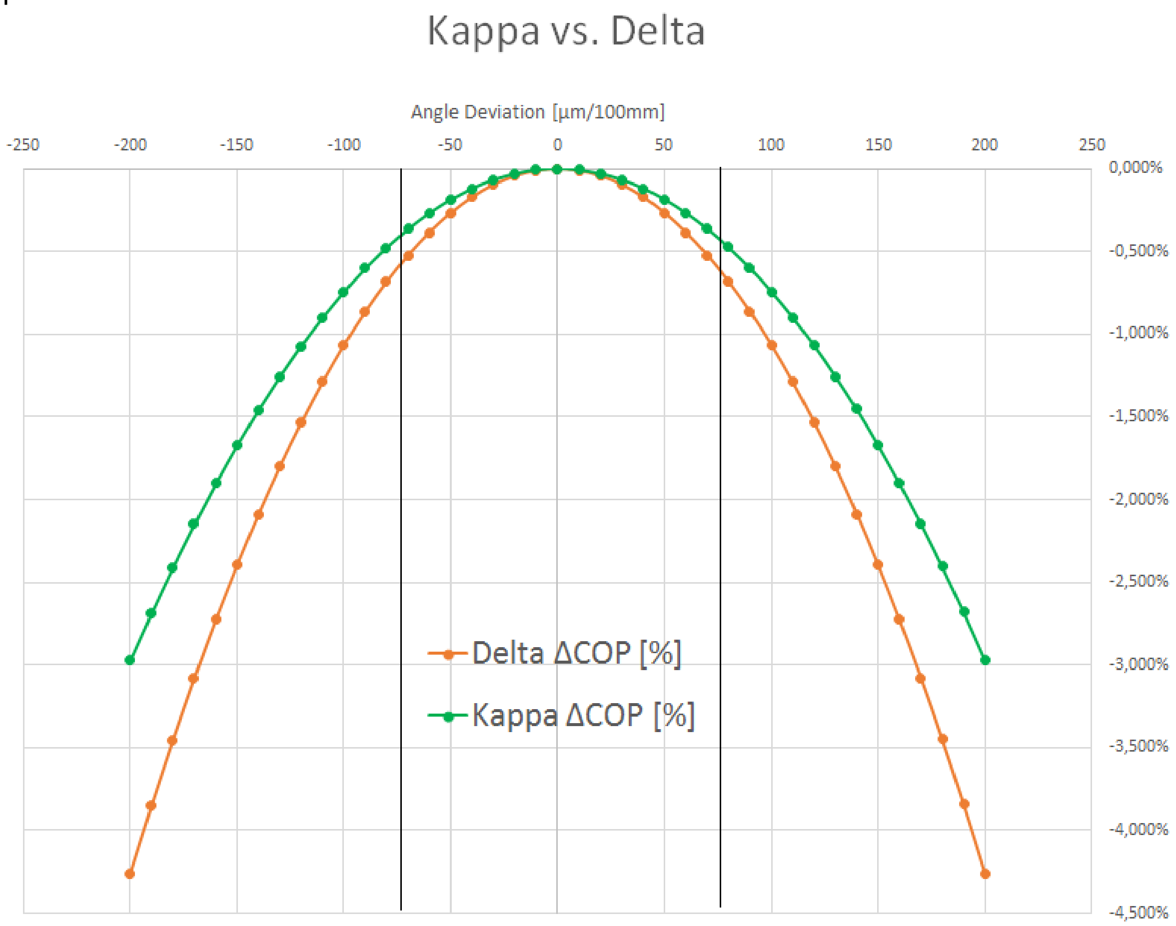


Figure 3.13: Delta vs. Kappa crank train angle deviation influence on the final COP, source: Own illustration

The x-axis stands for the angle deviation, which is measured in gradient of µm's per 100mm. Note that in Figure 3.12 this tolerance is measured in mm instead of µm. The y-axis stands for variation of the compressor's final COP, the two black lines represent the allowed interval of quality. Not only a misalignment just in one component could lead to an out of conformity quality issue, but also it must be observed that this effect stacks up with further misalignments of the other crank train components. The orange curve stands for the Delta compressor, it can be immediately concluded that the Delta COP is much more sensitive to angle deviations.

The next problem was to transform these results into one value that could help the management understand which CTQs have more impact on the COP. The main challenge was to reduce as much as possible information loss by simplifications. In this specific case one can immediately make one simplification which has no information loss: Only observe one arm of the parabola due to the almost symmetric values. The second simplification was to transform one of the parabola arms into a linear function, this was made using a regression trend line, finally the α value to be inserted in the CTQ table was the gradient of this regression. The method is represented in Figure 3.14.

For this example, the α values were 0,015% COP loss per µm of misalignment for the Kappa platform, and a 0,021% COP loss per µm of misalignment for the Delta platform, it might seem an insignificant amount, but that is because it is measured in µm, the order of magnitude of this tolerance is 100 µm which would lead to a loss of 1,5% COP (100µm misalignment in a Kappa compressor) and assuming a standard conversion rate of 0,5€ per 2% of COP, that would result in a loss of 0,38€ per compressor, (and considering that the Kappa platform has a 2 million yearly sales volume) equal to a loss of 760,000.00€ in one year, just due to a misalignment of 100µm in the crank train.

It is important to note that this approach is just an estimation to give an estimation values to management levels. Special care must be taken when using these values, specially inside the tolerance range (Figure 3.13) because the values vary less inside the tolerance range and vary more outside the tolerance range. To answer this problem additional models where created, one which uses the regression's gradient only of the values within conformity (α will be lower) and other which is based on a regression on the data out of conformity (α will be higher).

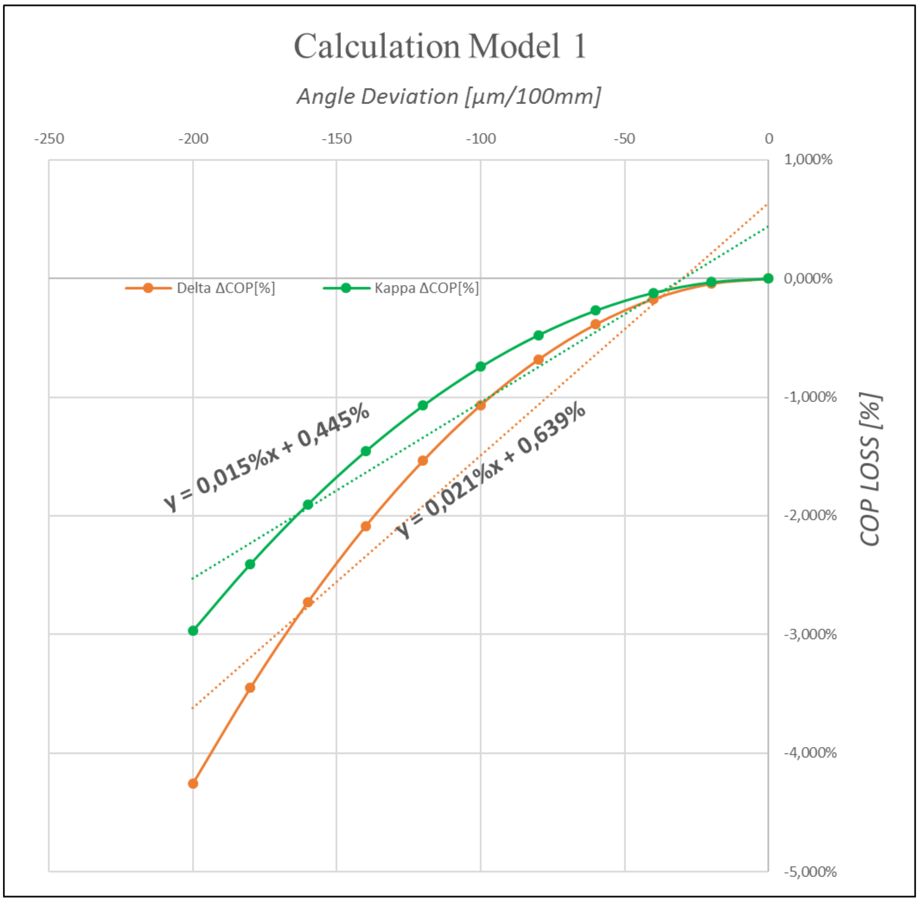


Figure 3.14: Angle deviation α values based on the linear regression gradient, source: Own illustration

3.3.2 Example 2: Air gap between stator and rotor

the α value was calculated for the Air gap between stator and rotor (CTQ). The air gap is, as illustrated by Figure 3.15, the clearance between the rotor and the stator, it is also the medium, between which, the power is transferred from the stator to the rotor.

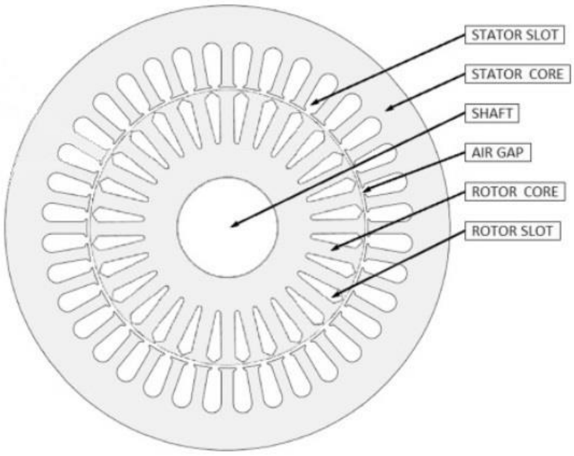


Figure 3.15: Illustration of the air gap, source: Bieler/Werneck (2018), p. 123

Basically, the air gap is a necessary geometrical feature but should be as small as possible to increase efficiency; the air has a very low magnetic permeability thus increasing magnetic losses. But also, due to mechanical design aspects it must have a minimum safety air gap (if the air gap wouldn't exist then the rotor would be in contact with the stator, thus highly increasing friction losses and disrupting the electrical and magnetic fields). The length of the air gap has many influence factors; like for example, the vibrations inside the motor, which can make accidental contacts between the stator and the rotor, which is an unacceptable situation, because it can greatly reduce efficiency.

Other influence factor on the air gap length are the manufacturing technologies, depending on the capabilities of these manufacturing technologies there will be a bigger or a smaller air gap. The HRCs of NGAA show a peculiar phenomenon for the starting region (for RPMs<1000), which is a loss of torque depending on the air gap. Basically, the lower the air gap the higher the torque losses, up to one threshold where the motor will not even be able to start, the following data interpolation illustrates this phenomenon (Figure 3.16, based on a Delta kit):

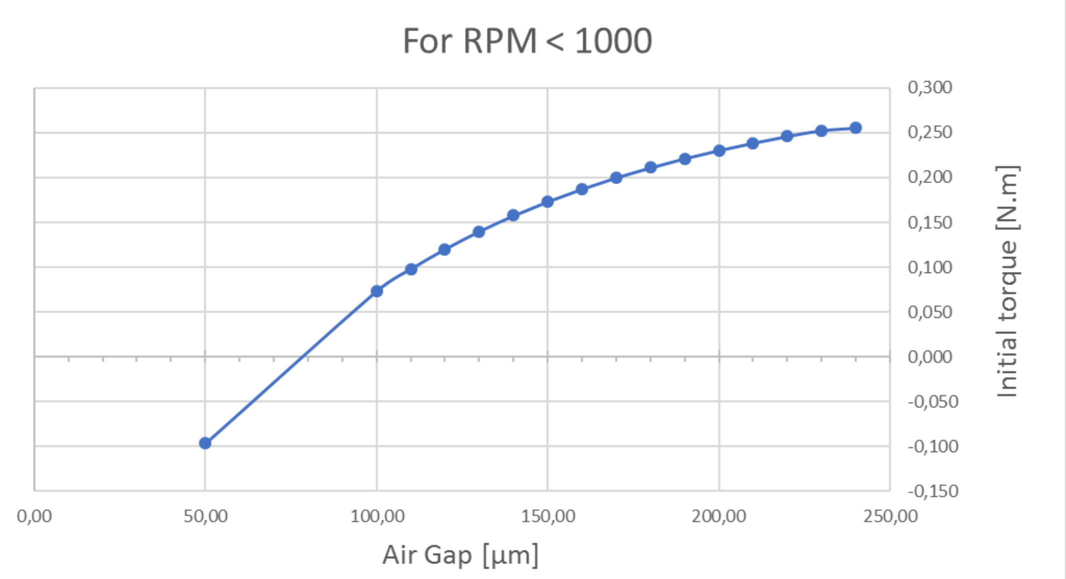


Figure 3.16: Air gap influence on the initial torque, source: internal NGAA data

Based on this phenomenon there is a practical threshold that should not be crossed, for Delta and Kappa this value is different.

As shown the α value will decrease as the air gap increases; this fact should not lead to the following wrong assumption: “The smaller the air gap, the better”, a more correct statement is: “The smaller the air gap, the better; up to a certain limit”, which is roughly 100µm.

To calculate the α value of this specific CTQ, meetings were undertaken with the engineering experts of the motor and electronics team. The different simulations that have been developed over the year show in fact the phenomenon that was described just now, it also shows that a bigger air gap reduces the efficiency of the motor. So again, as for the angle deviation CTQ, a regression was calculated based on data extracted from motors with different values of air gap, as exhibited in Figure 3.17.

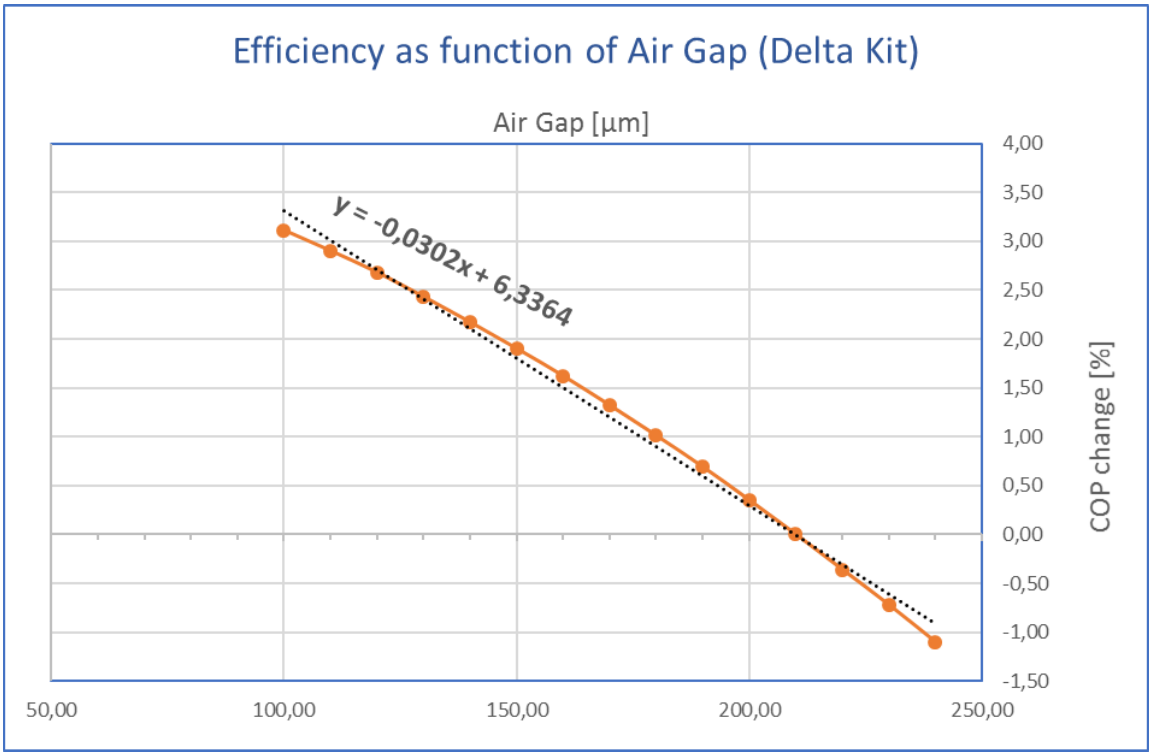


Figure 3.17: Air gap α values based on the linear regression gradient, source: Own illustration

This case is different to the angle deviation CTQ in two aspects: One is the fact that the regression has a negative gradient, the second is the fact that the function has no parabolic geometric form. These two aspects must be interpreted, for this reason the values are nonetheless assumed positive, as it would not be clear for the interpreter having negative and positive α values in the CTQs table (Figure 3.11), and remembering that the α is measured in % of COP lost per µm out of the nominal value, it is congruent to assume both values positive. The second different aspect is the parabolic geometric form which would make no sense for the air gap, as it is not physically possible to have a negative air gap (that would mean the rotor would intersect with the stator).

For this CTQ α value of 0,03% COP / µm was observed, it might seem it has the same order of magnitude as the angle deviation example, but due to the manufacturing tolerance capacity of the different processes (die cutting of the core laminations, stacking of the laminations, die casting of the rotor, grinding of the outer cylinder of the rotor, assembly of the rotor and stator, etc.) the order of accuracy for this geometric feature is 0,01mm or 10 µm, converting the α value from COP(%)/µm to COP(%)/10µm, one would realize that having a process with a +/- tolerance increase of 0,01mm would mean an increase of 0,3% COP per compressor; assuming again a conversion rate of 0,25€/1%COP gain this would mean a potential saving of 0,08€ per delta compressor, which means 800,000.00€ savings in one year (assuming a 1 million compressor sales volume).

As a conclusion for this chapter: first it is important to know *qualitatively* what are the CTQs of a HRC. Once the CTQs are defined, it is needed to calculate their influence on the efficiency of the compressor *quantitatively* (for future studies other quality parameters can be checked, like noise for example). This qualitative definition is the crucial part of the process. It is useful to have these values, as they will greatly aid the manager’s decision on which processes to improve, and thus bring more profits to the concern.

This requires that each product specification should be individually calculated and measured which can be sometimes time-intensive, these two examples served are suggestion on how to calculate such values. These values are calculated differently for each product parameter, and probably they will have different functions, so it is also important to interpret them and revert this functions to simple values which can be rapidly understood without loss of information.

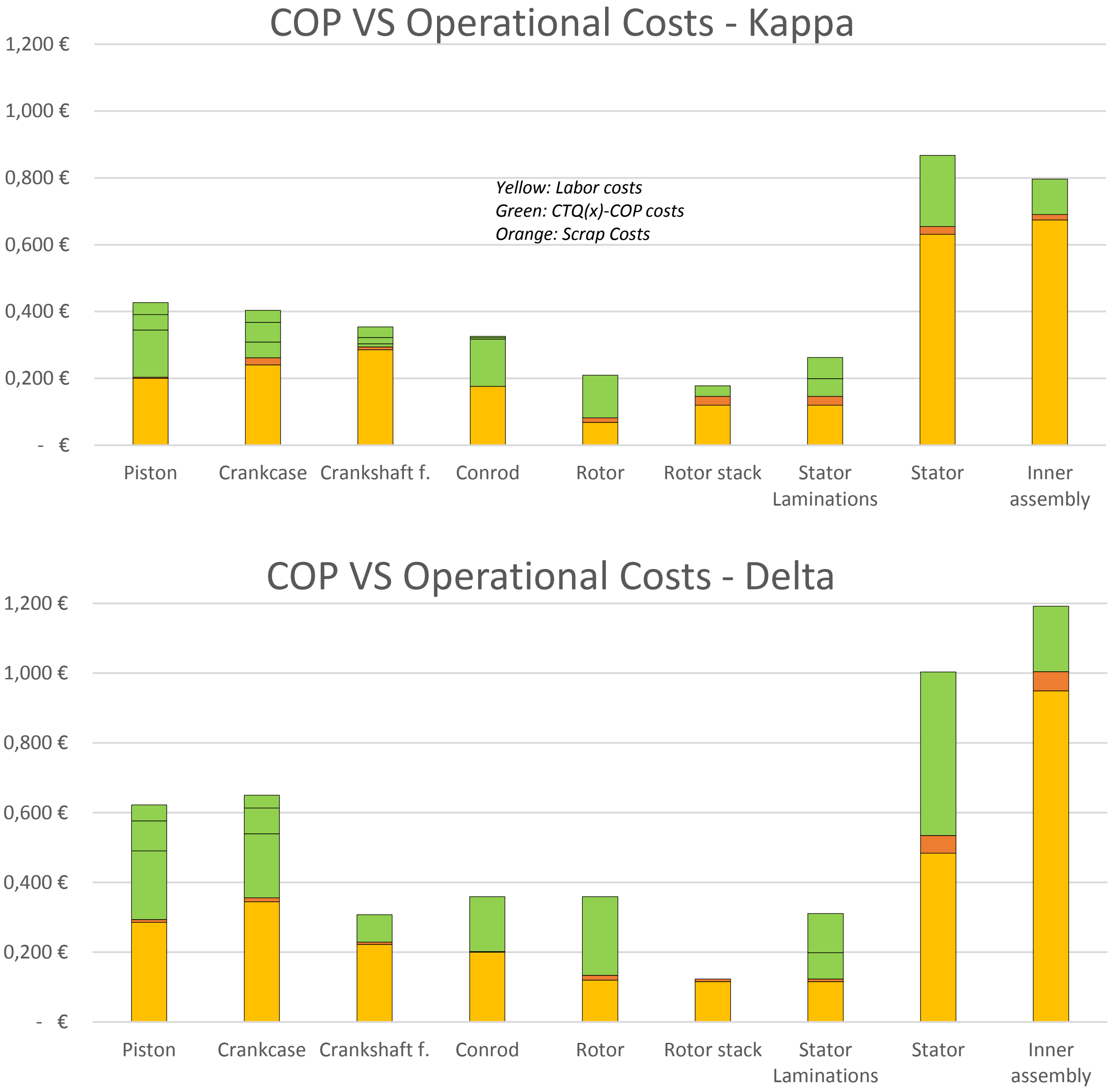
The key value is then the already introduced α value, which is measured in % of COP lost per µm out of the nominal value.

4 Conclusion

4.1 Findings

After a thoroughly investigation on the operational KPIs of both compressor platforms (Delta & Kappa), and deeper understanding the influence of each CTQ on the compressor, it was finally possible to see the cost differences between the production KPIs (like labor cost or scrap cost) and the manufacturing accuracy & preciseness (which are the costs of quality reduction due to manufacturing process fluctuation).

The following diagrams show these results and enable a comparison between the Kappa and Delta production costs, based on Figure 3.11 and on Table 3.2 - Table 3.12:



COP VS Operational Costs - Kappa

Yellow: Labor costs
Green: CTQ(x)-COP costs
Orange: Scrap Costs

COP VS Operational Costs - Delta

Figure 4.1: COP vs Operational Costs (Cost per produced part), source: Own Illustration

The green colored bars in Figure 4.1 stand for the COP losses with which each part contributes. These contributions are reverted to € values, which were calculated using the following modelling function:

$$f(\alpha) = \alpha \cdot \frac{USL - LSL}{2} \cdot x \cdot \frac{€}{COP\%} \tag{4.1}$$

The α value was already defined (% of COP lost per µm out of the nominal value).

The second term of the equation stands for tolerance range; this is the distance between the Upper Specification Limit USL and the lower specification limit LSL divided by two (for most of the geometrical features these values are symmetrical, like diameter for example) there are some exceptions though, for form tolerances such as roundness, parallelism or cylindricity the second term of the equation is simply substituted by the form tolerance value (e.g.: Roundness of 3µm means a tolerance range of 3µm).

The third term of the equation, x, is a factor that accounts for the machine capability, it is calculated based on the current cpk of a specific machine. This term has no units, it is a correction factor that shortens the tolerance interval, when an arbitrary machine cpk is for example 2, the machine will be running more accurately and precisely, this means the CTQ geometrical feature is very close to the target; for this example, x = 1 / $\#_\sigma$ (sigma level). For less capable machines, with a cpk in the order of 1, x = 0,3(3) (which means that in average a machine is producing 0,3(3) * [tolerance value] away from the target). This concept is illustrated in Figure 4.2. Fundamentally, this means that the higher the cpk of process is, the lower the COP losses in the parts within conformity will be.

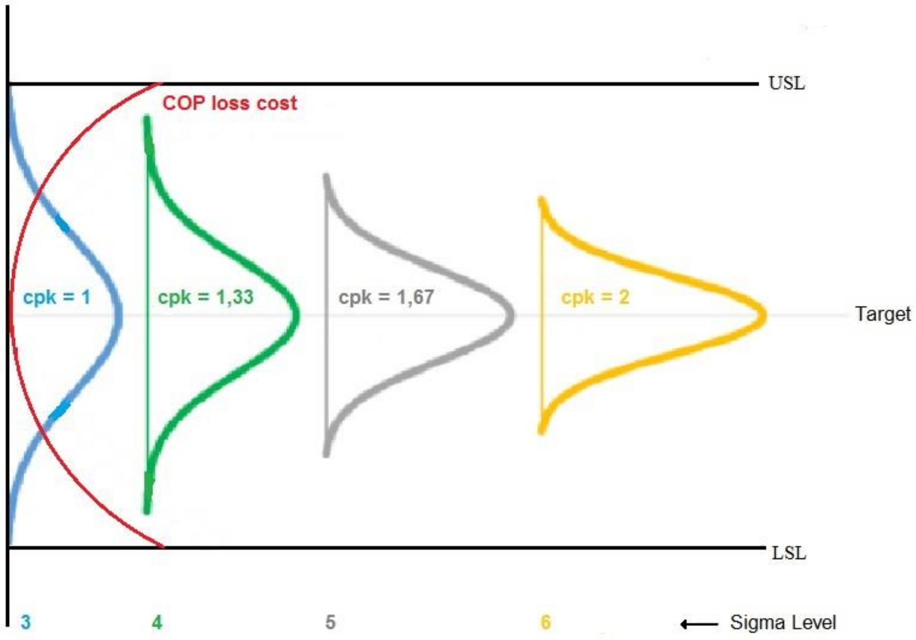


Figure 4.2: Cpk influence on the COP losses, online source www.spcforexecel.com [16.05.2019], modified

The last term stands for the conversion rate of 1% COP to €, this value is different for every compressor, and these values are usually available for every compressor model in house, the standard value of 0,25€ per 1% of COP was assumed, but it can always be changed in the template to accommodate for different compressor models that have different conversion rates.

Now, the yellow bars stand for the component labor costs c_L, as defined in equations **4.2** and **4.3**:

$$p, Productivity = \frac{Parts\ Produced}{Number\ of\ Worker.Hours\ Required} \qquad 4.2$$

$$c_L, Component\ Labor\ Cost = \frac{Worker.Hour\ Cost\ in\ Austria}{Productivity} \qquad 4.3$$

The blue-collar worker hour cost for a company in Austria is in the present roughly 30€ per hour.

Now the bar’s orange component in Figure 4.1 stand for scrap costs per part, which have been measured with the direct materials costs.

Having all in this in mind and looking at equation 4.1, there are two things which can be done to reduce COP loss costs (the green portion in Figure 4.1), either increase the process capability or tighten the Specification Limits. Assuming the process is already at its maximum possible capability with the available resources, a common strategy is to invest in new equipment, with more accuracy and precision, this option must be taken carefully as usually it involves high investment. Tightening the Specification Limits is also something to be very careful, as it can severely increase the scrap costs by increasing out of conformity parts. What is proposed in this master thesis is that there is an optimum amount of scrap rate that not always must be 0, this is due to the COP losses that are inevitable due to a component’s manufacturing imperfections.

What has been found for NGAA’s specific case is that for some production lines, like the piston production line, the ratio of scrap costs to COP loss costs is as big as 3 to 100. Additionally, the machines responsible for the CTQs that are accountable for these costs are not the bottleneck of the production line (Table 3.3), so having tighter tolerances after these two machines (finish grinding and piston pin drilling), can greatly reduce the COP loss costs. The same applies for other production lines such as: Rotor, Conrod and Stator Lines.

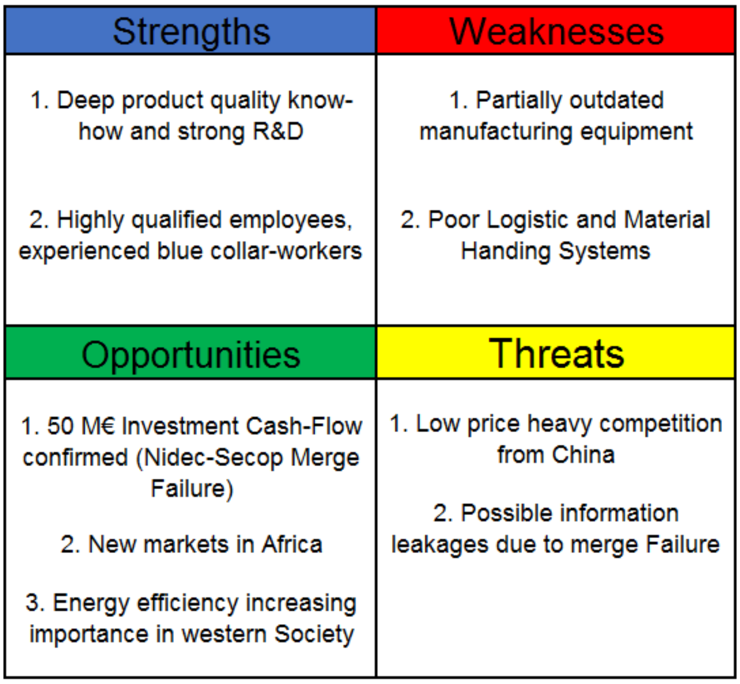
Care must be taken when the process responsible for the COP loss costs is also the bottleneck of the production line. By tightening specification limits in a specific process step that is also the bottleneck of a production line increases scrap rate in that process step, which reduces the overall capacity of the line, and therefore reduces productivity and increases labor costs.

4.2 Improvement suggestions

Now a set of improvement suggestions will be given based on the analysis and findings and in accordance to study.

4.2.1 Investing in new manufacturing equipment

After analyzing the production chain in NGAA GmbH and investigating the most influential product characteristics (and how heavily influenced these characteristics are by their respective manufacturing technologies), A SWOT analysis was developed to propose strategies in the field of manufacturing management. The SWOT analysis is presented graphically in Figure 4.3.



Strengths	Weaknesses
1. Deep product quality know-how and strong R&D 2. Highly qualified employees, experienced blue collar-workers	1. Partially outdated manufacturing equipment 2. Poor Logistic and Material Handing Systems
Opportunities	**Threats**
1. 50 M€ Investment Cash-Flow confirmed (Nidec-Secop Merge Failure) 2. New markets in Africa 3. Energy efficiency increasing importance in western Society	1. Low price heavy competition from China 2. Possible information leakages due to merge Failure

Figure 4.3: Current Situation SWOT Analysis, source: Own illustration

In the HRC manufacturing business COP is one of the key quality measurements, with regards to marketing it's like the fuel consumption of a car; the less fuel consumption a car offers, the higher the perceived value from the customers will be. Looking at the SWOT analysis an immediate Strength-Opportunity strategy is a strong investment in quality, this always requires energy, time, and money investments; to study deeper the product and to deeper understand how each individual component influences the COP of the HRC. This would then lead to the main point: The manufacturing technologies show a big room for improvement. Investing in new manufacturing equipment that nurtures quality as well as empowers the employees is highly recommendable, especially for the Delta platform where the study showed a bigger room for improvement. E.g.: Being able to reduce the angle deviation error of the piston pin bore in the Delta piston by 10µm can save NGAA 0,02€ per produced compressor and with a current production of one million compressors per year, that would mean 200 k€ savings per year.

Figure 4.4 illustrates the need for manufacturing process innovation, the study was based on an enquiry made on more than 200 top manufacturing firms.

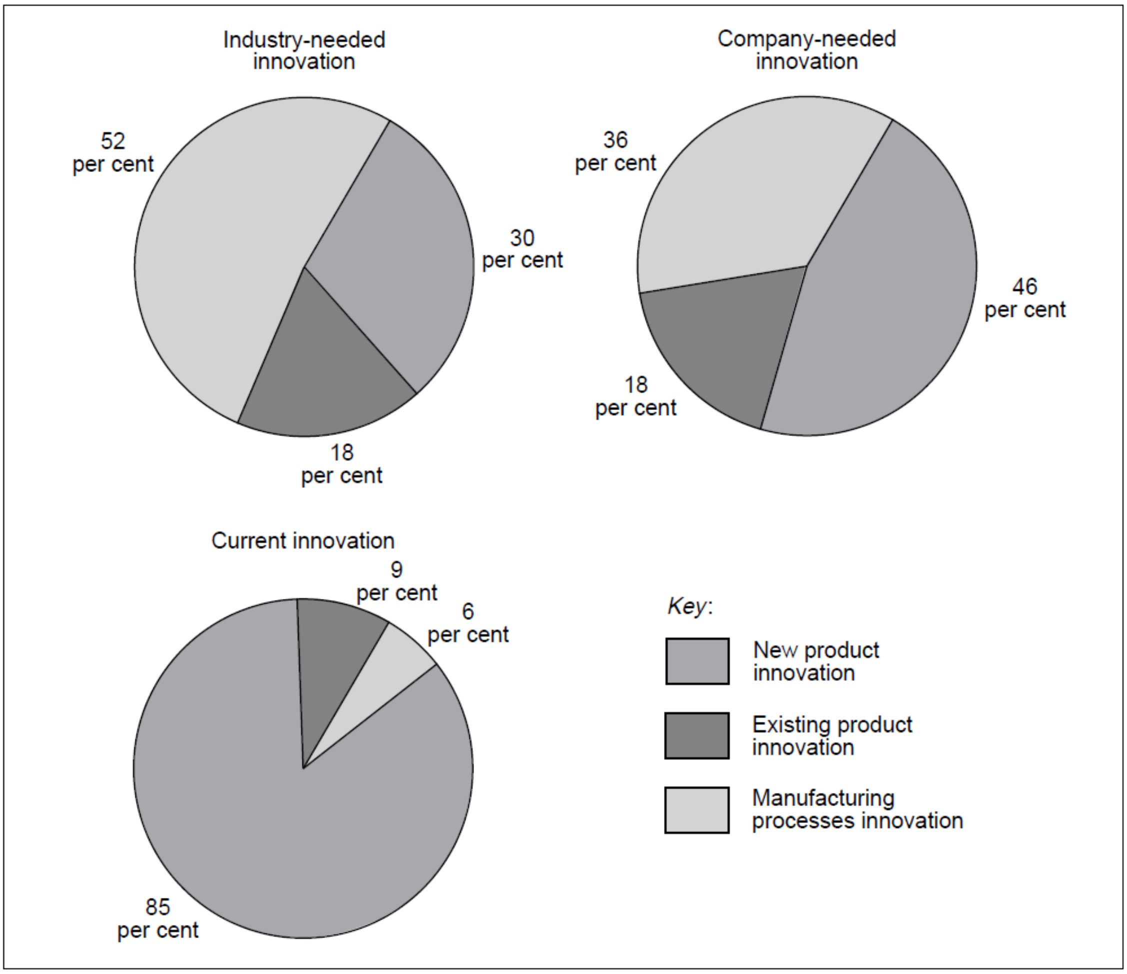


Figure 4.4: Areas of needed innovation, Cook/Cook (1994), p. 48

There are two kinds of innovation: Revolutionary and evolutionary, revolutionary innovation is always riskier, irrational, which is many times the reason for companies falling off from competitive status to bankruptcy. Evolutionary innovation is less risky and more long-term oriented, it is based on patience, it also fosters an atmosphere of confidence and self-realization in the employees.

NGAA shows a very adequate production layout for evolutionary innovation, it is not needed to disrupt the whole production chain to introduce newer systems, this is due to NGAA's process structure, which is broken in separated production lines that lead to a final assembly line. This fact allows incremental improvements one production line at a time, and then measuring via SPC tools how the component quality reacts as well as how the employees respond to new systems, if the outcome is good move to the next production line. This is known as the Plan-Do-Check-Act cycle.

4.2.2 Tracking scrap rate

Other problem was found at the beginning of the analysis, even though NGAA is running his production with the latest possible manufacturing technologies there isn't any kind of automated control systems that support the production managers. The production data gathering operation is still rudimental, where data is extrapolated as a per month basis. This leads to very rough numbers; the scrap production will be used as an example. The scrap produced, as mentioned in chapter 2, should not only be measured for accounting and finance reasons. It should be used as a KPI; KPIs also serve as management aiding tool, they reveal fragilities in the production chain, and allow better surveillance and forecasting of the different processes. In NGAA the only scrap measurement done is in the form of €/part produced, this measurement is important but as will be now discussed it could be further enhanced.

Basic cost estimation models or manufacture process feasibility studies include data such as: *Number of scraped parts per unit of time,* this kind of data is very useful to compare the manufacturing process capability using different machine setups or parameters, it is also an important component of the Advanced Manufacturing Technology Costing method[62]. It is used for example to compare different grinding wheels such as Cubic Boron Nitride CBN, Silicon Carbide SiC, Silicon Nitride SiN, etc.

Additional KPIs can be further calculated such as *scrap rate*, which is calculated dividing the number of scraped parts by the number of good parts plus scraped parts plus reworked parts (or total input parts). Production lines with high scrap rate (lets assume 10% scrap rate) might have very low scrap cost, because, for example, the raw parts could have low direct materials cost; in this fact resides the danger. As the manager reads through the scrap reports, which in NGAA only include scrap cost (€ of scrap per part produced), he might misinterpret the results; he will assume a production line is running in conformity just because it has low scrap costs, what he might not be aware of, is that this production line has a scrap rate of 10%, this means that out of an 8-hour shift, 48 minutes of production time is wasted (in case the scrap is being produced in the bottleneck of the line). This will then increase the labor cost per part produced.

There has been proven that for some manufacturing activities, like the cylinder boring in automotive industries, it is more rentable to use the more expensive superabrasive CBN grinding wheel than the conventional SiN grinding wheel[63]. Also, in more rigorous manufacturing processes, such as the internal profile grinding of an aero engine shroud assembly changing to a CBN grinding wheel costs were reduced by two thirds[64]. Both studies

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[62] Cf. Krar/Gill (2003), p. 121-129.
[63] Cf. Krar/Gill (2003), p. 126.
[64] Rowe (2014), p. 160.

required statistical data about the scrap produced either in absolute values like *number of scraped parts produced* or by relative number such as *scrap rate.*

It is a vital activity to know if operations are being productive, efficient and profitable and this is done by means of constant measurement and analysis of KPIs, therefore it is important to develop understandable and simple KPIs in manufacturing, it is also known that good unit count and bad unit count are extremely useful KPIs in manufacturing[65], both for the controlling staff as for the blue-collar workers as a motivational incentive.

4.2.3 Measuring the cpk of the CTQ processes

Based on the findings section (subchapter 4.1), the advantages of introducing SPC measurements were further interiorized. They can serve many purposes, such as having a better knowledge of what are the current limits of the available equipment, they also serve as a quality costing tool.

Having a deeper understanding of the existing capabilities will greatly facilitate decision-make on equipment investments. SPC tools show good synergy potential with a deep product know-how; knowing where it is worth to have an extremely accurate and precise process requires product know-how as well as current manufacturing process capability.

There is always a cost associated to higher accuracy and precision of a process, the art resides in finding the minimum where the COP losses (or quality costs) are balanced with the operational costs.

As suggested in equation **4.1**, it is possible to reduce the COP losses by having shorter tolerances, the limit would be having a 0-tolerance region, this would explode the operational costs and reduce quality costs to 0. The other limit would be having an infinitely big tolerance region, which would mean the reverse effect. This suggests that tolerances can be refined to an optimum.

The current status of many CTQ component features show a big disparity between scrap cost and COP cost for example. As already mentioned this can be changed by improving equipment, but also by refining tolerances, having in mind that both actions would influence the cpk value.

4.2.4 DOE for controllable manufacturing parameters of the CTQ processes

Other very effective SPC tool is the Design of Experiments DOE approach, which is basically a tracing mechanism of quality problems or quality improvement potentials. The approach is to develop targeted experiments by systematically varying controllable variables (or parameters) and then observing the effects on quality (it can also be cost, cycle time, employee

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[65] Cf. Newton (2017), online source [18.05.2019].

satisfaction, etc.)[66]. It can be applied to a big variety of controllable variables, in this study the suggestion is to apply them to manufacturing controllable variables, these can be the specific removal rate Q'_w of a grinding process or the number of components produced in a machine between setups (for example: setup due to changing the production of a Kappa component to a Delta component).

Design of Experiments for the Piston Manufacturing

Developing effective DOE for the centerless grinding using influence parameters like tangent angle γ_s (controllable by the work height h) or the blade angle θ has been proven to show significant improvement results as illustrated in Figure 4.5.

As mentioned in the sub-section 2.4.3, additional research also proposes other solutions to achieve better quality, one of them, which is relevant for NGAA, targets centerless grinding processes where there is a need for a first rough grinding followed by a finish grinding (this is the case for the piston production in NGAA, both Kappa and Delta pistons). The research paper suggests that having different tangent angles in the rough and finish grinding operations reduces roundness errors[67].

For these reasons it is recommended to undertake DOE studies on this phenomenon. Using, for example, the work height h or the blade angle as the controllable parameters.

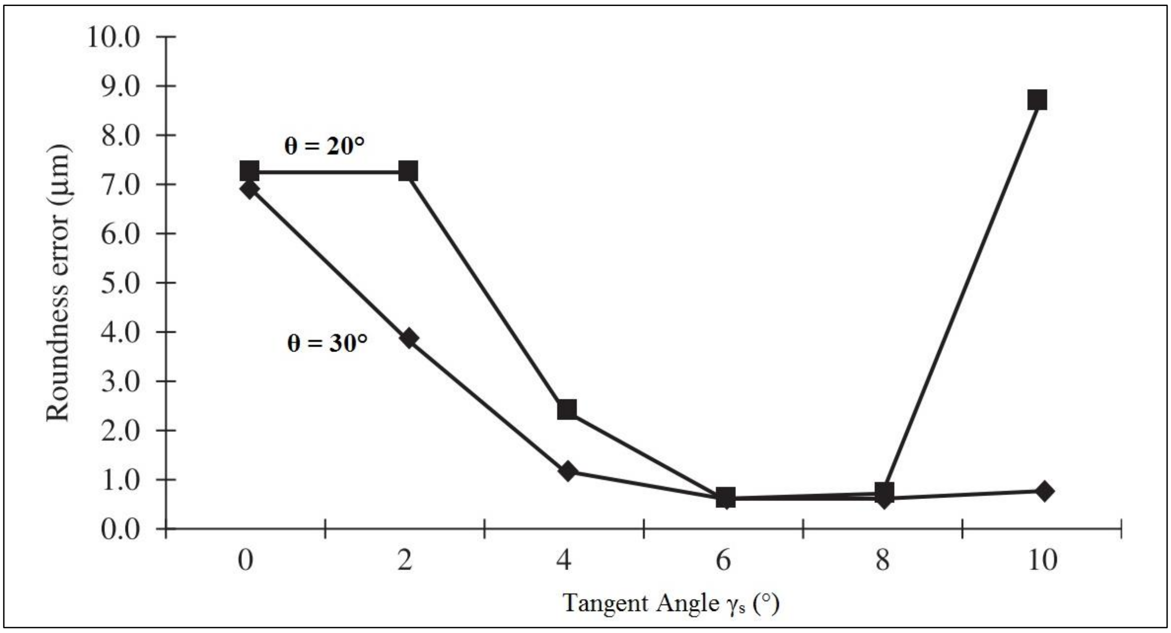

Figure 4.5: DOE: Tangent Angle Vs. Blade Angle, Cf. Rowe (2014), p. 270, slightly modified

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[66] Cf. Hopp/Spearman (2011), pp. 404-405.
[67] Cf. Harrison/Pearce (2004), pp. 159-164.

In Figure 3.11 the component features that have a bigger influence in the COP of a HRC have been illustrated. For the rotor, a relevant feature is the porosity of the aluminum casting[68]; as it can be seen in Figure 3.11 there is no α value for this feature, this is because there is no available system to measure the porosity inside the casted aluminum.

The first suggestion regarding the rotor manufacturing would be to introduce a measurement system to be able to the control quality of the die casting process. Such a system would also enable DOE applications. As it has been discussed in the sub-section 2.4.1, the porosity of the aluminum die casting process is influenced mainly by: pouring temperature, Filling time, die temperature and injection pressure[69].

One method that is often used to measure the porosity in the aluminum castings is the X-ray scanning which is often used in casting porosity quality studies (Figure 4.6).

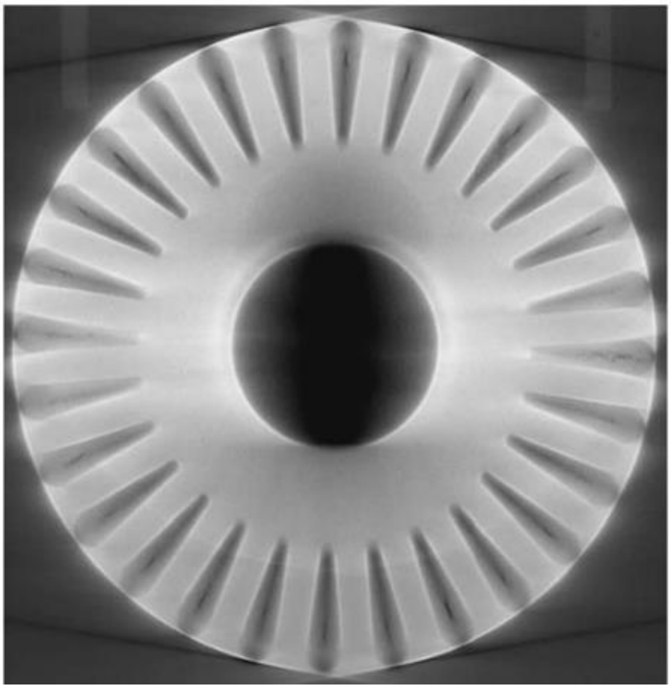

Figure 4.6: X-Ray Scanning of the rotor casting porosity, Yun/Lee (2018), p. 1

With a porosity measuring device it can be further investigated (quantitatively, and not just qualitatively) what is the actual influence of the porosity inside the die casted rotor in the COP of a compressor. If there is a big influence (α is high), then it would be fruitful to do DOE varying the manufacturing parameters suggested in sub-section 2.4.1.: Starting with the pouring temperature and the injection pressure which, of the four mentioned parameters, are the ones that have a higher influence factor[70].

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[68] Cf. Yun/Lee (2018), p. 1.
[69] Cf. Apparao/Birru (2017), p. 1858.
[70] Cf. Apparao/Birru (2017), p. 1859.

For the Delta rotor production line, DOE can also be applied to the centerless grinding operation after the die casting. Again, relevant influence factors include the specific removal rate Q'_w, the work height h (which sets the tangent angle γ_s), and the blade angle θ.

4.3 Out of scope problems, NGAA and the State-of-the-Art

To remain competitive in today's global economy, progressive management must integrate manufacturing and computing technologies and divest itself of old patterns of thinking that restrict manufacturing to a narrow concept of efficiency[71]. Additionally, the manufacturing mindset is still today influenced by Taylor's principles of scientific management, which essentially reduce tasks to mindless repetition, preventing workers from making intellectual contributions[72].

After having the privilege of being allowed to study a real manufacturing firm, a deeper understanding of the concepts learned during PSM was achieved. Production systems are very complex, similar to living beings, and in order to control them, more and more firms turn to digitalization, one reason for this is the increasing amount of boundary conditions a production plant has, it has reached a point where the human brain cannot compute anymore all the decision variables to achieve an optimum.

Additionally, an important role in manufacturing operations are people, which at the end of the day, are who making the systems run. Each individual has different a modus-operandi, and for this reason not always everything runs as planned. And, as already mentioned, the systems should evolve in a way that they empower and not impoverish people.

The challenges for the future are the increasing quality demands, the price competition, satisfying costumer needs on time and developing a flexible production plant in order to adapt to quick market changes. In this research, more attention was given to the quality aspects, in this regard, control systems and automated quality assurance could prove a big improvement, because it is only possible to manage what one measures.

After the background study, and comparing NGAA to other comparable manufacturing enterprises, it is strongly advised to make steps into a more digitalized plant layout, the key is to achieve a clear information flow between every member inside and outside the production. This motivates the production staff even more, making people feel they are part of a bigger picture. It will also help the production managers, foremen, and maintenance to react faster to unpredictable problems (which one should assume as a universal truth).

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[71] Cook/Cook (1994), p. 42.
[72] Cook/Cook (1994), p. 53.

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5.2 List of Figures

5.3 List of Tables

Appendix A Kappa Logistics

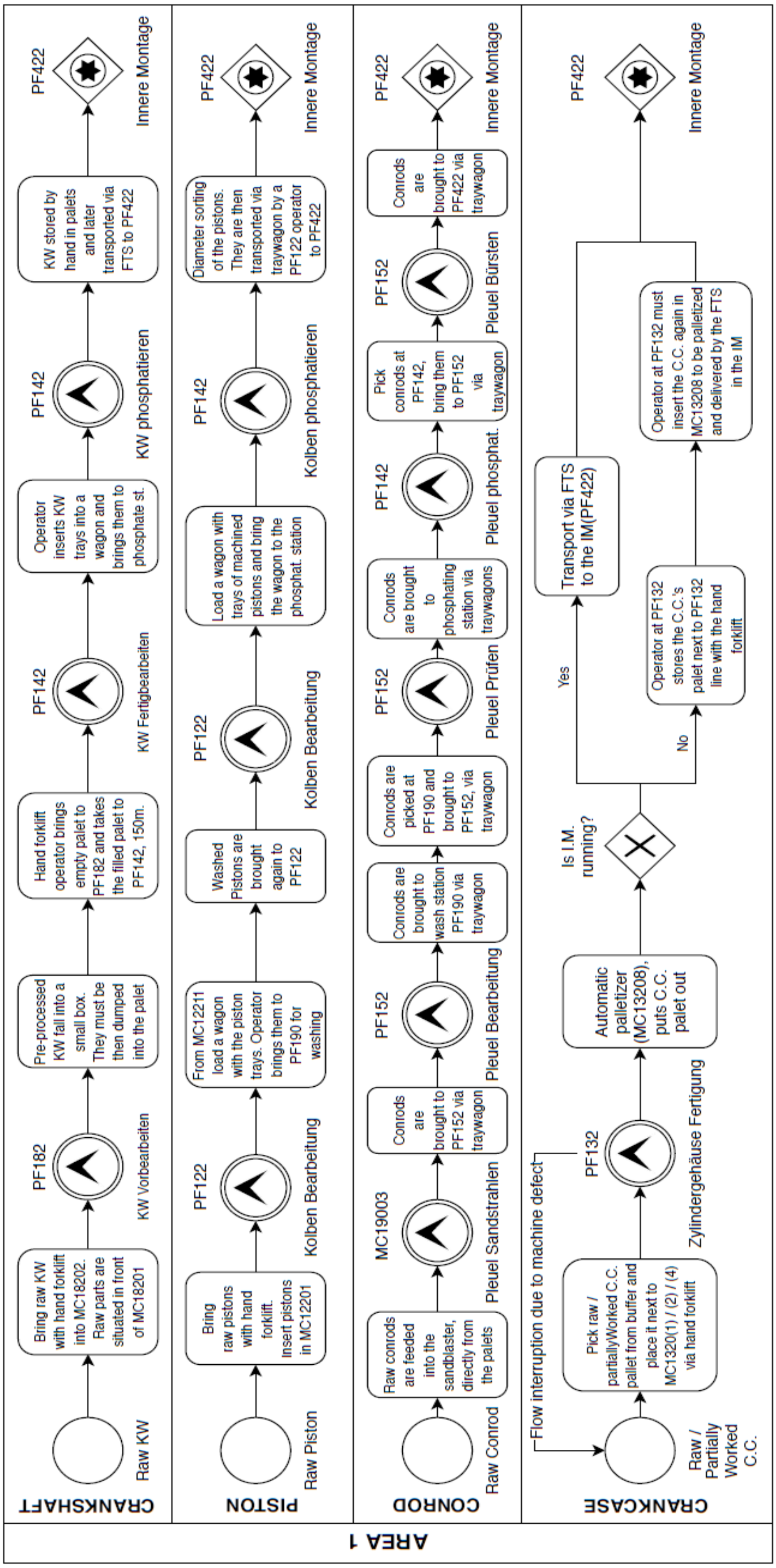


Figure A.1: Area 1 Kappa Logistic Analysis, Source: Own Illustration

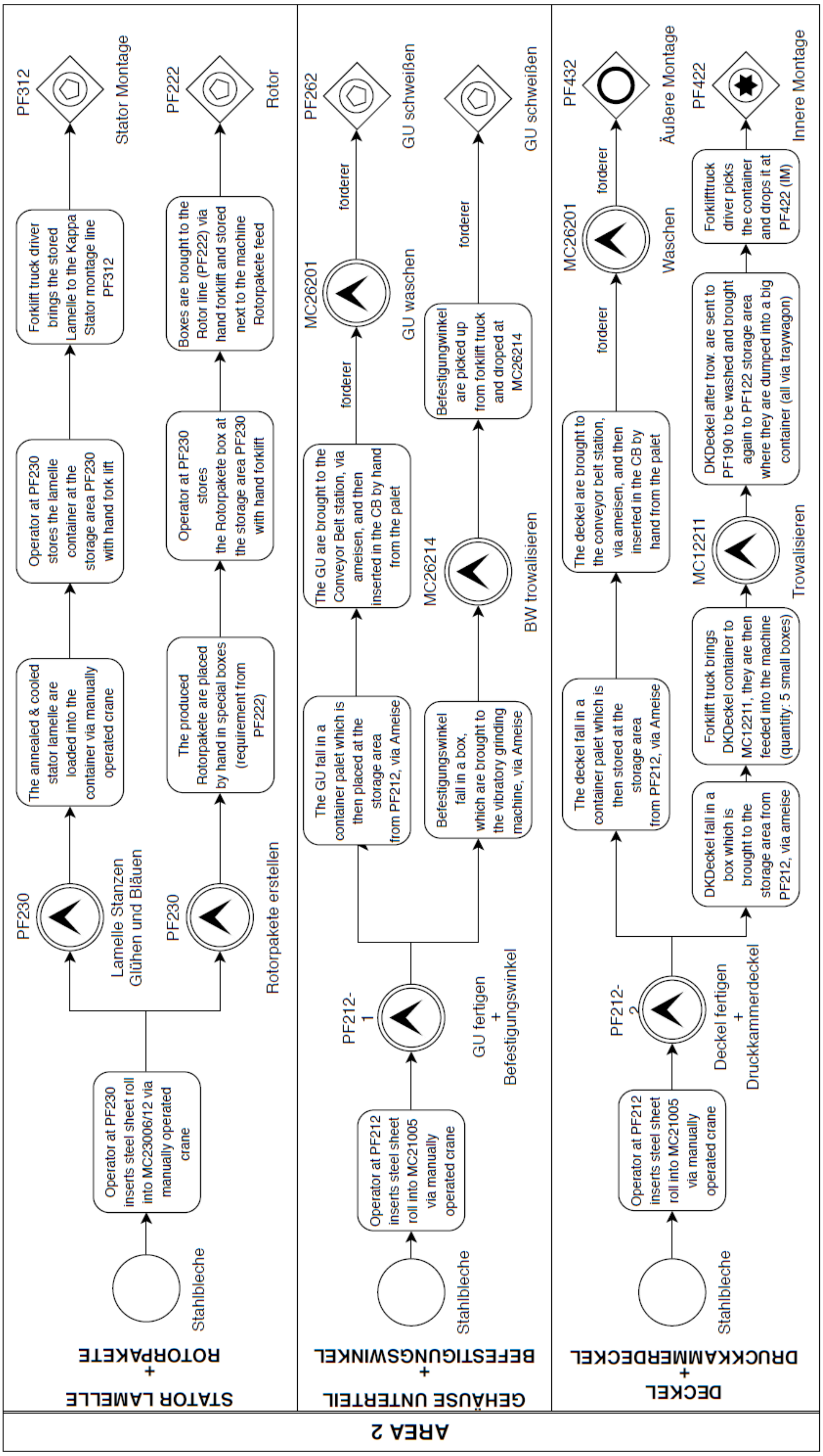
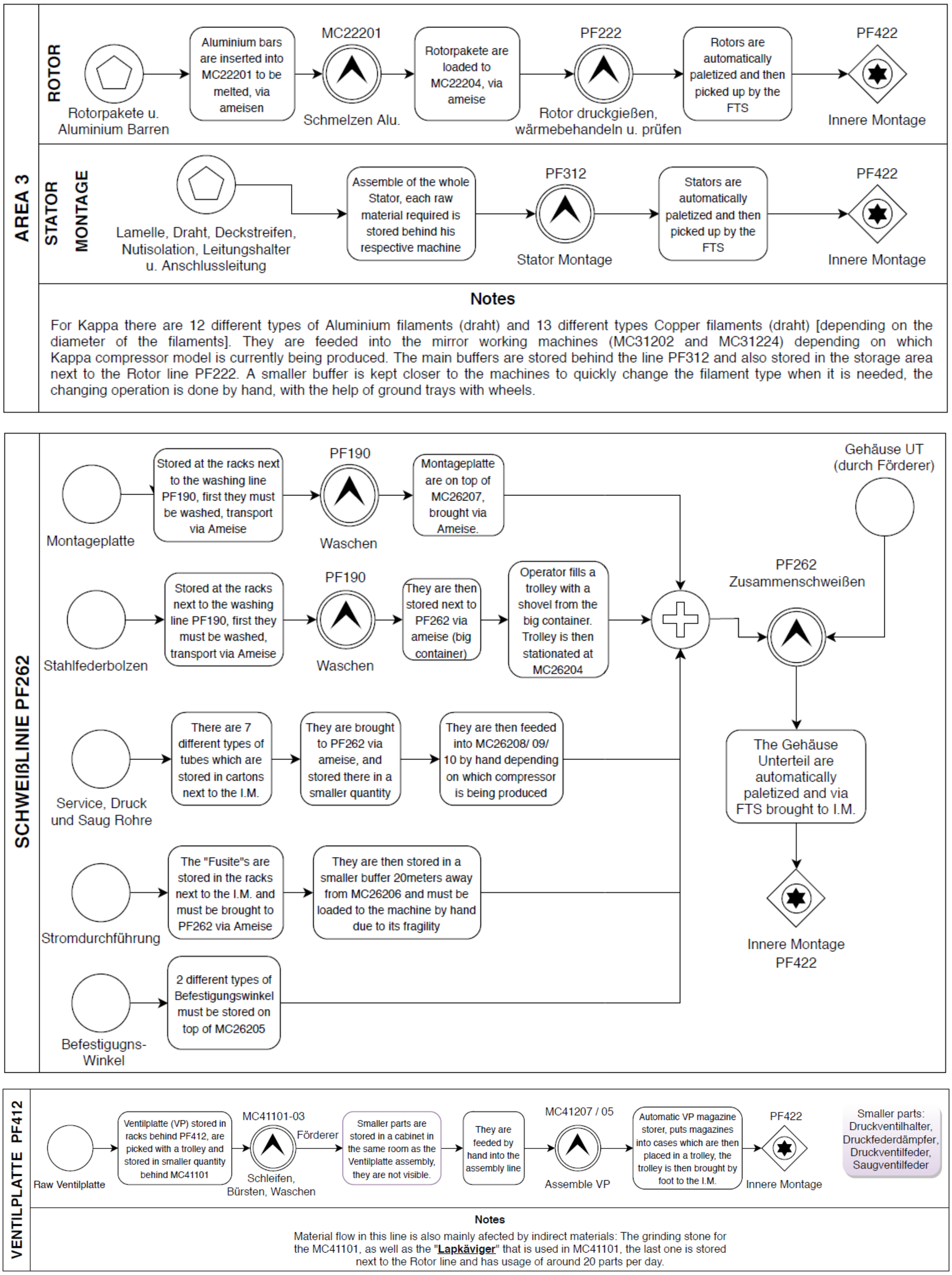


Figure A.2: Area 2 Kappa Logistic Analysis, Source: Own Illustration



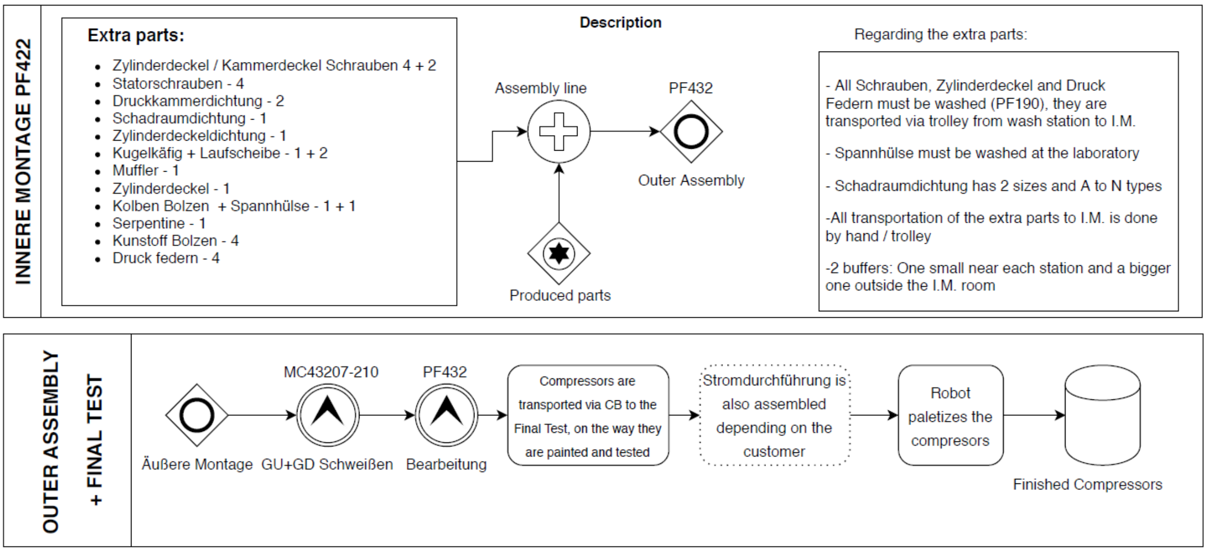
Notes

For Kappa there are 12 different types of Aluminium filaments (draht) and 13 different types Copper filaments (draht) [depending on the diameter of the filaments]. They are feeded into the mirror working machines (MC31202 and MC31224) depending on which Kappa compressor model is currently being produced. The main buffers are stored behind the line PF312 and also stored in the storage area next to the Rotor line PF222. A smaller buffer is kept closer to the machines to quickly change the filament type when it is needed, the changing operation is done by hand, with the help of ground trays with wheels.

Notes

Material flow in this line is also mainly afected by indirect materials: The grinding stone for the MC41101, as well as the "**Lapkäviger**" that is used in MC41101, the last one is stored next to the Rotor line and has usage of around 20 parts per day.

Figure A.3: Area 3 & Other Areas Kappa Logistic Analysis, Source: Own Illustration



Extra parts:

- Zylinderdeckel / Kammerdeckel Schrauben 4 + 2
- Statorschrauben - 4
- Druckkammerdichtung - 2
- Schadraumdichtung - 1
- Zylinderdeckeldichtung - 1
- Kugelkäfig + Laufscheibe - 1 + 2
- Muffler - 1
- Zylinderdeckel - 1
- Kolben Bolzen + Spannhülse - 1 + 1
- Serpentine - 1
- Kunstoff Bolzen - 4
- Druck federn - 4

- All Schrauben, Zylinderdeckel and Druck Federn must be washed (PF190), they are transported via trolley from wash station to I.M.

- Spannhülse must be washed at the laboratory

- Schadraumdichtung has 2 sizes and A to N types

-All transportation of the extra parts to I.M. is done by hand / trolley

-2 buffers: One small near each station and a bigger one outside the I.M. room

Compressors are transported via CB to the Final Test, on the way they are painted and tested

Stromdurchführung is also assembled depending on the customer

Robot paletizes the compresors

Figure A.4: Inner & Outer Assembly Kappa Logistic Analysis, Source: Own Illustration

Inner Assembly Logistic Flow Description:

1. Crankcase placed in Work Piece Carrier 1 (WPC1), axial ball bearing and lower washer of the Axial Ball Bearing are assembled. Automated station.

2. Critical: Cylinder bore is measured, after measurement the worker in notified to which piston category to assemble (there are 9 different possible categories, depending on which diameter interval the piston falls in). Worker inserts the piston inside the cylinder. Manual station.

3. Mounting of the ball bearing upper washer and the crankshaft on the crankcase.

4. Rotor is heated in the inside (expands material) through electrical conduction and then mounted to the crankshaft (shrinks and is pressed against the crankshaft).

5. Cooling of the Rotor.

6. Axial clearance measurement.

7. Torque test of the axial bearing.

8. Critical: Conrod, piston pin and clamping sleeve assembly. Two parallel manual stations.

9. Lubrification of the crank train line components.

10. Torque test: Crankshaft-Conrod-Piston Pin-Piston

11. Top Dead Center measurement.

12. Insert mounting pin in the crankcase (used to hold valve plate unit during mounting operation).

13. Valve Plate Gasket Mounting (gasket thickness 100% measured).

14. Critical: Valve Plate mounting.

15. Cylinder Head gasket mounting. 100% quality check on the discharge leaf holding capacity.

16. Suction muffler mounting. Manual station.

17. Placement of 2 diagonal cylinder head screws.

18. Removal of the mounting pin (valve plate holder).

19. Insert the two other cylinder head screws, and screwing the 4 screws.

20. Pump capacity test, clamping sleeve distance test.

21. First discharge chamber gasket placement.

22. Second discharge chamber gasket placement.

23. Discharge chamber covers (2x) placement

24. Screwing one discharge chamber cover.

25. Moving the inner assembly work piece to a new Work Piece Carrier.

26. Critical: Alignment and screwing of the stator to the crankcase. Scan of Stator model.

27. Air gap between stator and rotor 100% automatically checked.

28. Manual correction of stator errors detected. 2 Manual stations

29. Spring pins for stator placement. Stand by.

30. Springs are pressed against the shell spring pins.

31. The Inner Assembly work piece is placed inside the Shell supported by the springs.

32. Connecting the plug casing from the stator to the hermetic terminal. Manual Station.

33. Inserting the internal discharge tube, and a soldering ring between the discharge tube and the discharge chamber. Placement of the second discharge chamber screw. Manual Station.

34. Screwing of the internal discharge cover.

35. Electrical induction soldering of the internal discharge tube (with the soldering ring).

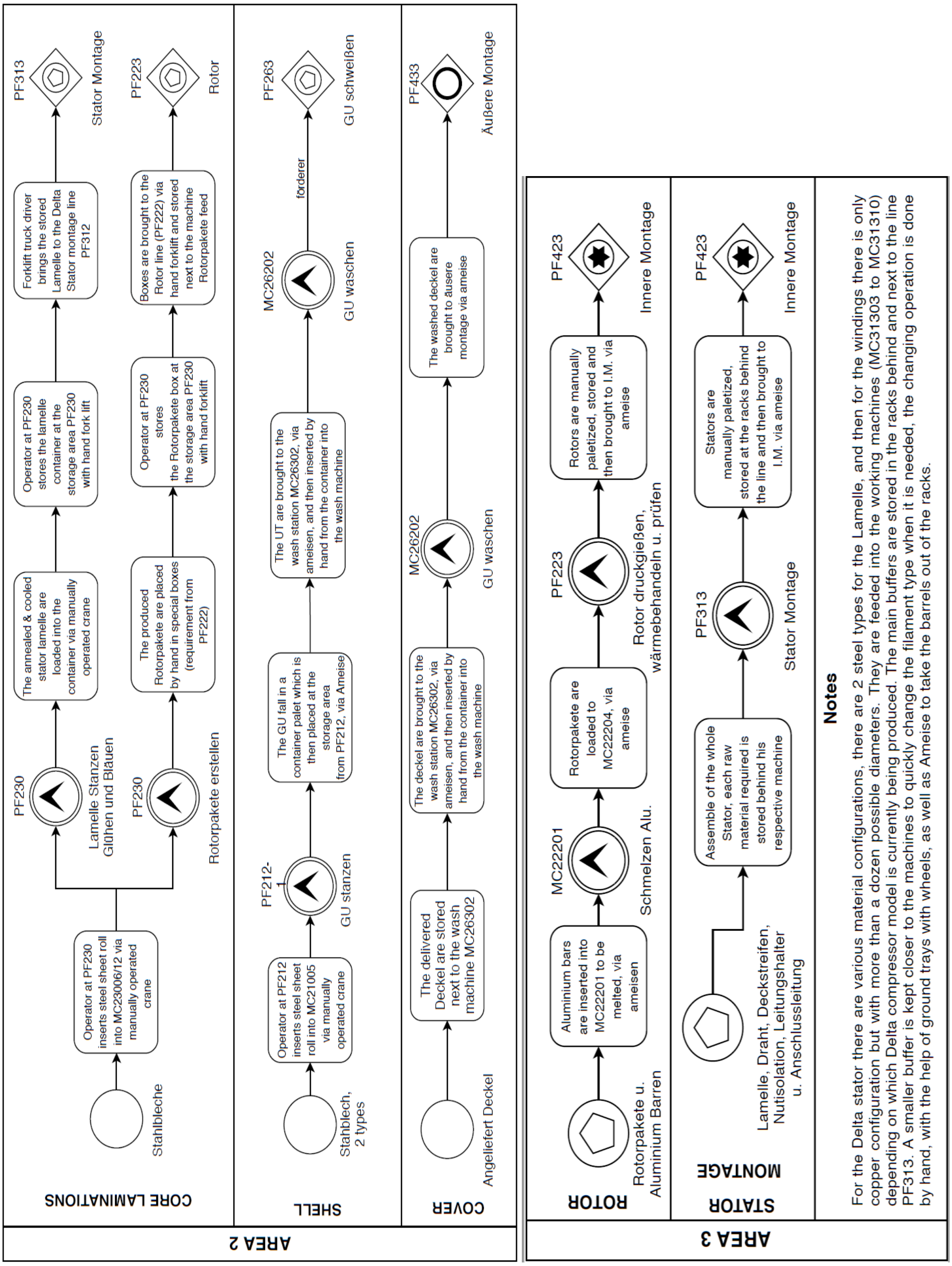
36. Final Test: Whole pump unit running.

37. Final Test: Electrical resistance and leakages.

38. Test compression and test high voltage. Scanning of the muffler for conformity.

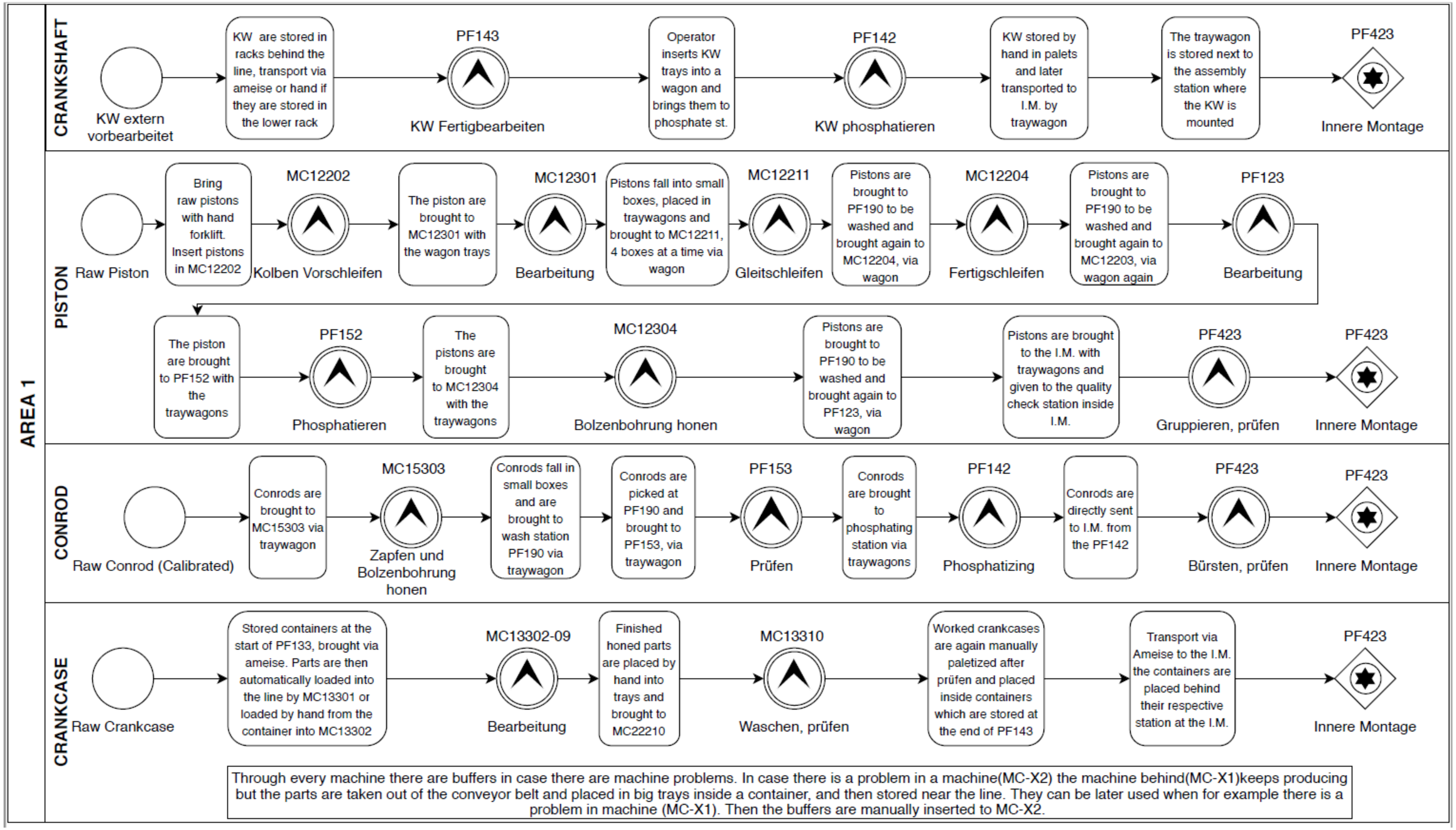
39. Marking the compressor shell (indentation in steel with diamond tool).

Appendix B Delta Logistics



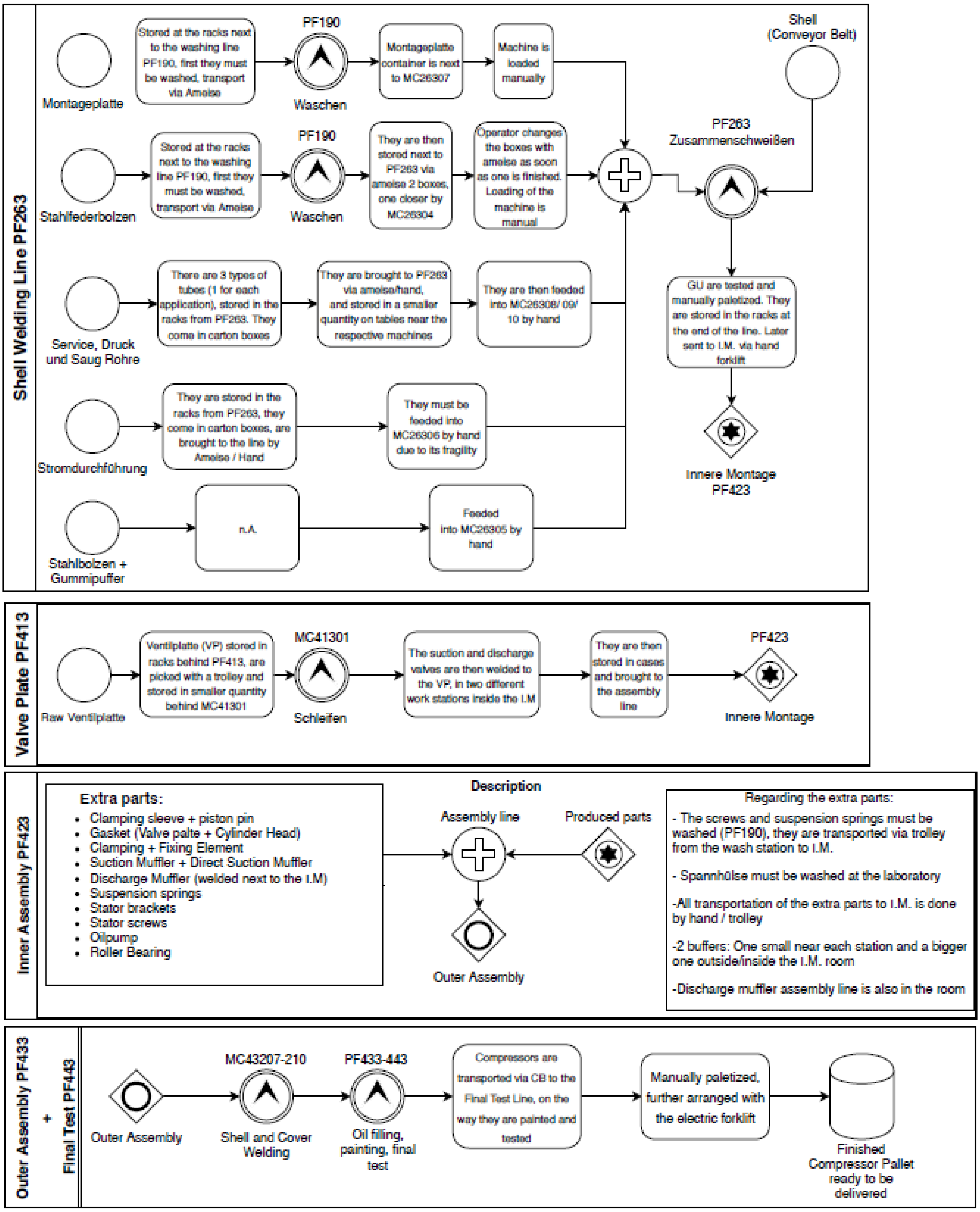
For the Delta stator there are various material configurations, there are 2 steel types for the Lamelle, and then for the windings there is only copper configuration but with more than a dozen possible diameters. They are feeded into the working machines (MC31303 to MC31310) depending on which Delta compressor model is currently being produced. The main buffers are stored in the racks behind and next to the line PF313. A smaller buffer is kept closer to the machines to quickly change the filament type when it is needed, the changing operation is done by hand, with the help of ground trays with wheels, as well as Ameise to take the barrels out of the racks.

Figure B.1: Area 2 & 3 Delta Logistic Analysis, Source: Own Illustration



Through every machine there are buffers in case there are machine problems. In case there is a problem in a machine(MC-X2) the machine behind(MC-X1)keeps producing but the parts are taken out of the conveyor belt and placed in big trays inside a container, and then stored near the line. They can be later used when for example there is a problem in machine (MC-X1). Then the buffers are manually inserted to MC-X2.

Figure B.2: Area 1 Delta Logistic Analysis, Source: Own Illustration



Extra parts:

- Clamping sleeve + piston pin
- Gasket (Valve palte + Cylinder Head)
- Clamping + Fixing Element
- Suction Muffler + Direct Suction Muffler
- Discharge Muffler (welded next to the I.M)
- Suspension springs
- Stator brackets
- Stator screws
- Oilpump
- Roller Bearing

Regarding the extra parts:

- The screws and suspension springs must be washed (PF190), they are transported via trolley from the wash station to I.M.

- Spannhülse must be washed at the laboratory

-All transportation of the extra parts to I.M. is done by hand / trolley

-2 buffers: One small near each station and a bigger one outside/inside the I.M. room

-Discharge muffler assembly line is also in the room

Figure B.3: Other Areas Delta Logistic Analysis, Source: Own Illustration

Inner Assembly Logistic Flow Description

1. Crankcase placed in the work piece carrier 1 (WPC1). Placement of axial ball bearing and lower washer of the ball bearing. Manual Station

2. Critical: Inserting the piston in the Crankcase. Inserting the upper ball bearing washer and the crankshaft, supported by the axial ball bearing, in the crankcase. Manual station.

3. Rotor is heated in the inside (expands material) through electrical conduction and then mounted to the crankshaft (shrinks and is pressed against the crankshaft).

4. Axial clearance measurement.

5. Cooling of the Rotor.

6. Critical: Conrod, piston pin and clamping sleeve assembly. Manual station.

7. Lubrification of the crank train line components. Oil pump pressed to the crankshaft

8. Top Dead Center measurement.

9. Torque test: Crankshaft-Conrod-Piston Pin-Piston. Circular run-out rotor to oil pump test.

10. Valve plate gasket and valve plate mounted to the work piece, according to TDC distance measurement a specific valve plate gasket category (categories vary from A to L) will be assigned. Manual Station.

11. Cylinder head gasket and clamping element are pressed against the cylinder head.

12. Discharge and suction mufflers are placed. Manual station

13. Fixing element pressing.

14. Measurement of clamping sleeve position. Measurement of the relative position of the fixing element to the clamping element.

15. Pump capacity test.

16. Delivery to the stator assembly. (Change of WPC)

17. Critical: Stator centered (in relation to the rotor). Screwing of the stator to the crankcase.

18. Change of Work Piece Carrier.

19. Air gap between stator and rotor automatically test.

20. Air gap between stator and rotor manually check. Manual station.

21. Stator brackets pressed against the compressor inner assembly.

22. Shell is placed in a new WPC. Manual station. Springs are afterwards automatically placed inside the shell.

23. Placement of the pump unit inside the shell, supported by the springs.

24. Connection of the stator plug casing to the hermetic terminal. Manual station.

25. Pressing the discharge muffler tube to the inside of the Discharge Tube.

26. Final test: Impermeability of the discharge unit.

27.Final test: Compression run test, high voltage test, No-load power test, noise measurement.

28. Marking the compressor shell (indentation in steel with diamond tool).

Appendix C Excel Program and Data Templates

For future analysis or benchmark of COP vs Operational costs an Excel template was created to facilitate these studies.

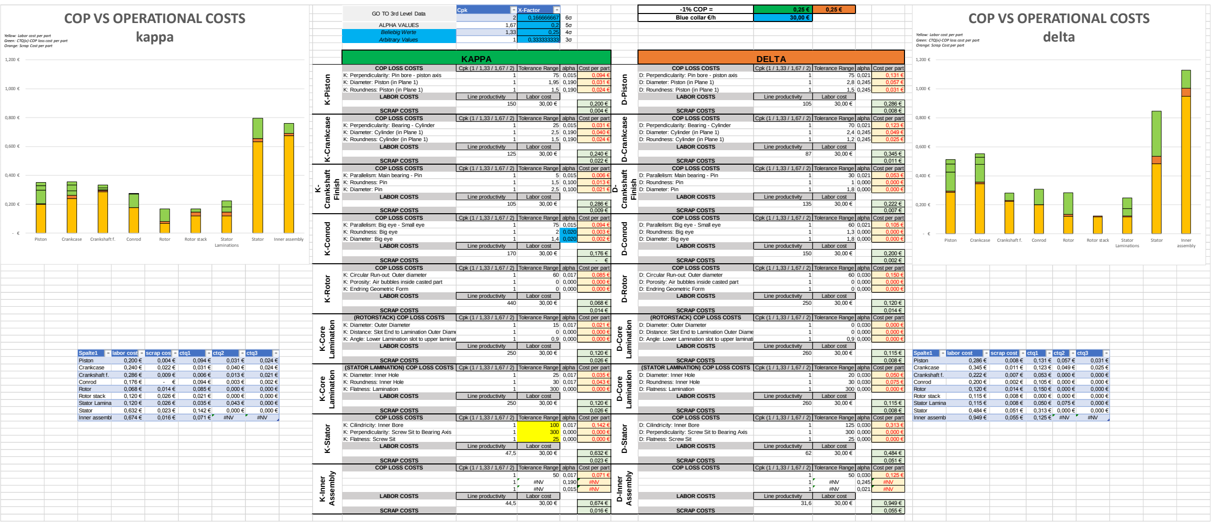
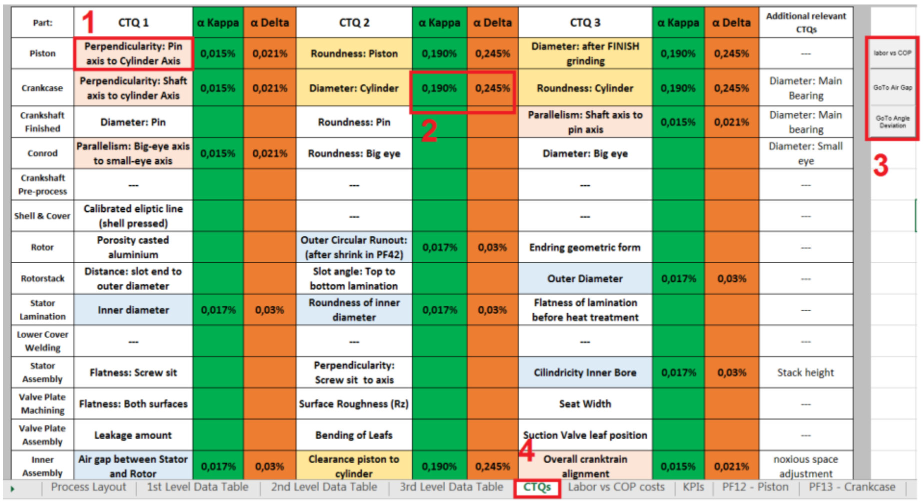


Figure C.1: Template Mother-sheet, source: Own Illustration

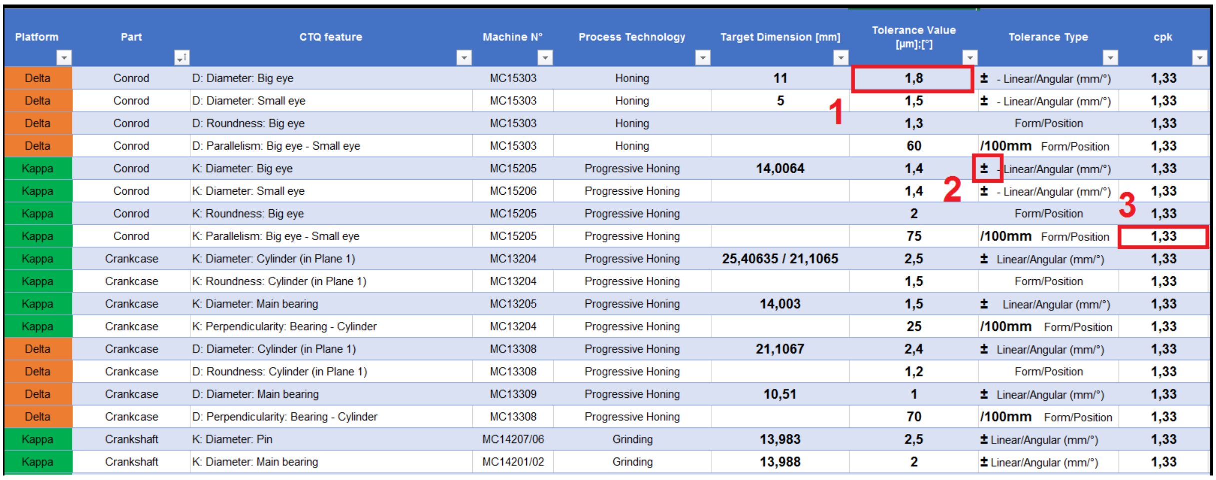
Taking equation **4.1** into consideration, the decision variables for the calculation of the COP can be found in the following Excel sheet, first the α values:



Part:	CTQ 1	α Kappa	α Delta	CTQ 2	α Kappa	α Delta	CTQ 3	α Kappa	α Delta	Additional relevant CTQs
Piston	Perpendicularity: Pin axis to Cylinder Axis	0,015%	0,021%	Roundness: Piston	0,190%	0,245%	Diameter: after FINISH grinding	0,190%	0,245%	---
Crankcase	Perpendicularity: Shaft axis to cylinder Axis	0,015%	0,021%	Diameter: Cylinder	0,190%	0,245%	Roundness: Cylinder	0,190%	0,245%	Diameter: Main Bearing
Crankshaft Finished	Diameter: Pin			Roundness: Pin			Parallelism: Shaft axis to pin axis	0,015%	0,021%	Diameter: Main bearing
Conrod	Parallelism: Big-eye axis to small-eye axis	0,015%	0,021%	Roundness: Big eye			Diameter: Big eye			Diameter: Small eye
Crankshaft Pre-process	---			---			---			---
Shell & Cover	Calibrated eliptic line (shell pressed)			---			---			---
Rotor	Porosity casted aluminium			Outer Circular Runout: (after shrink in PF42)	0,017%	0,03%	Endring geometric form			---
Rotorstack	Distance: slot end to outer diameter			Slot angle: Top to bottom lamination			Outer Diameter	0,017%	0,03%	---
Stator Lamination	Inner diameter	0,017%	0,03%	Roundness of inner diameter	0,017%	0,03%	Flatness of lamination before heat treatment			---
Lower Cover Welding	---			---			---			---
Stator Assembly	Flatness: Screw sit			Perpendicularity: Screw sit to axis			Cilindricity Inner Bore	0,017%	0,03%	Stack height
Valve Plate Machining	Flatness: Both surfaces			Surface Roughness (Rz)			Seat Width			---
Valve Plate Assembly	Leakage amount			Bending of Leafs			Suction Valve leaf position			---
Inner Assembly	Air gap between Stator and Rotor	0,017%	0,03%	Clearance piston to cylinder	0,190%	0,245%	Overall cranktrain alignment	0,015%	0,021%	noxious space adjustment

Figure C.2: α values, source: own illustration

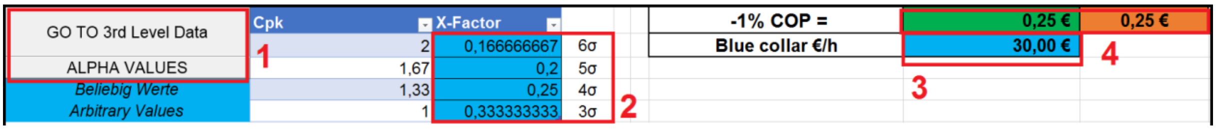
The red markings stand for: 1. name of the CTQ feature, 2. alpha value, 3. Go to calculation sheets of the alpha values (in future studies it is recommended to show how the α value was calculated). 4. This sheet can be found under the name of: CTQs. The alpha values must be manually inserted in the mother-sheet in the 4th column (column title: “alpha”) of its respective CTQ feature and platform. And the number format is standard (the function accepts only standard numeric values as function parameters, this means, 0,12% => 0,12 in 4th column as an alpha value).



Platform	Part	CTQ feature	Machine N°	Process Technology	Target Dimension [mm]	Tolerance Value [µm];[°]	Tolerance Type	cpk
Delta	Conrod	D: Diameter: Big eye	MC15303	Honing	11	1,8	± - Linear/Angular (mm/°)	1,33
Delta	Conrod	D: Diameter: Small eye	MC15303	Honing	5	1,5	± - Linear/Angular (mm/°)	1,33
Delta	Conrod	D: Roundness: Big eye	MC15303	Honing		1,3	Form/Position	1,33
Delta	Conrod	D: Parallelism: Big eye - Small eye	MC15303	Honing		60	/100mm Form/Position	1,33
Kappa	Conrod	K: Diameter: Big eye	MC15205	Progressive Honing	14,0064	1,4	± - Linear/Angular (mm/°)	1,33
Kappa	Conrod	K: Diameter: Small eye	MC15206	Progressive Honing		1,4	± - Linear/Angular (mm/°)	1,33
Kappa	Conrod	K: Roundness: Big eye	MC15205	Progressive Honing		2	Form/Position	1,33
Kappa	Conrod	K: Parallelism: Big eye - Small eye	MC15205	Progressive Honing		75	/100mm Form/Position	1,33
Kappa	Crankcase	K: Diameter: Cylinder (in Plane 1)	MC13204	Progressive Honing	25,40635 / 21,1065	2,5	± Linear/Angular (mm/°)	1,33
Kappa	Crankcase	K: Roundness: Cylinder (in Plane 1)	MC13204	Progressive Honing		1,5	Form/Position	1,33
Kappa	Crankcase	K: Diameter: Main bearing	MC13205	Progressive Honing	14,003	1,5	± Linear/Angular (mm/°)	1,33
Kappa	Crankcase	K: Perpendicularity: Bearing - Cylinder	MC13204	Progressive Honing		25	/100mm Form/Position	1,33
Delta	Crankcase	D: Diameter: Cylinder (in Plane 1)	MC13308	Progressive Honing	21,1067	2,4	± Linear/Angular (mm/°)	1,33
Delta	Crankcase	D: Roundness: Cylinder (in Plane 1)	MC13308	Progressive Honing		1,2	Form/Position	1,33
Delta	Crankcase	D: Diameter: Main bearing	MC13309	Progressive Honing	10,51	1	± Linear/Angular (mm/°)	1,33
Delta	Crankcase	D: Perpendicularity: Bearing - Cylinder	MC13308	Progressive Honing		70	/100mm Form/Position	1,33
Kappa	Crankshaft	K: Diameter: Pin	MC14207/06	Grinding	13,983	2,5	± Linear/Angular (mm/°)	1,33
Kappa	Crankshaft	K: Diameter: Main bearing	MC14201/02	Grinding	13,988	2	± Linear/Angular (mm/°)	1,33

Figure C.3: Tolerance Value and respective process technology, source: Own Illustration

This sheet is under the name of: 3rd Level Data Table. Point 1: Tolerance value, this is the value that equation **4.1** uses, the program will automatically use whatever value these cells contain. Point 2: Tolerance Type. Point 3: Cpk value of the responsible machine for the dimension machining, this is a fictitious value as these values are still not measured in NGAA.



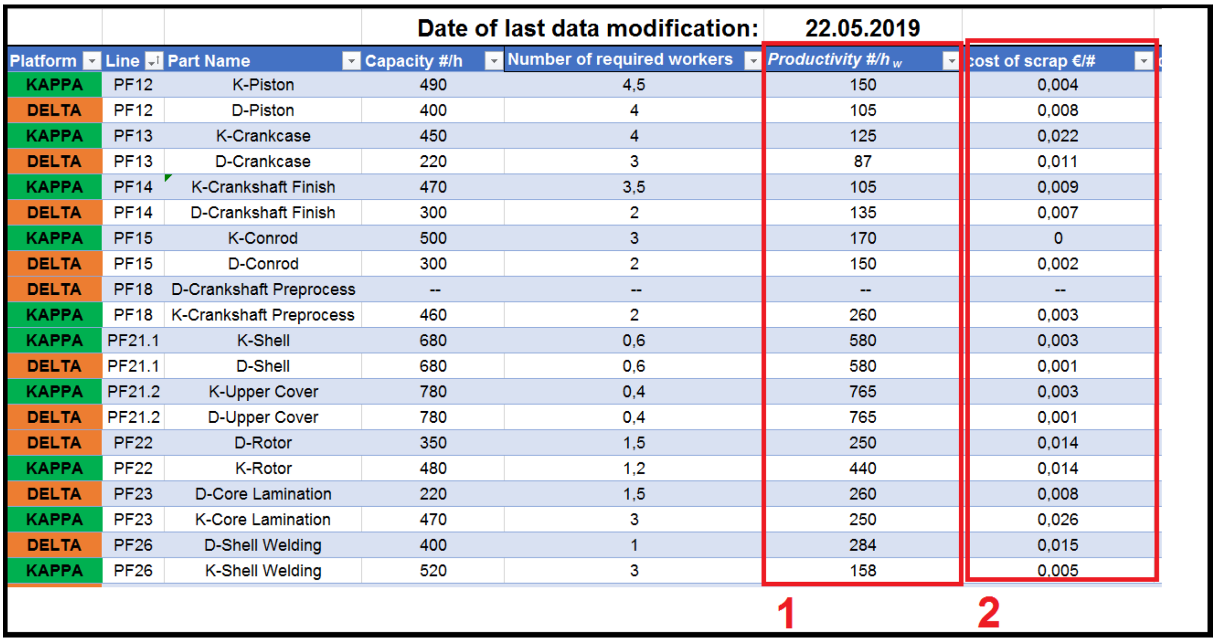
Beliebig Werte
Arbitrary Values

Cpk	X-Factor	
2	0,166666667	6σ
1,67	0,2	5σ
1,33	0,25	4σ
1	0,333333333	3σ

-1% COP =	0,25 €	0,25 €
Blue collar €/h	30,00 €	

Figure C.4: X-factor and COP to € conversion rate, source: Own Illustration

Point 1: Interface commands (the first button goes to the tolerance tables and the second to the alpha values table), point 2: X-factor (can be changed) point 3: Blue collar cost per hour, point 4: COP to € conversion rate (can also be changed; green is Kappa, orange is Delta).

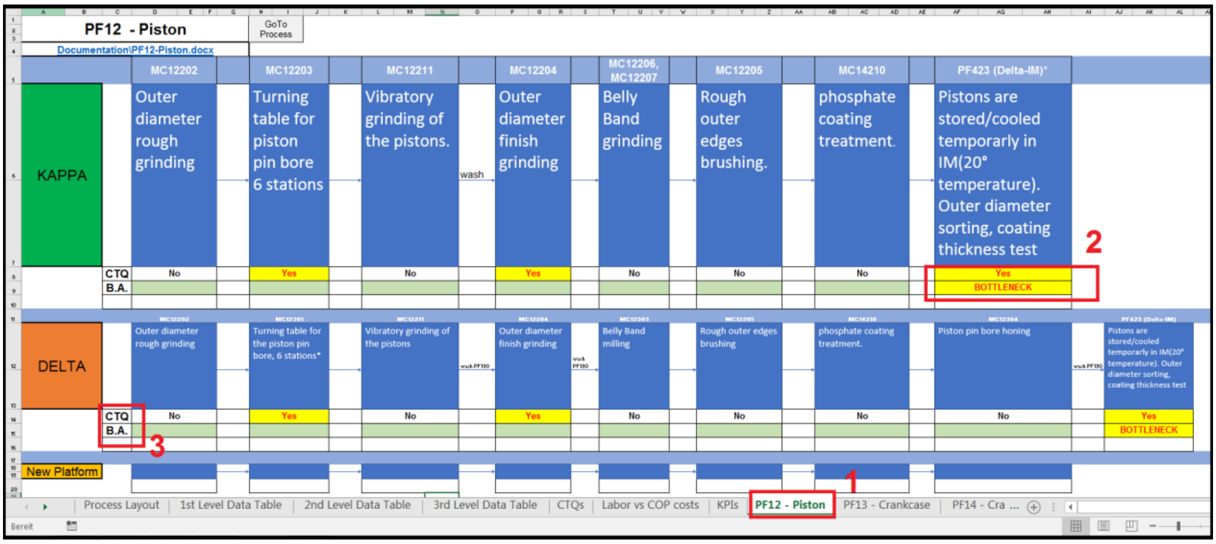


Date of last data modification: 22.05.2019

Platform	Line	Part Name	Capacity #/h	Number of required workers	*Productivity #/h w*	Cost of scrap €/#
KAPPA	PF12	K-Piston	490	4,5	150	0,004
DELTA	PF12	D-Piston	400	4	105	0,008
KAPPA	PF13	K-Crankcase	450	4	125	0,022
DELTA	PF13	D-Crankcase	220	3	87	0,011
KAPPA	PF14	K-Crankshaft Finish	470	3,5	105	0,009
DELTA	PF14	D-Crankshaft Finish	300	2	135	0,007
KAPPA	PF15	K-Conrod	500	3	170	0
DELTA	PF15	D-Conrod	300	2	150	0,002
DELTA	PF18	D-Crankshaft Preprocess	--	--	--	--
KAPPA	PF18	K-Crankshaft Preprocess	460	2	260	0,003
KAPPA	PF21.1	K-Shell	680	0,6	580	0,003
DELTA	PF21.1	D-Shell	680	0,6	580	0,001
KAPPA	PF21.2	K-Upper Cover	780	0,4	765	0,003
DELTA	PF21.2	D-Upper Cover	780	0,4	765	0,001
DELTA	PF22	D-Rotor	350	1,5	250	0,014
KAPPA	PF22	K-Rotor	480	1,2	440	0,014
DELTA	PF23	D-Core Lamination	220	1,5	260	0,008
KAPPA	PF23	K-Core Lamination	470	3	250	0,026
DELTA	PF26	D-Shell Welding	400	1	284	0,015
KAPPA	PF26	K-Shell Welding	520	3	158	0,005

Figure C.5: Labor and Scrap costs, source: Own illustration

This sheet is where the values for the labor and scrap costs are called from, the scrap costs are directly taken to the scrap costs per part, the labor costs per part are the productivities found in point 1 times the blue-collar cost in €/h which is found in the mother-sheet. This sheet is named: 2nd Level Data Table. The values are given by the production department.



PF12 - Piston

Documentation\PF12-Piston.docx

	MC12202	MC12203	MC12211	MC12204	MC12206, MC12207	MC12205	MC14210	PF423 (Delta-IM)*
KAPPA	Outer diameter rough grinding	Turning table for piston pin bore 6 stations	Vibratory grinding of the pistons.	Outer diameter finish grinding	Belly Band grinding	Rough outer edges brushing.	phosphate coating treatment.	Pistons are stored/cooled temporarly in IM(20° temperature). Outer diameter sorting, coating thickness test
CTQ	No	Yes	No	Yes	No	No	No	Yes
B.A.								BOTTLENECK

	MC12202	MC12301	MC12211	MC12204	MC12303	MC12205	MC14210	MC12304	PF423 (Delta-IM)
DELTA	Outer diameter rough grinding	Turning table for the piston pin bore, 6 stations*	Vibratory grinding of the pistons	Outer diameter finish grinding	Belly Band milling	Rough outer edges brushing	phosphate coating treatment.	Piston pin bore honing	Pistons are stored/cooled temporarly in IM(20° temperature). Outer diameter sorting, coating thickness test
CTQ	No	Yes	No	Yes	No	No	No	No	Yes
B.A.									BOTTLENECK

Figure C.6: Other sheets, source: Own illustration

Figure C.6: The rest of the Excel file contains graphical descriptions of the lines to identify bottlenecks and CTQ processes (point 2 and 3), it was created one sheet for each production line.