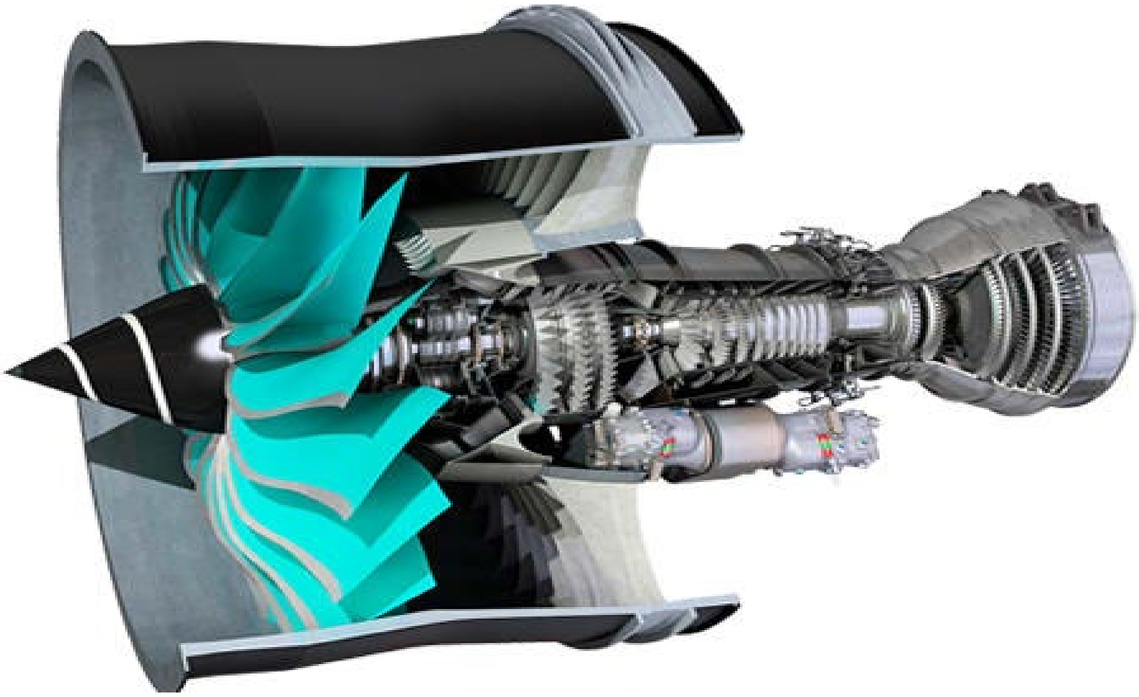

The potential cost savings of utilizing machine data

A study of the possibilities of using Real-Time SPC in production for potential cost reduction in a threading process

Master’s thesis in Quality & Operations Management

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Abbreviations

GKN Aerospace Sweden, Trollhättan (GAS)	The part of GKN group that has been studied.
Multi Task Cell (MTC)	Production unit that consist of multiple robots and NC machines.
Statistical Process Control (SPC)	Tool used to monitor variation in production, part of the measurement system.
Chief Manufacturing Engineer (CME)	Technical leader for Manufacturing Engineering and is responsible for the manufacturing.
SAP	The Enterprise Resource Management system used by GKN.
Zettabyte	The amount of data created annually, 10^{21} bytes.
QSYS	GAS own shared SPC system.
Internet of Things (IoT)	The creation of “smart” systems by connecting them to the Internet.
Cyber Physical Systems (CPS)	Systems with the ability to connect to others by digital I/O.
Operational Management System (OMS)	Descriptive multi-level organizational chart for operations and management at GAS.
Walk the Process (WtP)	Guidance in the manufacturing process for the examined engine part, to gain an understanding and increased knowledge for the process.
Industry 4.0 (I4.0)	The fourth industrial revolution.
AIM	Method to identify the root cause(s) of a formulated problem.
RPM	Rotations Per Minute.
Automated Tool Management System (ATMS)	The system used to automatically track and assign tools to the 5 MTCs’.

Abstract

Machines are becoming more and more complex and the tasks they are expected to complete are of similar complexity. If the machines are expected to take more complex jobs from humans, then they need to become more like humans. The machines need to be adaptable to their surroundings. They need to be able to “see” and adapt to what they “feel”. This intelligence is a cornerstone in the formation of Industry 4.0. The steps to get fully adaptive machines, or as it is called in this report, real-time statistical process control (real-time SPC), is not that far in the future.

Can tool breakage be predicted? Is it possible to detect tool wear? What are the potential cost savings if tool breakage and tool wear is predicted?

The findings of this thesis showed that only by measuring the torque within the spindle, and predicting the breakage and tool wear, significant payoffs can become a reality. The findings of the interviews along with the conducted analysis of the threading process, showed that predicting thread tap breakage and extending tool life is possible. If the tool life is extended by 25%, the cost savings for only this element is approximately 350 000 SEK annually. If all the thread tap breakages can be prevented and the life length of the tools are extended by 25%, the cost savings are instead approximately at least 600 000 SEK based on numbers from production year 2018. This is without considering the insights gained of the process and the contribution towards designing future systems for Industry 4.0. The value which emerges from taking small steps towards improving and expanding data collection are immense and any manufacturer that values their competitive edge should have started yesterday…

Keywords: threading, predictability, statistical process control, real-time SPC, machine adaptivity, machine learning, data value, cost savings, business opportunities, industry 4.0

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1. Introduction

"Some of the best theorizing comes after collecting data because then you become aware of another reality." – Robert J. Shiller, Winner of the Nobel Prize in Economics

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We are at the pinnacle of the next industrial revolution, commonly called Industry 4.0 (I4.0). A quick Google Scholar search for this buzzword yields 18300 results for this year alone (22/05-19). I4.0 is an immense subject and covers the migration from the current factory to the factory the future. I4.0 applies and combines new technological advancements to create the most competitive factory possible. The ability to create robust manufacturing processes that adapt to changing material characteristics is one of the main areas in I4.0 (Lasi, 2014). The development of sensors and implementation of cyber-physical components, i.e. components with the ability to connect to the internet, have granted manufacturers the ability to in real-time control and monitor processes. However, the systems capable of real-time control require substantial investments and a change in how organizations deal with data.

The ability to predict and monitor tool wear is also known as "*adaptive control*", at times referred to the use of fuzzy logic (Lin, 2005; Aliustaoglu, 2009). GKN Aerospace Trollhättan (GAS) commonly use the term "Real-time SPC (Statistical Process Control)" for this idea of adaptive control or fuzzy logic. Conventionally automated processes are controlled by strict paths and do not deviate from the plan. Tools are replaced after a set amount of usages regardless of the actual wear of the tool. The underlying idea behind fuzzy logic is to allow the automated process to control some of its process parameters, based on its sensor readings. The sensor data could be anything, from measured surface roughness to torque. By developing mathematical models of the manufacturing process and its parameters, it is possible to predict the process outcome. The automated machine can then apply the models and calculate, by itself, the best processing approach for speed, tool wear, and finished quality. Decreasing tool wear, preventing tool breakage, increasing quality, and maximizing tool usage. The focus of this report is predicting thread tap breakage and tool wear to maximize tool usage, and the cost savings corresponding to the predictability.

1.1 Background

In late 2018, resources were invested in trying to solve a particularly difficult problem with thread tap breakage on an engine part. The problem of the thread tap breakages was not able to be solved by conventional methods, so attempts were made with use of the Six Sigma methodology. However, the result of the Six Sigma work concluded that there was not enough data for effectively pinpointing the root cause. For this reason, GAS decided to try and invest in a new measurement system, which would monitor the robot servo sensors within the production cell in real-time. This would allow for real-time monitoring of the threading operations. This investment provided a new type of data, i.e. torque, spindle speed and positions in all axles. The type of data and amount of data have previously not been used in problem solving in the threading operations. In addition, this system enables GAS to use real-time SPC of the manufacturing process, this is a function already part of the installed measurement system. Therefore, when measurement system is referred to in the thesis it is understood that the real-time SPC is a function included in this.

The system was harder to implement than previously predicted, delaying the final launch. The system was not online until the start of this master thesis, when it was initially supposed to be online half a year before. The measurement data, (spindle speed, torque, position), is now being retrieved from the threading operations and corresponding drilling operations. It is however in its infancy and currently understanding what conclusions can be derived from the data is the main priority. Thus, it is of great interest for GAS to understand what value the data retrieved from the threading process carries. GAS translates *value* to profit, and as such, this *value* will be determined by investigating the monetary profits. This is done by comparing investment cost of the measurement system to the potential cost savings. Few want to invest in something that has no clear *value* to it, as it is instead only associated with non-product value adding costs by the managers, until the systems are shown to be profitable. This is due to it currently being unclear what the new measurement data can be used for and how it can benefit the organization. Therefore, a need exists to investigate how the data can help reduce costs in manufacturing and what is required to do so. The concerns expressed by GAS are as followed: will it be plausible to eliminate thread tap breakage with the installed system. Second, if the system can accurately predict thread tap breakage, then what does these threading defects currently cost GAS. Finally, do the potential savings from decreasing thread tap defects outweigh the cost of the system? A study of said measurement system has since been requested by management, with the goal to investigate the potential for tool wear predictability and process characteristics analysis.

1.2 Threading process

The threading process is carried out in the Multi Task Cell (MTC), MTC is a small production unit and comprised of five NC machines. The MTC are responsible for the final machining of a few engine parts. The measured processes which is carried out in the cell is drilling, broaching and threading in sequential order, as seen in Figure 1. Please note that multiple other machining processes are also conducted in the MTC, these are currently not measured by the system and are left out of this thesis. The process in focus in this thesis is the threading process. The process is similar to all holes on the part, first the hole is drilled, second a reamer is used for broaching, and finally a thread tap is used to create the thread.

The threading process is done in two different operations, at GAS called, operation 100 and operation 200. The difference in these two operations is that in operation 100 the rough work is done and in operation 200 it is more of a fine-tuning work. It is often in the operation 200 which the thread tap breakages occur, due to the process being more sensitive as thread taps with a smaller diameter are processed. This makes the thread taps in the operation 200 more sensitive to the forces and is therefore easier to break in this operation.

Figure 1- Showing the various operations MTC-cell carries out, in sequential order.

There are twelve different thread taps being used in the process of creating the threads on the studied engine part. These thread taps are of various size and the taps with a smaller diameter are usually those which are more common to break. An example of a broken thread tap is seen in Figure 2.

Figure 2- This thread tap broke in manufacturing during the course of the project.

1.2.1 Quality control for threads

All tolerances are checked several times after the threading process, and meticulously documented both on paper and digitally. However, if the thread tap breaks during processing the machine will not notice the break until after the scheduled holes are processed and the machine checks the tool length by optical sensors. If this is the case, the machine sends a warning message and stops, waiting for an operator to perform manual check and green light. Thread tap breakage can also be identified by sound, if an operator is within close vicinity of the MTC, a characteristic pop sound can be heard when the tap breaks. Occasionally the process will emit a distinct screeching noise when the tap is worn and is close to breaking. This is theorized to be because of cold welding of the working material on the tap, if lucky the adhered metal will fall off later. The experience level of the operator might determine if the operator will manually stop the process and change tap. From interviews, it was understood that newer operators would be more likely to stop and change the worn tap to a new one.

When tap breakage occurs, protocols need to be followed strictly. An initial report is filed out by the operator that requires a Chief Manufacturing Engineer (CME) to inspect and propose methods for removing the tap and check if the thread is compliant with the allowed tolerances. The part can then be redone and checked if compliant. The CME files a Q3 report that gets archived.

If the case is the accident causes lasting damage on the engine part, CME files a Q4 report. The Q4 is received by the quality department, depending on design right contracted by the customer and GAS the outcome is different. GAS must send a query to the customer for judgment and detailed repair plan. If GAS has design responsibility the Q4 is sent to the design and material department to evaluate and calculate the right repair plan that would ensure flight safety, otherwise it is the customer's responsibility to develop a repair plan. This is a long process and when completed needs to be sent back to the customer for approval. After customer approval, repair can commence with following additional quality checks. The process for this will be elaborated on further in chapter 5. The process described in chapter 5 was created based on interviews and the Operational Management System (OMS) at GAS.

1.2.2 Data handling for problem solving

When recurring tool problems occur, GAS investigates the root causes by the help of highly experienced internal personnel with long history of manufacturing and tool technology. In addition to this, a test facility, *Innovatum*, can be used to test tools and materials. The process characteristics are approximated at *Innovatum* and later translated to live production in the main facilities. However, limitation of live production makes it hard for testing in actual production therefore this makes *Innovatum* the favourable option. There are limitations to consider as there are several differences between the test *Innovatum* and the main manufacturing facility, e.g. different machines and material. These differences result in unpredictable parameters, which later hinders solutions to be effectively translated into live production.

The type of data available for problem solving differs between processes. Higher amount of data is usually available in complex automated welding processes, or newer machines with built-in system. Data for drawing and flight safety standard compliance are meticulously followed and GAS takes great pride in the quality they can offer customers (Axelsson, 2017).

1.2.3 The selling point of the new measurement system

The new measurement system was advertised by the seller to be highly useful for detecting tool wear and does not suffer from the limitations of testing facilities, as previously discussed. The following key points were claimed by the seller and will form the basis for the main report:

- Tap breakage can be seen easily from the measurement data, as well as the wear of the tap.
- The measurement system can calculate and apply control limits, if proper control limits are set then the process will be able to stop before tool failure.
- The data is a powerful tool for understanding the physical process and will allow the machines to adapt to supplier variation in the tool and casting goods quality, contributing to creating a robust manufacturing process.

These claims and the idea of further developing real-time SPC, lead GAS to invest in this system. From the perspective of GAS this will be the claims that need to be investigated and if proven true what is the Return of Investment (ROI) for this- and future systems.

1.3 Purpose

The purpose of this thesis is to determine whether the new real-time SPC system can be used to predict thread tap breakage and tool wear, and the current cost of thread tap breakage and low tool life, and how much these costs can be lowered by implementing a real-time SPC system. The potential cost savings will be compared with the total implementation cost of the system to calculate the profitability.

The research will focus on the threading process and complementary measurement system, but the idea of real-time SPC can be expanded to other machining processes. This generalisability will be emphasized upon in chapter 6.

1.3.1 Research questions

The purpose of the thesis is broken down into three research questions in attempt to divide the work into different research areas. The relationship between the research questions' (RQs) is seen in Figure 3. The first RQ, investigates if thread tap breakage and tool wear can be predicted. The second RQ, investigates and quantifies the current cost elements due to thread tap breakages and tool wear. The third RQ, aims to identify and quantify the costs elements for the implementation and data storage of the new measurement system. The final question, RQ4 is combining findings from the first, second and third question. RQ1 investigates if thread tap breakage and tool wear can be predicted, RQ2 investigates the current costs due to short tool life and thread tap breakages and RQ3 investigates the total cost of the measurement system. RQ4 is therefore based on the result from RQ1, shown that thread tap breakage and tool wear can be predicted, what is the potential savings of avoiding thread tap breakages and increasing tool wear in comparison to the cost of the system?
RQ4 therefore aims to understand and visualize the potential cost savings through a cost model.

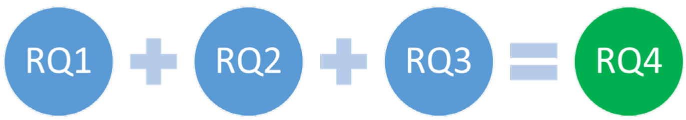

Figure 3- The foundation is laid in RQ1 and governed how the other RQs' were approached.

RQ1: Can thread tap breakage and tool wear be predicted?

The key selling point of real-time SPC is the possibility to predict breakage and avoid the use of worn tools. The question is, if this is possible in threading operations since it is perceived to be a highly sensitive process. The purpose of this question is to understand if it is possible to predict tool breakage and tool wear.

RQ2: What are the current costs for thread tap breakage and tool life at GAS?

If the threading problems can be reduced, then savings would be made in decreased extra labour. These savings need to be calculated to give a clear value of the measurement system. How much does thread tap breakage and short tool life currently cost GAS, in form of quality issues, increased maintenance and unnecessary tool change?

RQ3: What was the cost for implementing the real-time SPC system?

Management is often reluctant to invest resources in measurement systems that are not needed for customer compliance, i.e. ensure tolerances and that flight regulations are followed. The aerospace industry brings substantial tolerance controls, and the tolerances are measured in the hundredths of a millimetre. The current measurement systems capability of accurately measuring the parts are expensive as is and investing more without clear payoff is often seen as unnecessary and something which is avoided. The question remains how expensive the system was and what was needed from the organizations manufacturing and IT systems to successfully implement the measurement system.

RQ4: Do the benefits of a real-time SPC system for threading outweigh the cost of implementation and handling?

This is the final question for the thesis. In this step, the answer is based on the knowledge gained from RQ2 and RQ3. The answer of this question is based on a model where different cost and cost savings are shown and approximated. The model will consider the total implementation cost for the measurement system and compare it with the cost savings the system can provide – avoiding thread tap breakages and prolonging tool life. The costs which are included in the model are the costs found significant for the result, based on the empirical findings. The costs can range from, e.g. rework, and scrap, to implementation costs. RQ2 will contribute with the cost savings if thread tap breakage and tool wear can be predicted and RQ3 will for this question contribute knowledge regarding the cost and investments necessary for the measurement system and for handling the big data.

1.4 Project Scope

This project scope will be limited and focused to analysing one engine part at the GKN Aerospace plant in Trollhättan (GAS). This part is called engine part in this thesis. This thesis is based on solely one manufacturing process, the threading process. It is currently the only production process where the measurement system is installed and live reading of machine data is possible. This project will be limited to studying costs related to one engine part since this is the only product currently processed in the MTC cell. This project will derive a model for estimating the different costs due to not using real-time SPC in production. However, it will not provide any implementation or in-depth action plan for how GAS should go further towards realizing a reduction of these costs. This report will instead stand as an example of what is possible to accomplish with the implemented real-time SPC system, by showing the predictability of thread tap breakage and tool wear and which cost savings are possible with the usage of a real-time SPC system.

1.5 Thesis Disposition

The report is structured to first, introduce and describe the threading process and the problems experienced with the process, as well as the measurement system. This leads to the formulation of the purpose for the thesis. The research strategy which is used, is based on the purpose of the thesis. Depending on the purpose of the thesis different methodologies can be used. The methodology builds and explains the approach that was used to structure the literature review and empirical research for collection of data.

The empirical findings consist of two main parts. First the threading study is presented. The threading study will answer RQ1 by proving that the threading process can be effectively controlled by the new measurement system and be used for predicting tool breakage and tool wear. The threading study will form the basis for the second and final part of the empirical findings, the cost model by showing that it is possible to avoid thread tap breakages and to prolong tool life. Chapter 5 will list and analyse relevant costs and cost savings. The implementation cost for the system is studied along with the cost savings for avoiding thread tap breakage and for prolonging tool life. This will build up a cost model that describes the value of collecting data from measurement systems.

These findings are later analysed to understand if the purpose and research question can be answered based on the collected data. This analysis leads to a result and final answers to the research questions. If the thesis is divided into research areas, it can be said that the literature review and empirical findings are used for clarification and identification of the problem. The analysis is used to determine if the purpose can be answered, and the research questions are answered in the result or namely conclusions and recommendations based on the analysis of the findings. The disposition of the thesis can be seen in Figure 4.

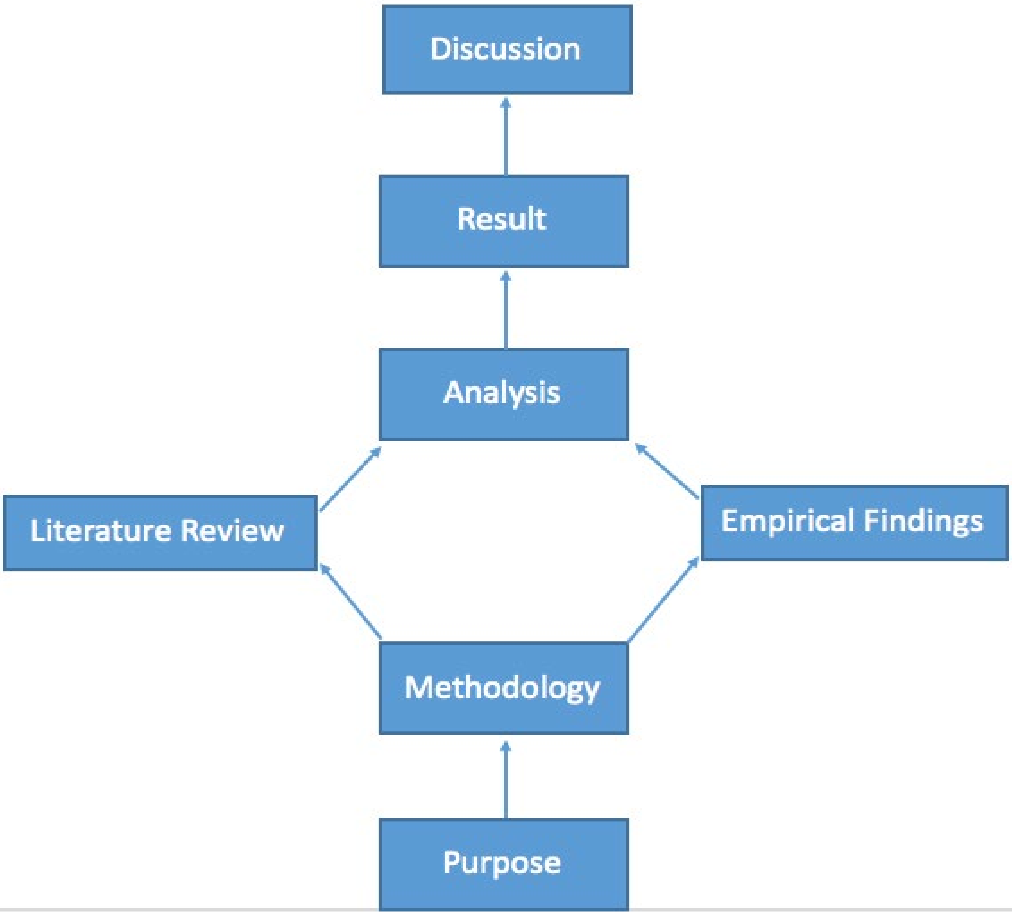

Figure 4- Logical structure of the report.

2. Methodology

This chapter describes how the study was performed. It describes the method used for data collection and for analysis of data. The research process is first described along with the research purpose, approach and strategy. Secondly, the various data collection sources are described. The chapter finally discusses validity, reliability and ethics of the thesis.

2.1 Research Process

The data was collected through interviews, literature review and internal documents. The connection between the threading process, cost model and various data collections methods can be seen in Figure 5.

The first step was to perform a Walk-the-Process (WtP) of the manufacturing for the studied engine part. This was performed to gain increased knowledge for the threading process. The second step was to perform a workshop – Affinity-Interrelationship Method (AIM). Findings from the workshop were used to support the development of an interview guide. Secondly, data was collected from literature and internal interviews to support the study on the threading process, to further increase the knowledge for the process. However, data from literature and interviews were used additionally to identify possibilities of prolonging tool life and predicting thread tap breakage. This was for supporting analysis of the study on the threading process. It was in the threading process analysed if thread tap breakages can be prevented and tool life can be prolonged by predictability. This was done by analysing the measurement data in two variables, torque and rotations per minute (rpm) in MATLAB. The purpose of analysing the measurement data in threading process was to answer the first research question, if thread tap breakage and tool wear can be predicted. The other three questions are related to costs, cost reductions and lastly development of a cost model. In research question one, it is investigated if thread tap breakage and tool wear can be predicted. The purpose of the other three research questions is proven that thread tap breakage and tool wear can be predicted, what are the potential cost savings and potential cost categories which can be reduced in the threading process as a result of this predictability. The cost model is therefore based on the result from the threading process, if predictability is possible. If thread tap breakages can be prevented and life length of tools can be prolonged, potential cost savings emerge due to avoiding thread tap breakage and increasing the life length of the tools.

The cost calculations are carried out in chapter 5. In the cost model, the potential cost savings are compared to the investment and handling cost of the system. The investigated cost elements are based on data collected from interviews, internal documents and assumptions. Interviews were held to understand which cost elements were associated with the implementation and handling of the measurement system. Internal documents were used to understand the internal processes and the process of handling thread tap breakages. Interviews were then further used to expand on the internal documents, to investigate the various times for handling a thread tap breakage and to understand the costs associated with the handling. Further, interviews were used to quantify the identified cost elements by having interviews with various departments, varying from quality department to finance. The costs which could not be retrieved from interviews or internal documents were made on assumptions. The assumptions which were done is motivated in chapter 5.1.1. The purpose of the cost model was to answer RQ2, RQ3 and RQ4.

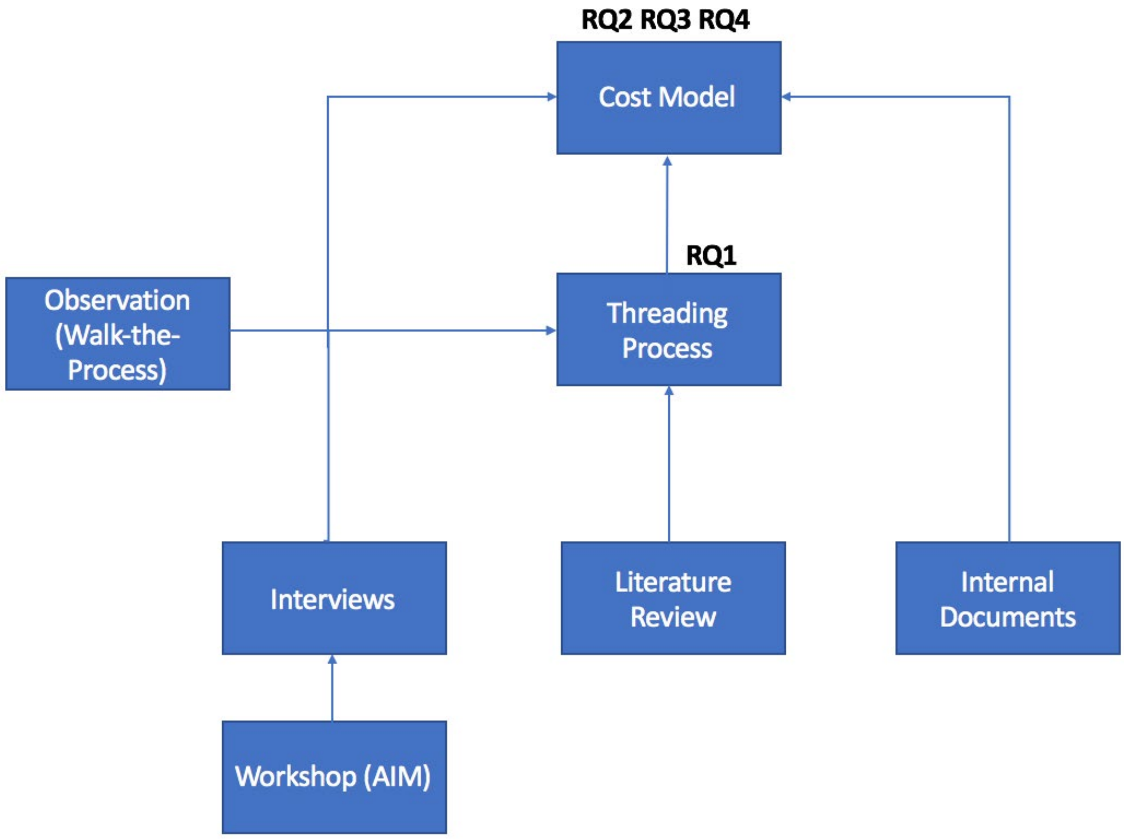

Figure 5- The following structure of methods were used to gain the necessary results for the analysis.

2.2 Research Purpose

To learn and understand a process which is previously unknown to the researchers, Sanders et al. (2007) recommends exploratory studies due to the lack of knowledge for the process. The research areas of the thesis determine the research purpose which should be used to conduct the research. The purpose of this thesis is to investigate if thread tap breakages can be predicted, and if so, which costs can potentially be reduced. This requires a two-fold research purpose as the approach differs for the two research areas. The first phase is the exploratory phase, when understanding and learning the process to see if thread tap breakages can be predicted and life length of tools prolonged. The next phase is the descriptive phase, where different costs are recognized, and a profitability analysis of the measurement system is conducted. The knowledge from the exploratory phase goes into the descriptive phase of the thesis, to answer the research questions. This is motivated by Saunders (2009) who states that the collected data would need to paint a clear picture of the process and the associated costs. The research would therefore take its final form as a descriptive research (Robson, 2002).

2.3 Research Approach

This thesis followed two different approaches as seen in the thesis disposition. It contains two different approaches as the first research area was to see if thread tap breakage can be predicted and second is to derive a model to show upon potential cost savings using real-time SPC in the threading process. According to Davidsson (2003) an inductive approach is used together with a qualitative method, while a deductive approach is used with a quantitative method. If both approaches are combined, inductive and deductive, abductive approach is said to be achieved. In practice this approach means that a combination of theories was studied in parallel with empirical data and hypothesis tests. Adopting abduction for this thesis provided the opportunity to use both induction and deduction in a complementary way. As stated by Dubois (2002) it is wise to apply both approaches in research, since the process is seldom linear. Saunders (2009) explains that using a mixed method research enables the usage of both qualitative and quantitative analysis and techniques, which is the research approach found suitable for this study. For investigating the threading process, the approach was testing of theories based on a hypothesis. Inductive approach was used for the cost model focusing on the development of a theory based on the acquisition of the data (Saunders, 2009). For the cost calculations, quantitative data was obtained from semi-structured interviews and internal documents at GAS. The threading study was instead initially based on semi-structured interviews and observations (WtP) in the exploratory phase of the case study but also analyse of numerical data later, which was analysed to verify the hypothesis, hence a combination of qualitative and quantitative research. Quantitative research is the process of transferring information into numbers and amounts and then performing statistical analysis (Creswell, 2009). In quantitative methods, words and researcher's interpretation and perception of them is instead in focus (Abrahamsson, 2000). The aim of an exploratory approach is to understand the process and its characteristics of its nature. The study also aims at the applicability of the knowledge gained and it is this phase which would mark the end of the analysis on the threading process.

2.4 Research Strategy

The research strategy in this study is based on a case study as the aim of the thesis was to investigate a specific process, the threading process, and to identify if thread tap breakage and tool wear can be predicted. Predicting and visualizing tool wear have no value unless it can be translated to short- and long-term monetary gain, hence it was investigated if potential cost reduction can be carried out in the threading process. The case study provides the ability to review a specific process and extrapolate to describe the larger surrounding context (Ejvegård, 2009). The defining feature of conducting a case study research is its focus on *how* and *why* questions (Myers, 2009). This is the reason for case studies functioning as a suitable choice for performing exploratory studies (Mouton, 2001; Saunders, 2009). Case studies support the testing of theoretical framework (Eisenhardt, 1989). Case study research has a significant role in extending the knowledge of a subject (Merriam, 2019). The findings of the thesis are centred on testing the hypothesis that the real-time SPC system can be used to predict thread tap breakage and tool wear and the purpose of the case study can therefore be the testing of a theory (Bryman & Bell, 2011). The strength of formulating case study as the research strategy is the flexibility and adaptability which allows for multiple data collections to investigate the formulated research problem (Cavaye, 1996). Due to the nature of the case study and the development of a cost model the report is based on research around quantitative data and usage of qualitative data for strengthening the quantitative data through the process of triangulation (Bogdan, 2006). The result of the threading study will form the basis for the cost model, development of the cost model will need both the support from quantitative and qualitative data. The qualitative and quantitative data is extracted through interviews, seminars and internal documents at GAS. The findings will then be supported by triangulation process between both qualitative and quantitative data.

2.5 Data collection

The data collection consisted of both primary and secondary data. The quantitative and qualitative data set the foundation and was extracted through literature review, internal semi-structured interviews, internal documents, observations and through data from the installed measurement system. The qualitative data collected in the process was used to support and strengthen the findings derived from quantitative data.

2.5.1 Literature review

The conducted literature review is aligned to the purpose mentioned by Bryman & Bell (2011) the purpose with conducting literature study is to identify which knowledge is already known for the researched subject. The literature study was additionally used as an aid to guide the selection of various methods which could be used to help answer the research questions (Bryman & Bell, 2011). The literature review was done in accordance with Gillham (2000) and Andersen (1994) who emphasizes that the knowledge for a topic should first be researched on a broad level, to gain general knowledge regarding the subject and afterwards the research should be conducted on a narrow level to gain expertise knowledge regarding the studied topic. Literature review was carried out continuously parallel during all the different phases in the study after the pre-study. The information which was requested from the literature was everything from information regarding how machine data is used to control production processes, which costs and savings are associated with machine data to literature around the concept of real-time SPC system to see how it can be applied to various production processes.

The literature used in the literature review was mainly based on books and scientific articles. The relevant literature was found by using the Chalmers library electronic database and Google Scholar as a search engine by searching for keywords. The literature which was found was additionally expended by the process called snowball-sampling or chain-referral sampling which implies that one study subject leads to another by cross-references (Bryman & Bell, 2011).

Additionally, the supervisor at GAS continuously recommended several scientific articles and presentations which could be of interest for the study. Keywords which were searched for: *Artificial intelligence, Big data, Machine learning, Industry 4.0, Real-Time SPC, Data management, Data value, Machine data in production, Production control, Adaptive process control, Knowledge from data.*

The search results which were generated, were later sorted based on the number of citations and selection was done based on their relevance for the study.

2.5.2 Observations (WtP)

The absolutely first phase of the project was to get an understanding for the threading process. This was done through an observation or more precisely, Walk-the-Process (WtP). The advantage of observations in comparison to interviews is that observation contribute to a more objective point of view on the process (Bryman & Bell, 2011). Liker (2008) further elaborates on the advantages of observations as he means simply collecting data is not enough. Observations help understand how machines and operators interact with each other, this can only be managed through observations and cannot be collected from e.g. interviews.

The observation was conducted by having a WtP for the manufacturing around the different phases for the engine part. Phases in focus were Operation 100 and 200 which is the two operations where the threading process is being carried out as described in chapter 1. In these two operations, the MTC cell was studied in detail to gain knowledge for the threading operation which is one of many operations it carries out.

2.5.3 The Affinity- Interrelationship Method (AIM)

AIM is a step by step approach for understanding a complex problem. The AIM is conducted as a workshop and allows for groups of people to analyse and dissect a problem, breaking it down to its roots and show how the parts interact (Alänge, 2009). Prior to performing the interviews, an AIM workshop was conducted at GAS involving a group of people that have influence and are associated with the handling of machine data in production. When performing the AIM before the interviews, the problem areas will be identified, allowing the interview guide to take these into consideration to have more relevant questions included in the interview guide. The participants for the AIM have been chosen due to them being of great interest for investigating which costs are taken into consideration when investing in measurement systems. This workshop was conducted for understanding which requirements the measurement system needs to conform to. This would help answering the third research question, RQ3, to identify the cost categories when implementing measurement system. The findings from the AIM were additionally used in the discussion of the thesis, to help understand the mind-set for investing in measurement systems at GAS. The findings of the workshop can be found in Appendix A. The question which was investigated at the workshop:

How do we future proof our measurement systems to meet the challenges of tomorrow (Industry 4.0)?

2.5.4 Interviews

Internal interviews were carried out at GAS to acquire information for the threading process but also regarding the handling of thread tap breakages, costs and to support findings of internal documentation. The interview guide with the posed questions can be found in Appendix B.

Gill (2008) motivates that there are three different structures of interviews, structured, unstructured and semi structured. Gillham (2000) motivates that semi-structured interviews is the most important way of structuring the interview guide in a case-study. This is the reason why this interview guide was based on a semi-structured format, as the research strategy is defined by a case study approach. However, another reason for choosing the semi-structured format is due to the nature of it. It contains several predetermined questions, it gives flexibility, allows for more open answers and allows the interviewee provide additional information which was not thought of before the interview (Gill, 2008). To acquire information regarding the handling of thread tap breakage and to support internal documentation, interviews were held internally at GAS. The interviews were of semi-structured format and held in non-standardize format in accordance to Saunders (2009).

The interviews were performed by a group of two persons, this is done in accordance with Bryman & Bell (2011) who emphasizes the benefits of having two researchers as one is leading the interview, asking follow-up questions and determining the direction of the interview, while the second person is taking notes and focusing on analysing the answers. All the interviews were conducted in Swedish language as this was the primary language of all the interviewees. However, the interviews were not recorded and transcribed afterwards. The interviews were only noted during the interviews. The choice of not recording and transcribing went against the comely recommended approach (Saunders, 2009; Ejvegård, 2009; Davidsson, 2003) It was deemed that recording and transcribing the interviews would take time from analysing the data from the measurement system. The data gained from the interviews would be mostly approximations of time and cost that would later be weighed against internal documentation. Such, this approach was deemed not to jeopardize the validity of the thesis. Another reason for not recording the interviews was to try and keep the interviews informal and let the interviewee talk freely during the sessions, instead notes were taken during the session (Bryman & Bell, 2011. Twelve interviews were held at GAS, however participation was done in several other informal meetings during the project to gain additional insights for the threading process. The introduction of the interviews started with a description of the project and what was expected from the interviewee. The choice of the interviewee was based on the data needed and identification of who could know was a substantial part of the project. The dedicated time towards the interviews were approximately 45 minutes to one hour and if there were additional questions which could not be answered now, the answer was followed up afterwards. If the interviewee could not answer the question as it was not his or her field, name of other interviewee which could assist us with a specific question was proposed. The interviews were conducted face to face as there are several advantages according to Denscombe (2009), it is more flexible, and it allows for taking the interviewee's opinions and attitudes into consideration.

2.5.5 Analysis of threading process

The purpose of conducting a study on the threading process, was to investigate RQ1, if thread tap breakage and tool wear can be predicted, given the former *if* it can be predicted, what cost savings can be done. The concept of the threading study is that by understanding the machine characteristics and trying to link this with the measurement data, process characteristics can be analysed. The aim is to show basic correlations between factors in the MTC based on the measurement data. A model will be created based on the correlations found in the data to predict when thread tap breakage has a high chance to occur. The model's ability to predict tap breakage will be one of the metrics for assessing the cost reduction possible.

It will be shown how data from the measurement system can be used to gain greater insight in the threading operations, and how it could be used in real-time SPC to potentially reduce the costs due to thread tap breakages and early change of tools. The data which was analysed from the measurement system was done in MATLAB. This was done in MATLAB by writing scripts to extract knowledge by identifying trends and patterns from the big amount of data which was handled. The key step of the process for this study was the data mining, to identify trends and correlations in the data sets (Fayyad, 1996).

The idea of self-regulating and adaptive machine processing is not new. The outcome of a machine process is directly linked to the material properties and the machine characteristics (Dimla, 2000). Hence, the machine should be able to apply a model to adapt itself to changing characteristics and compensate for these changes in real-time, so the outcome always remains within the allowed tolerances (Burke, 1989). See example of such SPC system in Figure 6 for the process subtractive manufacturing, as developed by Takenori & Takashi (2008). It is however of great interest to investigate how this can be done in real-time through real-time SPC.

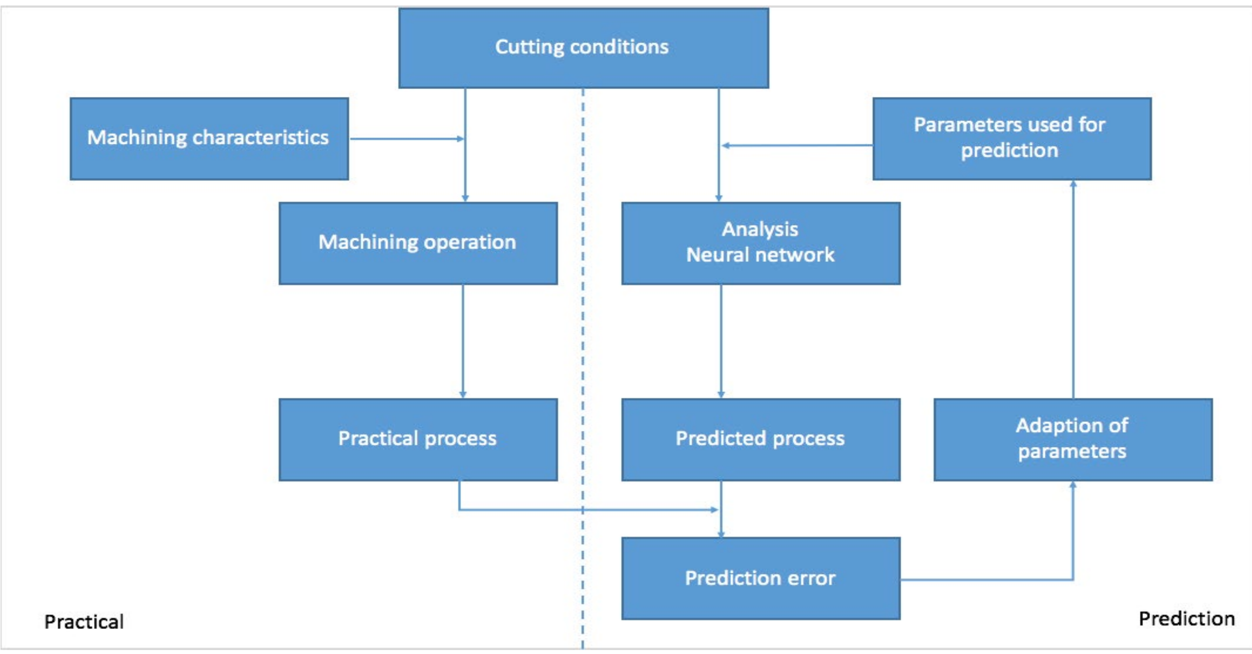

Figure 6 - Example of machine correcting itself in subtractive manufacturing adapted from Takenori & Takashi (2008)

The focus will be on understanding the use of the data and how real-time SPC can potentially reduce costs for identified cost categories. The threading operation is a form of subtractive manufacturing removing material from the object. Several processes fall under this category and the principles are the same, i.e. drilling, milling etc. If one process can be understood and predicted that would open opportunities to understand others as well (Dimla, 2000). The mobility to apply this to additional processes opens a world of possibilities. The threading study was conducted by employing the Knowledge Discovery in Database (KDD) approach by Fayyad (1996), dividing the process into five different phases as specified in the approach that is further explained in chapter 3.3.

- Selection. Identifying data sets of interest and discarding data deemed unnecessary for the task at hand.
- Pre-processing. Analysing and handling the data as well as handling the noise and missing values.
- Transformation. Transforming the data sets the right formats necessary for further processing.
- Data Mining. Deploy statistical tools for identifying trends and correlations in the data sets.
- Interpretation/Evaluation. Interpret the detected patterns and evaluate if it is plausible to make any conclusions. If necessary, revert to appropriate previous stage and change the process or include new raw data.

2.5.6 Internal documentation

The internal documents made it possible to gain additional knowledge for the handling of thread tap breakages, to investigate which costs are frequent in the production processes and to find the quantity of these costs. However, it was also used during the analysis of the threading process, to find additional information for validating and verifying findings from the measurement system. Internal documentation is used such as the internal quality discrepancy system by investigating the Q3- Q4s which are defined as two different levels of quality defects. This will be done in the second research question, to identify the current costs at GAS due to thread tap breakages and tool wear. The databases of interest were the SPC system QSYS, business system SAP, the measurement system which logs the machine data in the MTC, Operational Management System (OMS), for identifying additional data related to the MTC as the systems are working complementary to each other. Data which could not be found in the measurement system of the MTC cell was found in the auxiliary Automated Tool Management System (ATMS). The data which was retrieved from ATMS was used in the threading study to track a specific tool, to identify how many operations it had run before and if it had been in other machines. This was done in the progress of monitoring the tool wear to identify the health of the tool. Operational Management System, (OMS), was used for understanding the process of handling thread tap breakage. Through OMS, the activities which are conducted when thread tap breakages occur and which departments are involved in the process of resolving the quality discrepancy could therefore be found.

2.6 Research Quality

The trustworthiness is important to consider for any thesis. Can the result of the thesis be trusted and why should it be trusted?

Bryman & Bell (2011) recommends the trustworthiness to be evaluated out of four different criteria: *credibility, transferability, dependability and confirmability*. Credibility in the project was evaluated through continuously presenting the progress of the data collection along with the threading study during weekly meetings at GAS. If something was unclear during an interview, a clarification was required from the interviewee. Transferability refers to the external validity of the thesis. This requires a description of the environment and the assumptions during the project to understand the foundations which the thesis is carried out on. To further strengthen the transferability the methods which were chosen for conducting the thesis was followed strictly and the prerequisites and scope for the project is defined clearly. Addition to this, documentation was done continuously during the project. By having documented all the steps clearly in the project from beginning to end it ensured that the project had been done in an appropriate way, which is done to fulfil the dependability. This was strengthened additionally in the cost model, where the assumptions for some costs was done and motivated. The last step to ensure trustworthiness is confirmability. This step is to ensure that the researchers do not have any personal values in the research. This was accomplished by continuously during the project discussion our ideas and thoughts with other representatives at GAS before jumping to any conclusions.

To confirm the trustworthiness of the thesis additionally, triangulation was done as much as possible in the project. This was to verify the result from various sources. The threading study, literature review and additional findings from data collection were triangulated as seen in Figure 7 to increase the research quality of the thesis. This is done to derive the same information from various sources, to strengthen the information. Triangulation was often done between literature, interviews and the threading study. This was mainly done to strengthen and support the analysis from the conducted threading study.

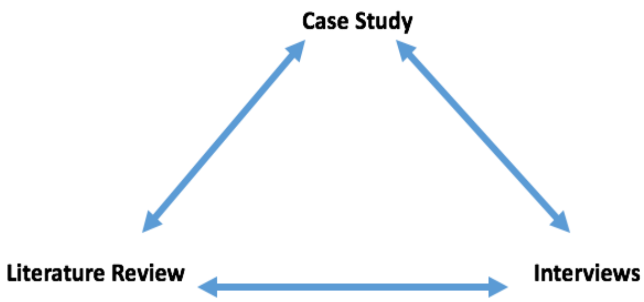

Figure 7 - By showing the same result from different sources the results increase in validity.

2.6.1 Reliability and Validity

Reliability describes the ability for future researchers to reach the same conclusions by using the same data. In accordance with the literature, Yin (2009) and Bryman & Bell (2011) great importance was put in ensuring the reliability of the observation, data, and logical steps leading to the conclusions of this thesis.

The same is true when it comes to the validity of the research methods the importance of following and questioning the methods of which data is generated cannot be understated. Bryman & Bell (2011) discussed this in detail for qualitative research and the four areas they defined: Internal & External reliability and Internal external validity has been the base from which methods have been assessed. (Alänge S. &., 2014) is a further inspiration with his also four-part model:

- Measurement validity – does the measure reflect the concept that it's supposed to demonstrate
- Internal validity – does the casual relationship hold water
- External validity – can result be generalized beyond the specific research context
- Ecological validity – are the findings applicable to people's' everyday natural social settings

2.6.2 Ethics

There are four different areas which needs to be taken into consideration when performing research, this due to ethical issues becoming an important factor to consider. The four different areas of research have been defined as: harm to participant, lack of informed consent, invasion of privacy and deception (Bryman & Bell, 2011). There is a risk the participants become harmed in the interviews, therefore the transcripts of the held interviews will be sent to the participant upon request, for them to make sure it is fully anonymous and that the information has not been misinterpreted by any of the involved parties. The consent is also important to be clarified before the interviews. This will be managed by presenting the purpose and how the data will be used for the study. The privacy and deception will be promised to both GAS as an organization and the involved persons. The interviewed individuals will have the possibility to avoid answering an asked question and the questions and formalities will be made clear before the interviews to the interviewee. Due to invasion of privacy and deception, the term *engine part* is used in the text to describe the studied detail, this is to not reveal any product specific information as it can harm GAS. Another applicability of this is that in the cost model several assumptions were made for costs which were considered sensitive. Additionally, figures containing sensitive information were blurred out.

3. Theoretical framework

This chapter will present the theoretical foundation that lays the basis for the analysis of data, cost model and final discussion. This chapter will additionally further motivate and explain the terms used later and previously in the report.

3.1 Statistical Process Control (SPC)

GAS uses the term *real-time SPC* to describe the new, more commonly referred to, adaptive control. Statistical Process Control (SPC) is an old concept and the *real-time* approach has emerged because of new technologies. Real-time SPC is traditional SPC applied in real-time, enabling the system to make changes in real time. However, the underlying idea of statistically calculating the process capability, and differentiate normal variation to malicious variation to in short time apply corrective measure is the cornerstone of both techniques. The ideas and tools of SPC were used to analyse the measurement data of the new measurement system in Chapter 4. The main purpose of SPC is to prevent defects by monitoring the process while parts are employed, instead of detecting defects after the process is finished (MacGregor, 1995; Montgomery, 2013). SPC is a powerful collection of problem-solving tools useful in achieving process stability and improving capability through the reduction of variability (MacGregor, 1995). An important tool for working with real-time SPC is the control chart and traditionally the control chart by Shewhart (Montgomery, 2013). Perhaps the most important message of SPC is as quality continues to improve, the cost of producing the product will decrease. By using SPC it is therefore possible to reduce scrap, improve overall quality and improve productivity (Stamatis, 2002). SPC is used for monitoring the behaviour of the process. Therefore, some people refer to SPC as the ”voice of the process” (Montgomery, 2013).

Reduction of variability plays an important role in improving process performance in all types of industries. SPC is an effective tool to work towards a reduction of variability and increasing robustness. However, SPC is only applied in a situation where it is assumed that it is possible to bring the process into a state of statistical control. SPC is an effective tool for reduction of variability through the ability of the control chart to detect assignable causes. When the causes are detected and controlled, process variability is reduced, and process performance is improved. ”statistical control” means that only stable random variation around the process target is observed. A process that is operating with only chance causes of variation present is said to be in statistical control. In other words, the chance causes are said to be an inherent part of the process (Montgomery, 2013). Processes do not naturally operate in an in-control state, and the use of control charts is an important step that must be taken early in an SPC program to eliminate assignable causes, reduce process variability and stabilize process performance (Montgomery, 2013). To improve quality and productivity, we must begin to manage with facts and data and not simply rely on judgment (Bergman & Klefsjö, 2011). Control chart is an important part of this change in management approach.

3.1.1 Setting control and warning limits

The control chart displays a quality characteristic that has been measured versus the number of samples or time. The control chart contains a centre line which represents the mean value of the measured quality characteristic. Two other lines are visible in the chart, Upper Control Limit (UCL) and Lower Control Limit (LCL). This can be visualized in Figure 10 which displays a typical control chart, where LCL, UCL, center line and data points that violate the set limits are outlined. The UCL and LCL are commonly assigned 3 standard deviations away from the process mean (Montgomery, 2013). If a point is found outside of these limits, a search for an assignable cause if made and corrective action is taken if necessary. Therefore, these limits are usually called action limits. If the upper and lower control limits are set from a distance of three standard deviations away from the process mean, then the probability of generating an incorrect out-of-control signal or false alarm is in 27 out of 10,000 point on a stable process (ibid.). Montgomery (2013) states that no process is truly stable and if the mean shifts +/- 1.5 from the target value the error estimation is instead 688 errors on 10 000 points. However, process performance is not predictable unless the process is found to be stable.

There are other limits, warning limits, Upper Warning Limit (UWL) and Lower Warning Limit (LWL). The warning limits are usually assigned 2 standard deviations apart from the process mean (Montgomery, 2013). The warning limits are used as ”soft limits” which are used when a point falls between the warning limits and the control limits. This can tell the operator that something is going wrong before it eventually falls out of the control limits. Depending on the sample size and the frequency of samples the control chart will have a different design and function as seen in Figure 8. In general, larger samples will make it easier to detect small shifts in the process (ibid.). When choosing the size sample, it must be compatible with the size of the shift, depending on the size of the shift it puts a different requirement on the sampling (Montgomery, 2013). If the process shift is relatively large, then smaller sample size is preferred. The sample points are usually connected with straight lines to visualize how the points are evolving over time. Analysing points within the chart is done by identifying patterns and applying rules, these rules will be discussed later in chapter 3.2.2.

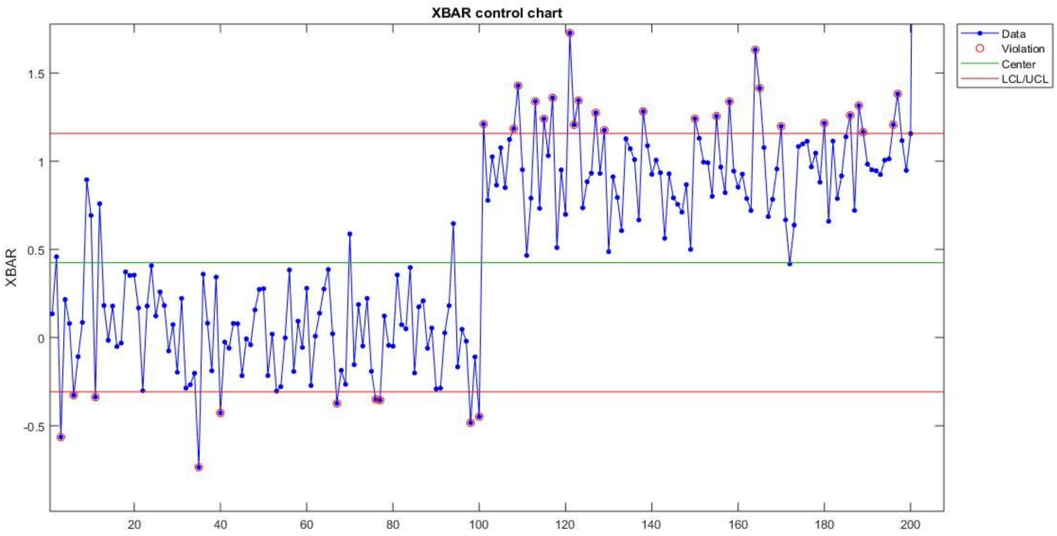

Figure 8 - This model displays a typical control chart.

The implementation of control charts is divided into two different phases which serve different objectives. The first phase, phase I, a set of process data is analysed in a retrospective analysis, trial control limits are constructed to see if the process has been in control over the time the data has been collected and to find suitable control limits to monitor future production. This is the first step performed when applying control charts to any type of process. In Phase I, it is mainly assisting operating personnel to bring the process into a state of control, to set the base for the Phase II where the process is assumed to be stable and therefore can be used to monitor the process.

3.1.2 Identifying patterns in statistical process control

To understand and analyse patterns in the process data, it is important to understand the fundamental nature of the process first. The patterns in the control chart describe the physical process, shift and slides in parameters, measurement errors etc. (Montgomery, 2013) identifies three different sets of data that can occur; *Stationary & uncorrelated, Stationary & auto correlated* and *Nonstationary.* Please refer to Figure 9, the process is noted a, b & c respectively.

- *Stationary & uncorrelated (a):* the data show a clear mean and spread and show no greater correlation to outside parameters.
- *Stationary & auto correlated(b):* the data show a clear mean but no clear spread, instead show a tendency for outside correlations.
- *Nonstationary(c):* the data show a shifting non-fixed mean.

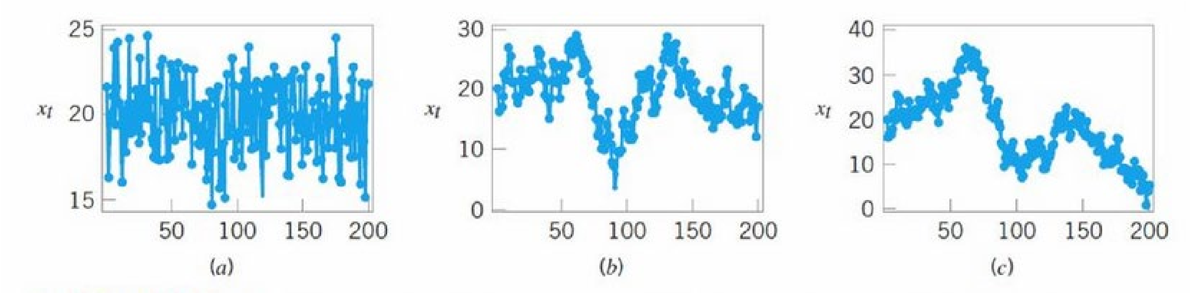

Figure 9 - Three different data sets as presented by Montgomery (2013)

The fundamentals show if the process observed is dependent of internal variation or external variation, a *Stationary & uncorrelated* process would need to be investigated internally as it shows no or little tendency for outside correlation. In contrast to the other two that indicate that external factors greatly correlate to the observed process outcome, hence the external factors are needed to be further understood and controlled.

Next type is identifying *subgrouping* in data, the idea as explained by (Montgomery, 2013), is to divide the process after batches and identify changes in process mean and variation. The difference in the subgroups can be correlated to process inputs and help identify key process characteristics. Please note that this will be of importance later in the study of the threading process. The same applies for *cyclic patterns.* See Figure 10 for example how this could look, chart generated in MATLAB.

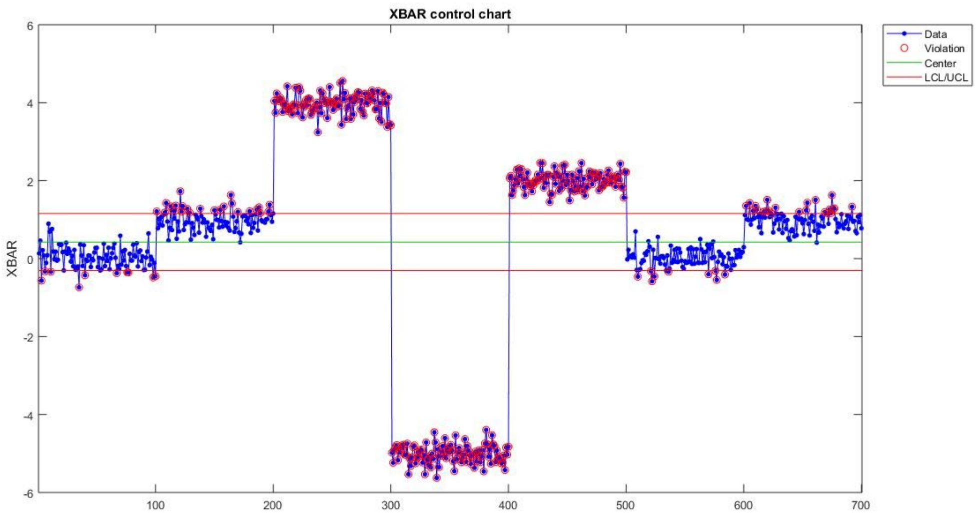

Figure 10 - Subgrouping can drastically change the mean value of a batch but standard deviation for each subgroup is the same.

Cyclic patterns are common in control charts and are often the result of natural wear and variation that occur due to scheduled and repeated changes in the observed process or initial processes. This could be the result of heat build-up machine/operator fatigue etc. The threading data is theorized to consist of *Cyclic patterns* and of *subgrouping,* the *cyclic pattern* will occur from the wear and change of tool, while the *subgrouping* will result from the changing raw material batch. Figure 11 displays a simplified chart modelled after both *cyclic patterning & subgrouping,* modelled in MATLAB.

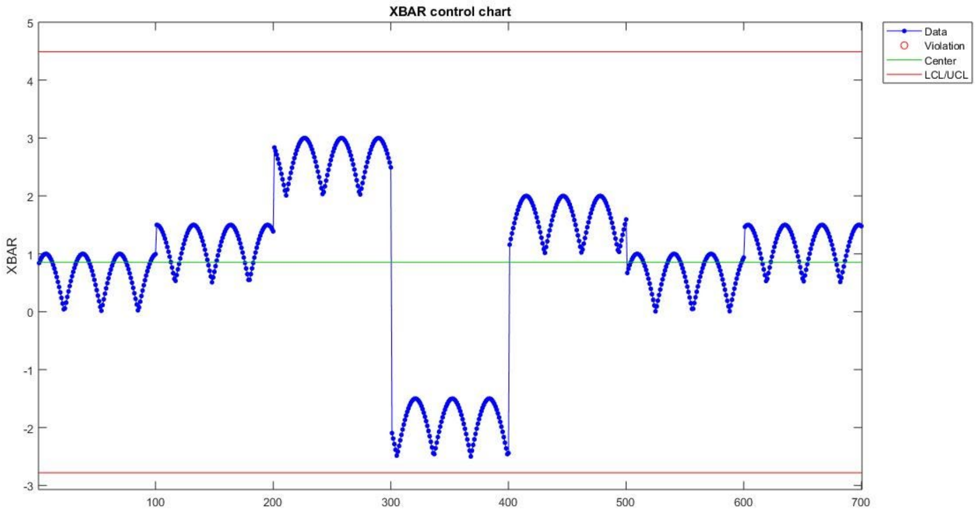

Figure 11 - The period of cyclic patterns will be a strong indicator for what the underlying cause is.

3.1.3 Rules for investigating anomalies

As the process is observed it is important to distinguish when a signal is important or is result of natural variation. This is commonly done by a set of rules describing sets of points and once fulfilled give cause for further investigation. The rules are based on predefined zones in the control charts. Montgomery (2013) describes the zones based on the Western Electric rule that defines the three zones as the following:

<u>Zone Regions</u>

- Zone A Between 2σ from the mean and the control limit (3σ)
- Zone B Between 1σ and 2σ from the mean
- Zone C 1σ of the mean

And the rules to determine if the process is in statistical control is as followed:

<u>Rules</u>

- Rule 1: Any measurement that falls over the control limit. (over the 3σ line).
- Rule 2: Two or more consecutive (in a set of at least three) measurement points in zone A, on the same side of the mean.
- Rule 3: At least four points in a consecutive set of five, on the same side of the mean.
- Rule 4: Nine consecutive measurements on the same side of the mean.

If any of the rule listed above is fulfilled, the process cannot be said to be in statistical control. Montgomery (2013) describe the Western Electric rules, however other commonly used are the Wheeler and Nelson rules. However, Western Electric rules are the ones that will be used in the report.

3.2 Machine diagnostic and tool health monitoring

The techniques for diagnosing machines and tools described in this chapter was used for analysing the threading process. All machines and tools degrade over time losing performance. Loss of performance is highly troublesome in the aerospace industry where tolerances are tight, and manufacturing requires high precision and reliability. The common way of dealing with degradation is time based preventative maintenance (Jardine, 2006). The maintenance is scheduled and performed periodically; this is done without taking the actual degradation into account. This is a costly process but needed since the result of quality discrepancies, stops or machine downtime would be even more expensive (Montgomery, 2013).

IoT, development of Cyber-Physical Systems (CPS) and sensors have made it possible to monitor the health status of the machines in real-time and diagnose the performance and the risk for machine failure (Wang & Hu, 2011). This could potentially decrease unnecessary maintenance and identify machines that need early maintenance. This is done by computing statistical models that describe machine degradation, same process is done to diagnose the tool wear (Lin, 2005; Aliustaoglu, 2009).
The combination of CPS and advancement of machine learning have created the opportunity for adaptive control and allows the machines to adapt to changing material, tool, and machine characteristics, enabling increase of reliability and precision in manufacturing processes (Lin, 2005).

Dimla (2000) lists the different types of wear which the cutting operations suffer from:

- Adhesive wear associated with shear plane deformation
- Abrasive wear resulting from hard particles cutting action
- Diffusion wear occurring at high temperatures
- Fracture wear such as chipping due to fatigue

These types of wear are often seen as comorbid. Adhesive wear can increase the working temperature causing diffusion. These types of wear will be theorized in the analysis. Understanding the cause of wear is not the focus of this report, instead the ability to predict and stop the process before failure is of interest.

To detect tool wear, several different techniques are employed, Dimla (2000) compounded an extensive literature review and compiled a list of five process and tool parameters that are used to identify tool wear: Acoustic emission, Tool temperature, Cutting Forces Vibration signature. The last is the use of miscellaneous methods, ultrasonic and optical measurements, workpiece surface finish quality, workpiece dimensions, stress/strain analysis and the current of the spindle motor (ibid.).

3.3 From Data to Knowledge

As described in chapter 1.1, GAS have no best practice in handling this new type of measurement data or tools for problem solving with this big amount of data. To effectively gain insight of the data produced of the system several steps were required before knowledge was extracted. This chapter describes the approach that was used in this thesis to create knowledge from data.

Data is not worth anything in its raw form, before it is processed. Quality of the data has no importance if the data is not processed and evaluated or interpreted to finally turn the raw data into knowledge. Wang & Wand (1996) means that data becomes valuable first when it is processed, and knowledge can be extracted from the raw data. The process of extracting useful insights from raw data is called knowledge discovery. Data mining is another term used interchangeably for describing the process, this is due to data mining being the key part of the knowledge discovery process (Priyadharsini, 2014).

Fayyad et al. (1996) describes the knowledge discovery process as the ''non-trivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data.'' The knowledge discovery process is the entire process of creating data to knowledge and data mining is the key step of the process where data is transformed into valuable patterns.

The knowledge discovery process can according to Fayyad et al. (1996) be divided into nine different steps. The nine different steps are categorized and visualized in four different categories which are divided into selection of data, pre-processing, transformation, data mining and interpretation/evaluation before the knowledge is generated through the process as seen in Figure 12. According to Fayyad et al. (1996) data mining is the value adding activity of the model, however the initial phases, selection, pre-processing and transformation are the prerequisites for data mining.

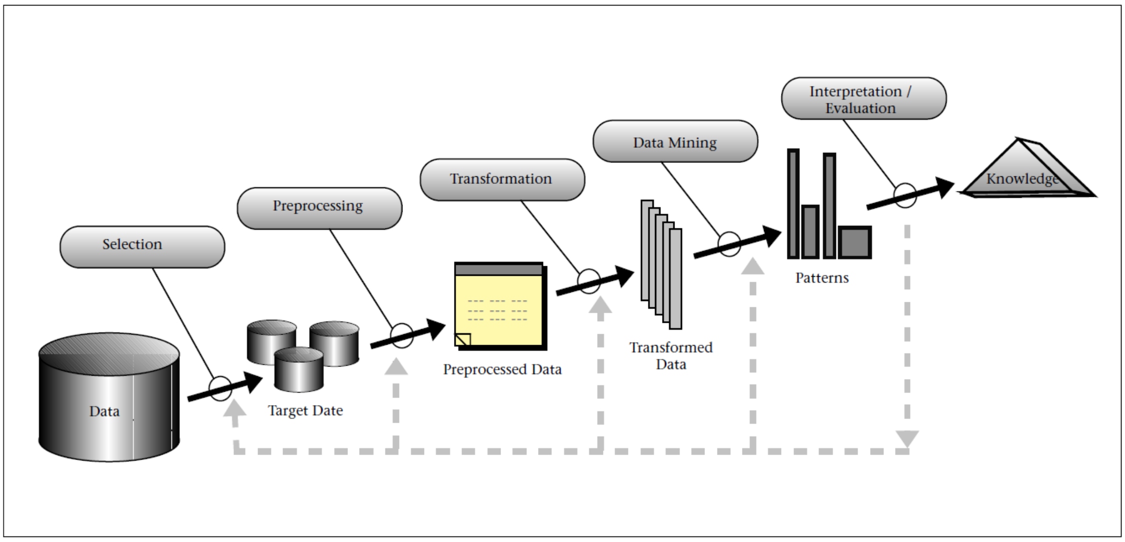

Figure 12 - The data to insight process as described by Fayyad et al. 1997

Fayyad et al (1996) and Priyadharsini & Thanamani (2014) describes the data mining process to be the core of the knowledge discovery in databases process (KDD). Maimon (2005) describes the process of data mining as the science of modelling and generalizing common patterns from large sets of multi-type data. Priyadharsini & Thanamani (2014) instead motivates data mining as the process of extracting previously unknown and processable information from large databases. Fayyad et al. (1996) distinguishes between two main types of data mining verification-oriented (the system verifies user's hypothesis) and discovery oriented (the system finds new rules and patterns autonomously). The verification-oriented methods are common methods of traditional statistics as goodness-of-fit, t-test of means and analysis of variance. Although, KDD is supposed to perform data mining on any data, it cannot be expected that one data mining method is applicable to any data structure (Chen, 1996).

3.4 Data Quality

The thesis is centred on showing the value of data from the installed measurement system, and as such, it is important to understand how to approach the collection and usage of data. In this chapter the foundation for how the data quality was assessed is laid out, and how it is used to build up arguments in the discussion of the intrinsic value of data.

IBM estimated the yearly cost of poor-quality data to be $3.1 trillion in the US for year 2016 (HBR, 2016). The lack of accurate data comes with a price for the organizations in the correction activities, lost customers, missed opportunities and incorrect decisions (Wang, 1998). Thus, any available information about possible quality problems in data should be taken seriously (ibid.).

”Garbage in, garbage out - incorrect or poor-quality input inevitably produces faulty output”. This phrase originated in the middle of 20th century in the computer field, however it has a broader application. The information collected needs to be highly accurate otherwise data analytics conducted on the data will not be reliable. High-quality data is the precondition for analysing big data and for successfully guaranteeing the value of the data (Cai, 2015). Wang & Strong (1996) defines the concept of data quality as the fitness for use. The quality of the data depends on the design and production processes involved in creating the data (Wand & Wang, 1996). Having accurate data is a fundamental requirement of good information systems but still most systems contain big amounts of inaccurate data (Wang, 1998). There are several different ways of working towards higher data quality both Lee et al. (2002) and Wang (1998) elaborates that having software tools is essential for analysing the big amount of data.

Conducting the KDD process on big data of low quality will yield faulty or poor output. Therefore, the quality of the data needs to be assured to yield accurate data mining and analysis as it is dependent on the quality of the collected data. This is something which has become difficult lately due to the concept of big data. McGilvray (2008) explains the problem of integrating data with various structures from different sources. Another issue is due to the tremendous data volume, it is difficult to judge the data quality within a reasonable time frame (Cai & Zhu, 2015).

U.S National Institute of Statistical Sciences (NISS , 2001) lists the principles of data quality as:

1. Data is a product, with customers, to whom they have both cost and value
2. As a product, data have quality, resulting from the process by which data are generated
3. Data quality depends on multiple factors, including (at least) the purpose for which the data is used, the user, the time, etc.

The data quality dimensions are divided into two categories depending on if it is an internal or external perspective Wand & Wang (1996). It is the internal view which is of interest for this thesis as it is the dimensions in this category which evaluates the objectivity of the data while the external view is instead dimensions which describes the circumstances the data is collected in. According to Hazen et al. (2014) the dimensions which data quality can be evaluated through include accuracy, timeliness, consistency and completeness. These dimensions are confirmed by Wand & Wang (1996) however reliability, flexibility, precision, currency, relevance are additional dimensions mentioned by the authors. The dimensions which are of interest for this thesis is limited to the dimensions by Hazen et al. (2014) through the internal view, this due to it being mentioned that it is these factors which are important to secure the quality of the raw data (Wand & Wang, 1996; Hazen et al., 2014). It is essential to ensure these dimensions of the internal perspective to validate the quality of the data. Hazen et al. (2014) defines the dimensions as:

Accuracy: refers to if the collected data is correct and if it represents what it is intended to
Timeliness: if the data is up to date, the time between the data collection and the conducted analysis
Consistency: refers to the usability of the data, if the data is formatted in a consistent way
Completeness: if the data has collected what was expected or if any data is lacking for the intended purpose

3.5 Internet of Things

One of the key selling points of the implemented measurement system, was the connectivity to external sources. This is a part of the phenomena IoT, and is a key factor for Industry 4.0. The benefits of and requirements for IoT can be arbitrary, and this chapter will briefly explain the phenomena, and later translate it to a competitive edge in this chapter.

The term Internet of Things, IoT have been mentioned in previous chapters and refers to the trend of connecting products to the internet. I.e. merge physical systems with cyberspace, creating cyber-physical systems. Great value can be retrieved from the ability to do so. In the industrial sense IoT, is the foundation from which I4.0 emerges, the ability to monitor and control devices over the internet allows for new business opportunities, such as: (Daugherty, 2016)

- Dynamic process control
- Predictive maintenance
- Optimization of process
- Increased health and safety control
- Enable AI and machine learning

Please note that IoT is a much bigger subject and affects more than just industries, the rise of "smart" products are a part of IoT. However, these will not be explored any further in this report.

3.6 Big Data

'Big Data is at the heart of the smart revolution'' – (Marr, 2015)

The amount of data produced by the measurement system is several magnitudes larger than what is normally analysed. The ability to collect and analyse large data sets of data, Big Data, have increased over the last years. However, the value of it can be hard to extract. The insights that can be gained based on analysis from the data from the measurement system is great and will be seen in the findings from the threading process.

Many of the applications today need to store and process data in time. In year 2000, volume of data stored in the world is of size 0,8 zettabytes. Data amount in the world is expected to reach 35 zettabytes by the year 2020 (Zikopoulos, 2012).

The basic idea behind the phrase 'Big Data' is that everything we do is creating data which can be used and analysed to become smarter (Marr, 2015). Storing such data is of no use unless the data is processed to become manageable and decisions are made based on the available data (Mohanty, 2015). However, Marr (2015) further explains that it is worth remembering that just because it is now possible to measure, monitor and access nearly everything, it does not mean that it should be done. There is a risk that the intentions get lost in the big sea of data, which delivers no value to the organization.

According to IDC (2011) Big Data is defined as following:
"Big Data technologies describe a new generation of technologies' and architectures, designed to economically extract value from very large volumes of a wide variety of data, by enabling high-velocity capture, discovery, and/or analysis."

Laney (2001) defines the typical characteristics for Big Data as separated from the 3 V'S: Volume, Velocity and Variety. Volume refers to the large amount of data which is handled, Velocity refers to data rapidly being created and growing. The final v, Variety refers to the different types of shape the data holds such as text or video. However, Mohanty (2015) agrees with the 3 V's defined above, however he has added an additional fourth V, Value. Value of big data refers to the process of extracting 'hidden' information from the emerging data (Mohanty, 2015).

IDC (2011) writes that organizations which are best to make real-time business decision by using Big Data will thrive and those who are unable to make use of this shift towards a data-intensive business will find themselves at a competitive disadvantage in the market and face a potential failure. Biswas (2017) supports this by writing that the decision-making process within an organization can be improved by basing the decisions on the big data which is created. This can be managed by better predicting the future by coping up with uncertainties (Biswas, 2017). The real value which can be extracted is not found in the large volumes of data, but is found in what we can now accomplish with it, it is not the increased amount of data that is making a difference, but it is the ability to analyse vast and complex data sets in an improved way which could not be managed before (Marr, 2015). Innovations such as cloud computing in combination with a more stable network and increased network speed and creative solutions to analyse data have resulted in new techniques to approach the phenomena of Big Data (ibid.). The complex data can now be turned into value. The analysis is no longer requiring investments in form of supercomputers but can instead be performed on typical workstations, this enables any business or anyone to now use big data to base their decisions on data to enhance the decision-making process (ibid). Big Data is changing the nature of the business in all aspects everything from manufacturing to agriculture and beyond. The rate which the data can be collected from every activity means that there are increased opportunities to improve the procedures and processes to increase the efficiency of the operations (ibid).

3.7 Industry 4.0

The fourth industrial revolution (I4.0), as promoted by the Germans, promise to re-industrialize the western world, promising higher quality, lower cost and greater flexibility. I4.0 is a key benchmark GAS use to gage the competitive edge of their manufacturing capability. The new measurement system was thought to be a step in the right direction, and thus the capabilities of the measurement system needs to be compared to the ideas of I4.0. To understand what I4.0 is, one needs to understand the previous three revolutions (BMBF, 2013). The presentation of each revolution is brief and only the main aspects of each is presented:

The first industrial revolution, this is probably the most well-known, it is the introduction of steam/coal powered machines. The revolution started with the introduction of spinning machines that could create textiles in an unprecedented speed. Without going in to the details the increased production capacity increased the living standards and while removing some jobs, new were created (David, 1969).

- The second industrial revolution, introduced electricity and standardized parts, allowing the creation of the first production lines. Increasing the speed as well as the idea of standardizing parts and processes. (Engelman, 2015)
- The third industrial revolution is attributed to the rise of robotics and automation; it is also the move from analogue devices to digital devices. Previously manual production lines got replaced with robotic production lines. This form of automation might at first glance be what people consider attribute to I4.0. However, the digitalization and automation in I3.0 is only a minor part of I4 (Ryder, 2012).

The fourth industrial revolution emerged due to Internet of Things (IoT). Previously the robots and production processes were separated, limited to the operation and movements programmed, a robot might have several different operations pre-programmed but not smart enough to handle new operations without pre-programming. A fourth-generation industry is flexible with robots that can learn and adapt to new product specification, and make decisions without input from a machine operator, instead a fully autonomous factory can track the raw material entering, decide the best manufacturing process and track the quality to the end process ensuring all predefined product characteristics are met without the need of human intervention. Table 1 below describes the factors that have marked the points for revolution, the key contributing factors for each revolution have been marked in red.

Table 1- Key invention caused worldwide changes from power to process control.

Industrial revolution	Power source	Tools/Machines	Machine control	Production Planning	Product Design	Connectivity
0	Animal/Man	Unpowered tools	Man	Man	Man	Almost none
1st	Steam/Coal	Big powered machines	Man & Analog			
2nd	Electricity	Elecric-powered machines & tools	Analog			
3rd		Robots etc.	Digital	Man with CAM	Man with computers (CAD)	
4th			Digital with AI support	AI & man	Computers with support of man	Endless potential

Please note that the previous revolutions have all been focused on strengthening man and overcoming the weaknesses of the human. The problem is, humans have always been needed in the production process for control, planning, design and flexible work. However, I4.0 aims to replace the brains of the production and replace it with Artificial Intelligence (AI) making the classical operator obsolete (Monck, 2016). We are slowly becoming what the horse is to the car.

4. Predictability of the threading process

The following chapter will cover the new measurement system, and how the system can be used to predict thread tap breakage and tool wear. The result showed that not only is it possible to detect and predict tool wear but also construct control- and warning limits that would detect and warn when abnormal taps were processed, successfully answering RQ1.

4.1 Introduction to the threading problem

During the implementation of producing the new engine part it was discovered that the threading process did not operate under the set boundaries, and would at periods cause critical tool failure leaving parts of the thread tap in the newly threaded hole as seen in Figure 13. In attempt to decrease the frequency of failure new lower tool life was set, as the cause for the problems could not be accurately identified.
The current solution of lowering the tool life was not satisfactory, and it was in interest for GAS to understand this problem as it is recurring in other products as well. Multiple projects were conducted to analyse the threading operation. A project was done earlier in collaboration with Chalmers University applying the six-sigma methodology. However, the project could not pinpoint any direct root cause, instead it pointed at the lack of process data that was available and theorized that if more data from the process could be collected, the problem could potentially be solved.

In the spring of 2018 talks started with a provider of such measurement system. The system was operational in the end of January 2019 and is since then continuously measuring the drilling and threading operations in Multi Task Cell (MTC) 5.

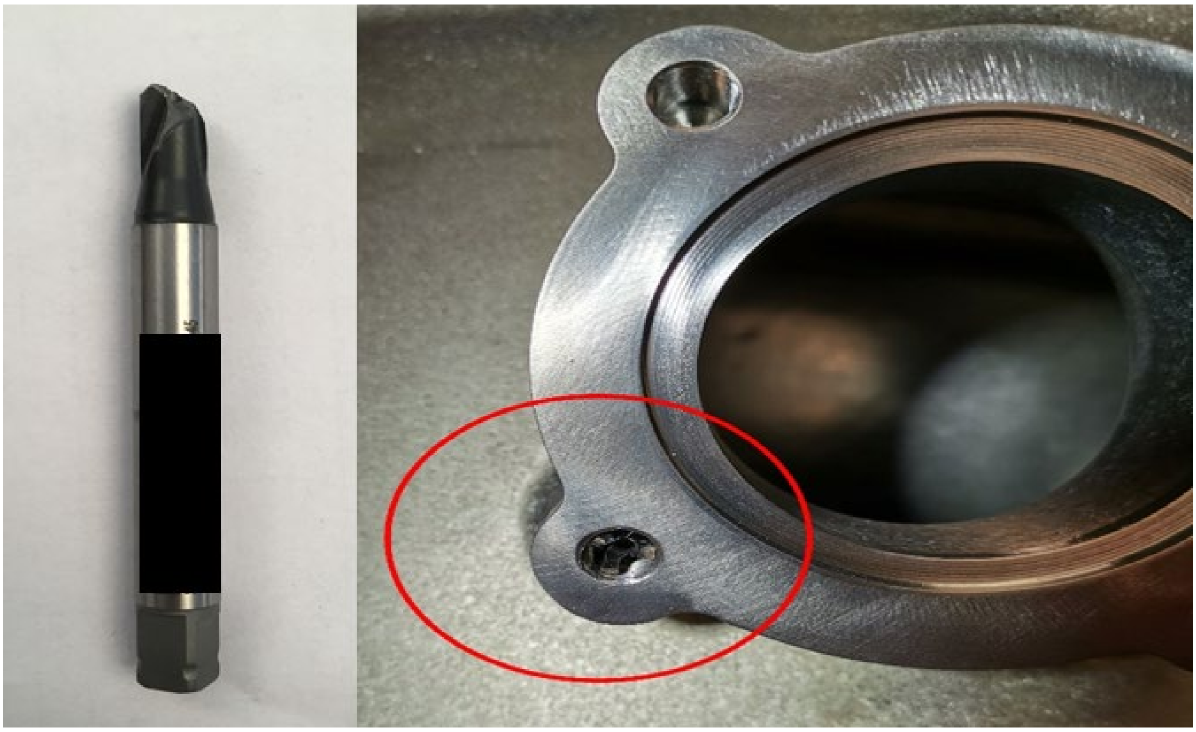

Figure 13 - The thread tap broke during the final part of the threading process and stuck in the bottom of the hole.

4.1.1 Production unit

The production unit consist of five MTCs and an automated tool storage solution with an overhead robot on a rail. A part gets placed in the MTC and several operations are performed with various tools varying from milling, drilling, broaching and threading. Please note that the part does not move between MTCs instead the tools are changed automatically from a shared pool of tools. In the shared pool of tools there are twelve different thread taps with various diameter. The MTC requests a tool and the tool robot takes the tool from the tool storage, there are usually three copies of each tool type since multiple MTCs can perform the same operation on different parts. The tool is often set to handle multiple parts before being changed to a new. Hence a tool used in MTC 5 could have been used in the other four MTCs. This complicates the tool traceability since the measurement system (MS) is only installed on MTC 5. See Figure 14 below for simplified version of the described production unit.

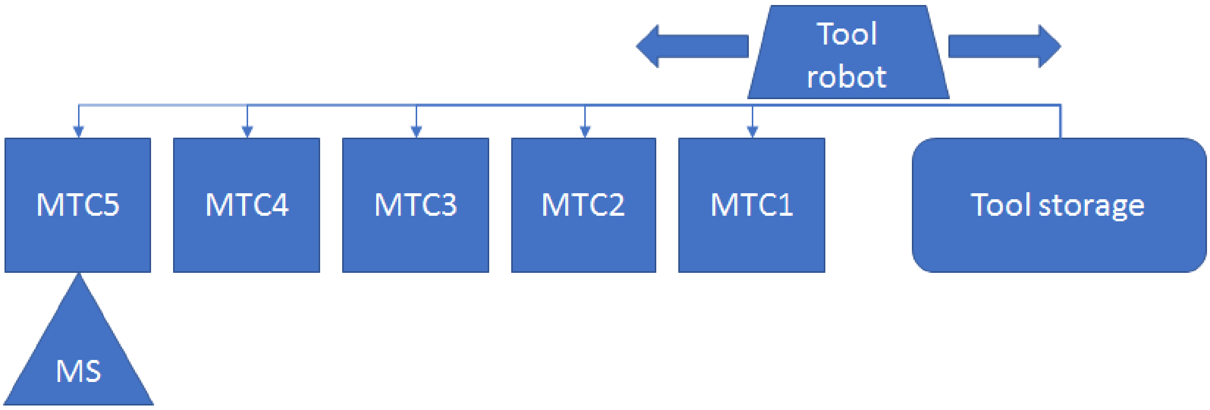

Figure 14 - The Tool robot runs on a rail above the NC machines and the tool storage.

4.2 Goals and limitations

The goal of the threading study was to answer RQ1, i.e. be able to predict thread tap breakage and tool wear. The purpose behind this was to investigate if it is possible, to reduce the costs that stem from thread tap breakage and short tool life, RQ2. The result of this study creates the foundation for the cost model. This is the first time this type of data, machine data, have been analysed at GAS and the analysing process will therefore be exploratory, since no work process have been pre-defined within the company as described in the research strategy. I.e. identifying root causes to discrepancies will not be prioritized instead the team will, with consultation from experts within the company, suggest probable causes. Neither will the final quality of the thread be considered, only if the tap broke or not, unless strong indications show that it could be of interest for the final discussion.

During the writing of this report only one tap breakage was recorded. There were several thread tap breakages, however in other MTCs without the measurement system installed. So, the remainder of the time was spent on analysing the tool type with a recorded tap breakage.

4.3 The measurement system (MS)

The MS contains a hardware that connects to the process cell. The MS acts as a part of the machine and reads the servers electrical currents, position and spindle RPM. With this information, the MS can calculate the working torques in all axles, as well as the torque of the spindle. This is all done in real time and the providers of said MS, stated that it could be used for preventing tool breakage and identifying the tool wear by using adaptive control (real-time SPC) which is part of the measurement system, see Figure 15.

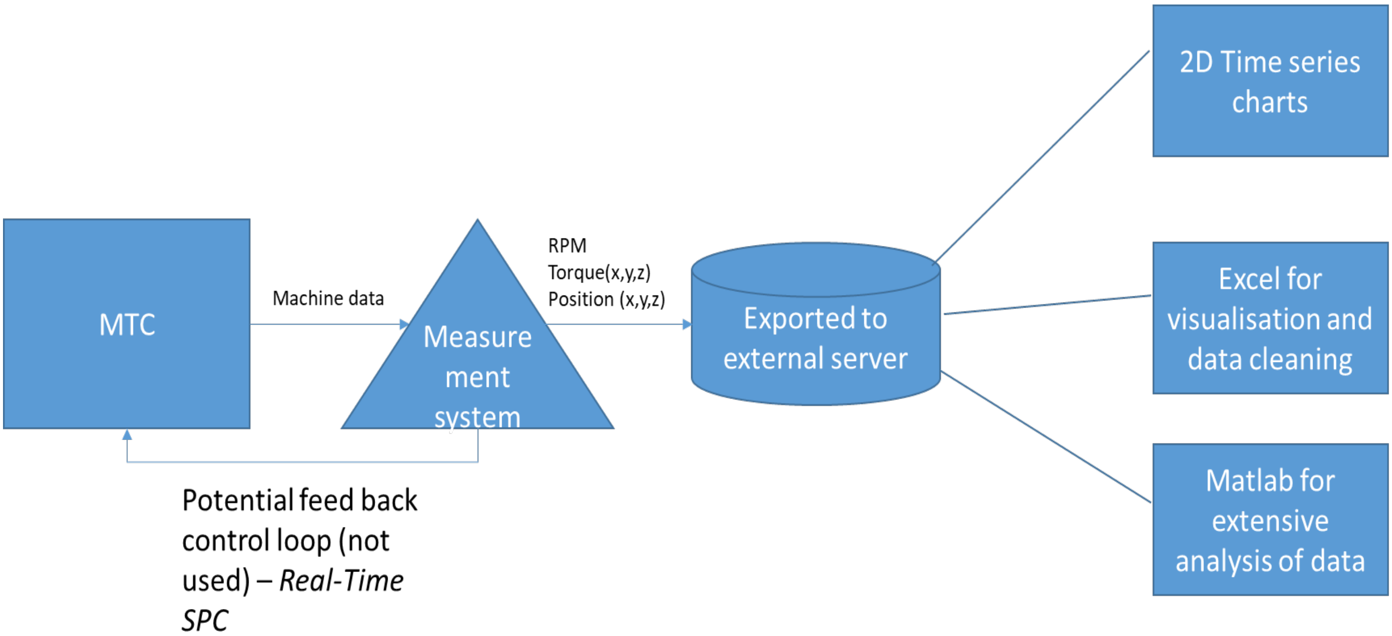

Figure 15 - The unique feature of this system is the potential built in feedback loop.

Currently this feature is not in use, instead the MS creates and exports image files (see Figure 16for example) of the operation, as well as, the raw data in individual .CSV file for each drill and thread operation in the MTC. At the time of writing this report *29000* unique operations have been exported. The files are then available for further analysis in MATLAB.

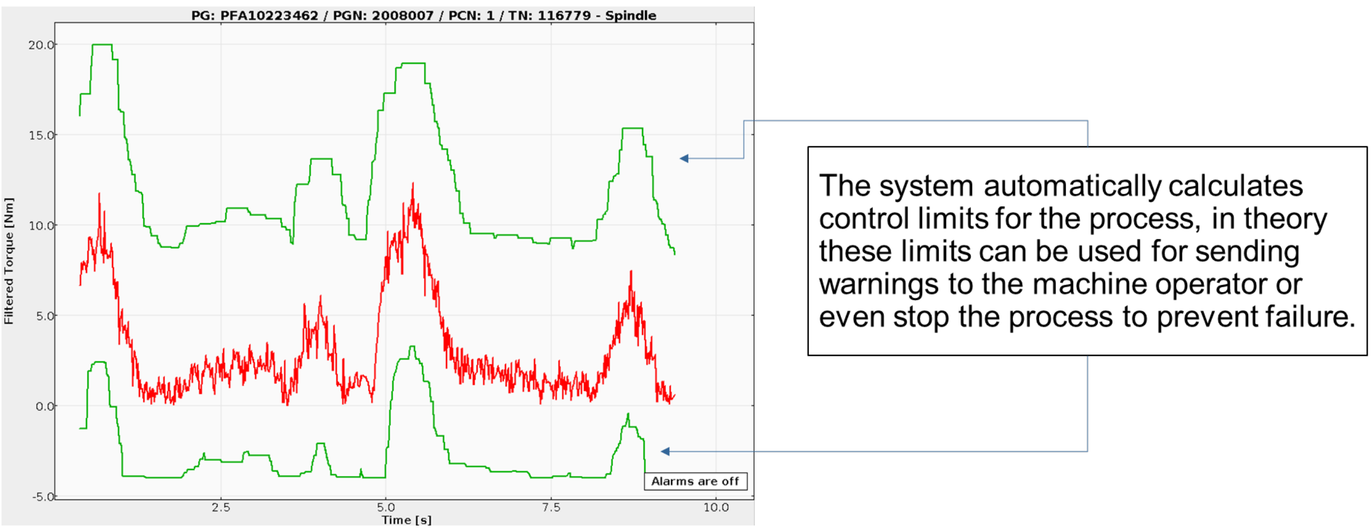

Figure 16 - The systems own control limits decide if the system should warn or stop the process.

4.4 Analysis of measurement data from threading process

The process of understanding the data was structured to first understand the threading process, the key characteristics and how it compares to a simpler drilling process. After properly understanding the threading process. The next step was to identify when there was a risk for tool breakage, if degradation on the tools could be seen and if it was feasible to use this data for said purpose.

4.4.1 Extracting and understanding key characteristics of the threading process

The process characteristics were identified by help of the systems own GUI, the threading operation showed a clear torque curve that could be split into different zones. The zones described the different stages of the operation. Each operation has different variables that could later explain the behaviour of the threading process. As seen in Figure 17. This was a crucial step for understanding the process in further analysis.

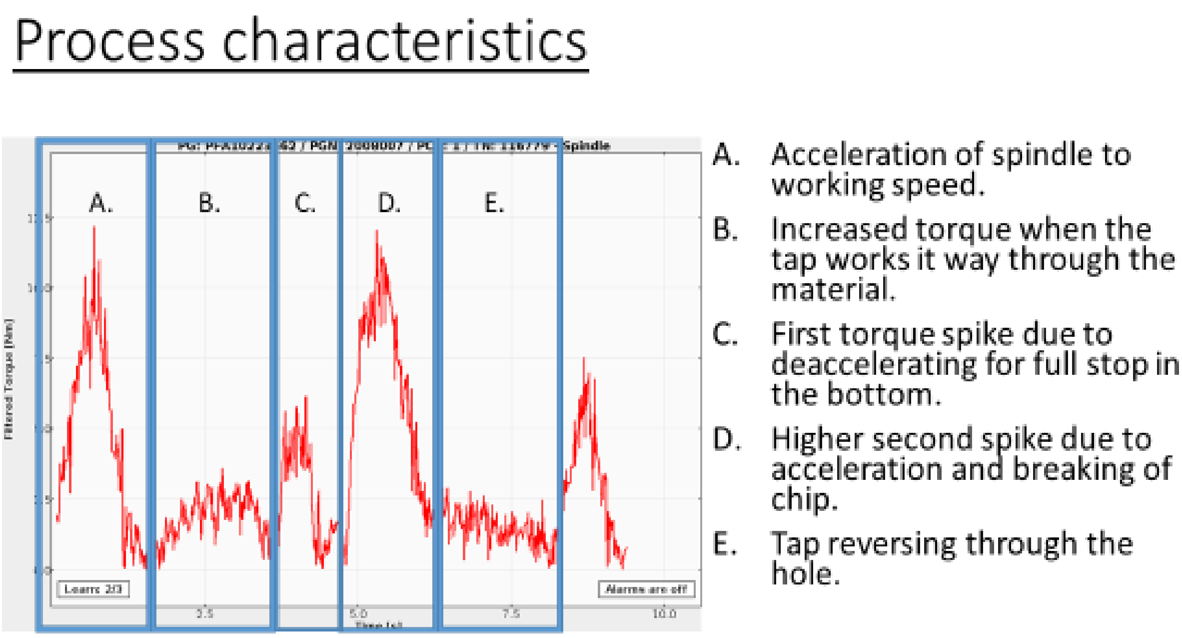

Figure 17 - The torque graph clearly shows the threading process and can be split into different zones.

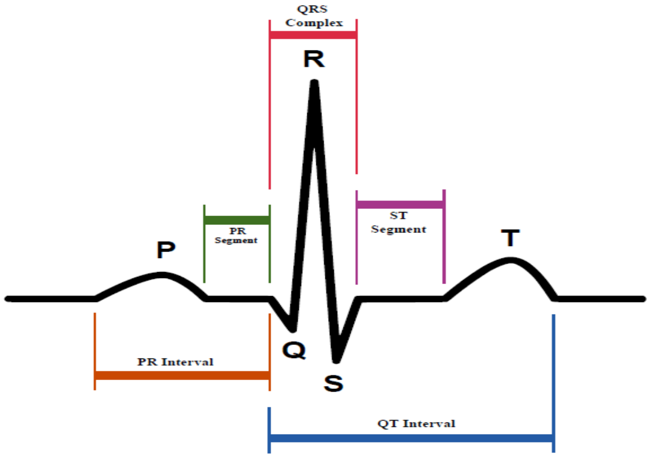

Figure 18 - ECG uses the peaks and zones in between to diagnose health issues adapted by Agateller (2013).

The measurement systems own GUI could only show one operation at a time and for more in-depth analysis the raw data needed to be extracted and used. Initial tries were made with Excel; however, Excel has strict limitations on the amount of data available for plotting, 255 rows to be exact, (the files exceed 2000 rows). Instead MATLAB was chosen for further analysis. The analysis was inspired from ECG and how it uses the characteristic curvature to diagnose different heart conditions, as seen in figure 18.

The threading operations distinct peaks and valleys were identified, see Figure 19. The typical threading torque curve has three key peaks/valleys. Three points were identified, the first drop before the reversal of the tap, the null point where the tap is stationary in the bottom of the hole, and lastly the torque spike for breaking the chip. These three spots were theorized to show different kinds of effects. However due to the lack of observed thread tap breakage the team only approached this as a beginning for future study.

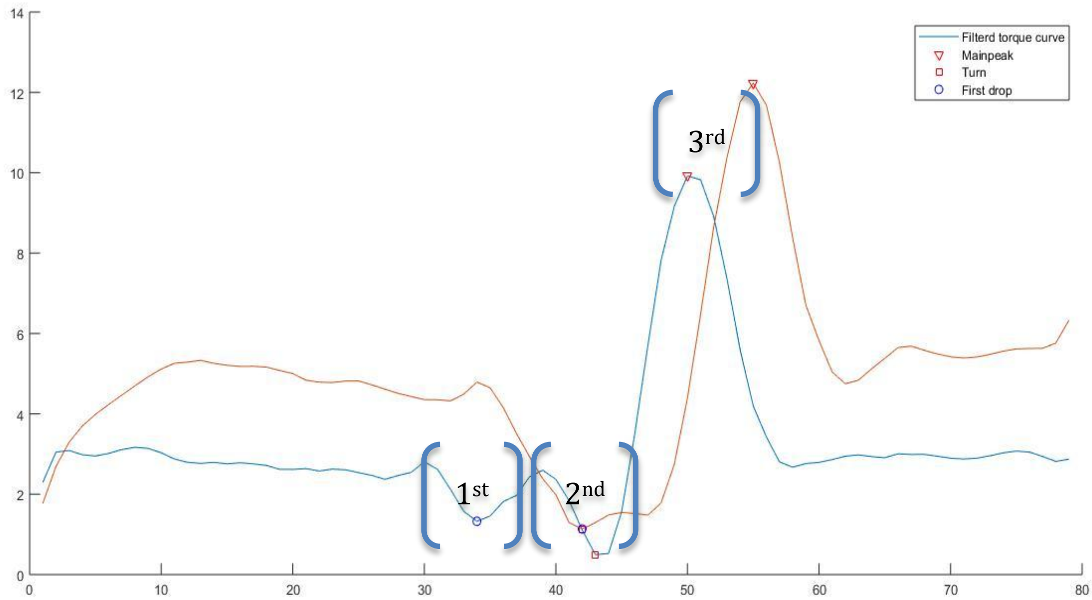

Figure 19 - The typical threading torque curve has three key peaks/valleys.

- (1st) The first drop is due to the machine slowing down towards the end and therefore needing less energy. The machine does however apply some breaking power to slow down the spindle, this causes the peak between the first drop and the null point. The amount of energy needed to stop the spindle decreases if the hole dimension is smaller or if the tap is worn due to the increased friction. Please note that if the friction gets too large then the machine needs to work harder and these characteristics disappear in significantly worn tools. This can be seen in Figure 20, where the blue curve is a new tap and the red is the last run before tool breakage occurs.
- (2nd) The turn/null point indicates where the tap has stopped and tries to reverse, this point could potentially indicate if the machine is trying to turn before it has reached to bottom of the hole. The displacement and value of the point can indicate that the tap has not been able to complete the hole completely.
- (3rd) The chip breakpoint directly after the turn/null point is the max torque the tap will experience during the entire operation. This is however not the point where the tool usually breaks instead it is shortly after. The amplitude of this point correlates with the wear of the tool, most likely due to the dullness of the cutting eggs or the wear of protective coating causing cold welding and adhesive wear.

Not only are the mentioned points of interest but the areas between the points shows altering properties from tool wear. After dividing the curve by linear abruptions noticeable differences can be seen between a new (top) and a worn (bottom) as seen in Figure 20.

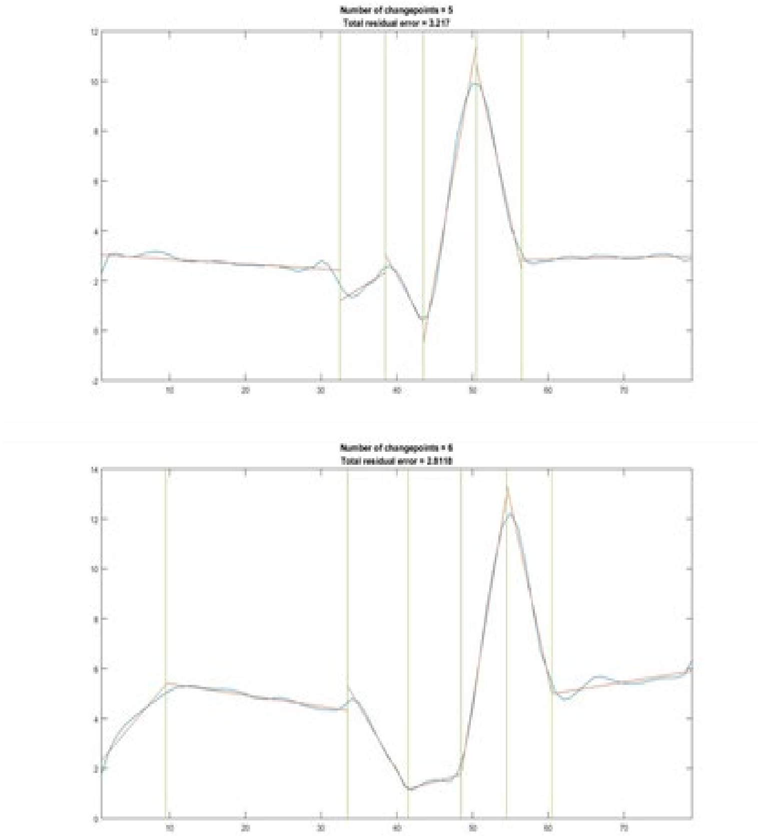

Figure 20 - A new and previously unused tap (top) vs worn and in the end of its life (bottom) show large differences in their respective peaks/valleys.

The new tap has clear areas and the torque required for processing the material is steady in both the insertion and exertion of the tap, the turn and chip breaking is also clear. Compare this to the parabolic increase in torque needed in the insertion of the tap, that later plans, which is seen in Figure 20. This can be the result of material build up on the tap or dullness of the edges, making it harder for the tap to penetrate and cut through the material. The turn point is also different in its structure compared to a new tap. Please note that due to the increase in friction the torque spike for de-accelerating the tap before the turn is missing in the worn tap, the average torque is also significantly higher in all other zones.

4.4.2 Identifying tool wear and tap breakage

The next step was to detect and track the progress of tool wear. This was first done by extruding the 1200 runs side by side along the Z-axis creating a mesh structure. The X and Y-axis remained the same displaying time and torque respectively as seen in Figure 21. As an added feature a heat map was added to highlight the torque levels between zero and five Nm.

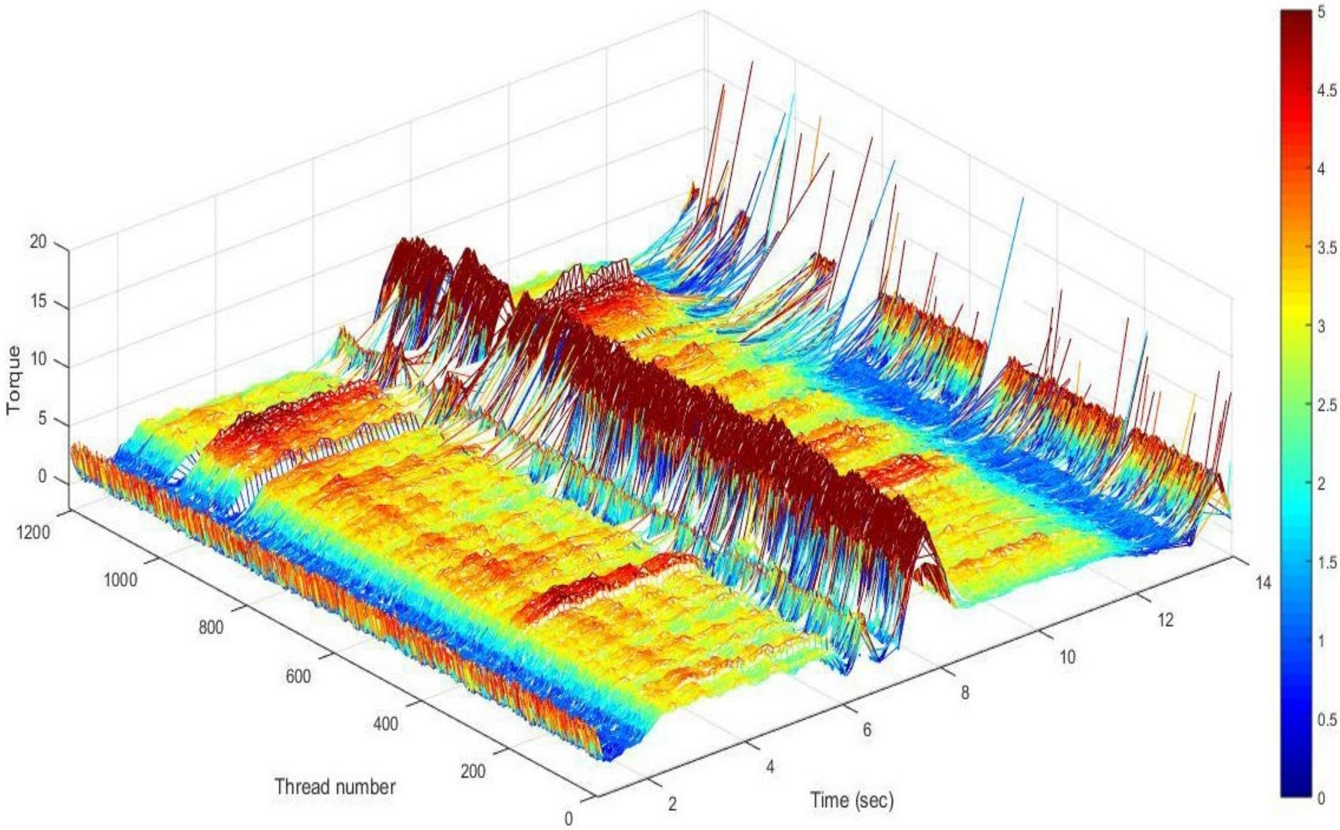

Figure 21 - Surface plot created by ordering the consecutive runs after each other, offering a previously lacking in-depth view of the process.

The threading process peaks are further noticeable in this representation, the yellow/red working torque in the insertion exertion of the tap with the two clear peaks in the middle where the turn of the tap occurs. Note the wave-like feature along the mesh surface during the tap insertion zone, colour alternates between shades of yellow and red. This feature is even more predominant from a top down perspective as shown in Figure 22.

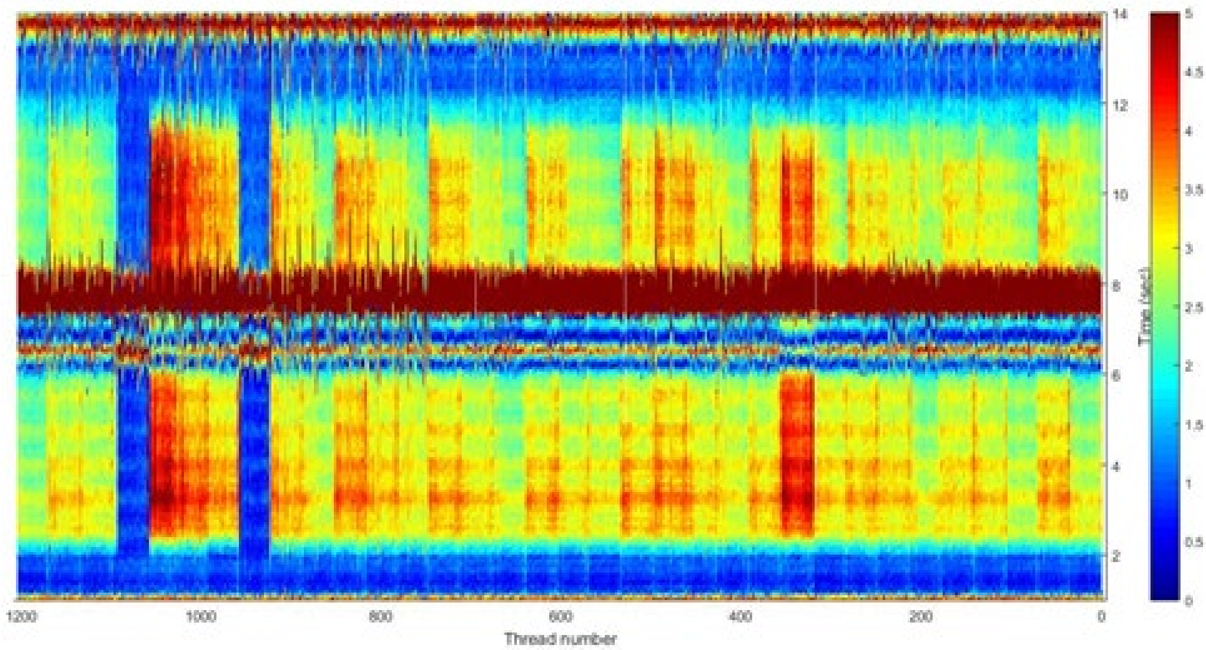

Figure 22 - Top down view of the process, with several interesting characteristics visible that was previously not thought off.

The wave feature is now replaced with some noticeable vertical striped features. These striped segments denote different orders, and each stripe consists of 34 threading operations on the same part. The astute reader might have observed several deviating areas of this plot: The two cold areas, the three red ones in between the cold stripes, and the singular red stripe between run 200-400.

The two cold areas are there for two different reasons, the first (before run 1000), was a test run where the machine performed the threading operation without any material to measure the machine's own proper motion. An interesting observation here is the first peak for deceleration is higher, redder, than the others. This is due to the lack of friction adding natural breaking, since no material was there. The second cold stripe after the three red stripes is due to tool breakage and the machine running a threading operation without any tool showing a similar effect as running without any work material.

The three red stripes were the three runs leading to tool failure, and finally tap breakage in the last run. The tool life for this tool was set to three parts and was at the end of its life. Highlighting this area in Figure 23 clearly show an increase of torque of the consecutive runs leading to tap breakage, and that the average working torque is significantly higher from the offset. This is in accordance with the findings by Dimla (2000).

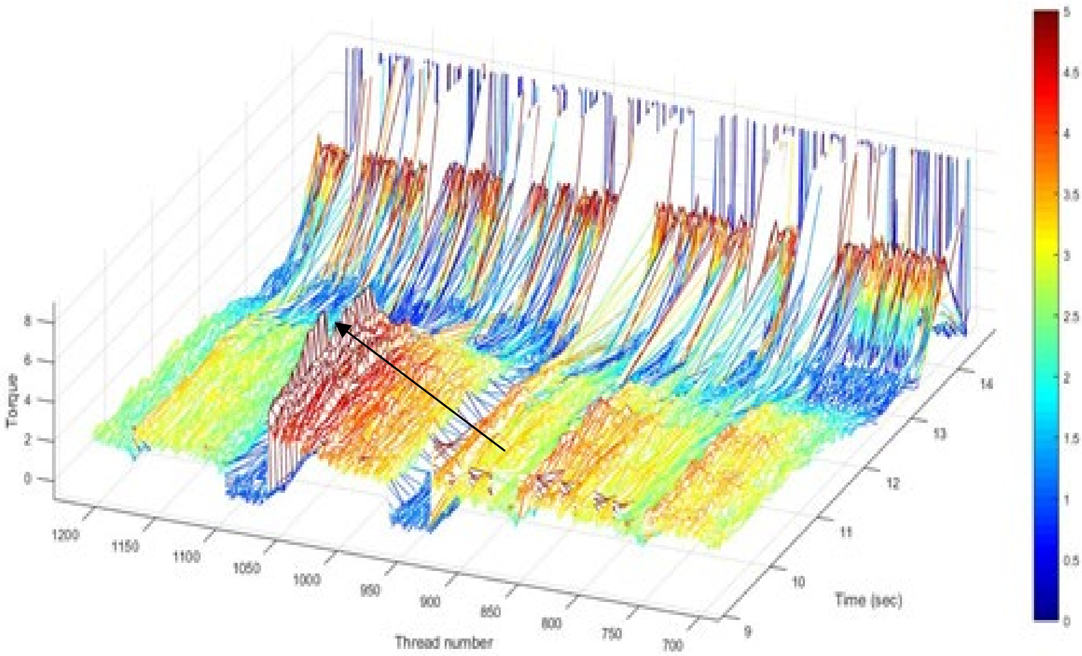

Figure 23 - The zoomed in part clearly show how the torque steadily increase over consecutive runs.

Figure 23 depicts a zoomed in part of Figure 22, precisely after the turn in the bottom of the hole, please note that the last spikes in torque are significantly higher than the rest, it was at the last spike that the tap broke. The black arrow in Figure 23 shows the linear increase in torque.

The ability to show consecutive runs and the visual difference in torque led the team to calculate the mean working torque. The mean torque is displayed in Figure 24 on the Y-axis and the threading number on the X-axis.

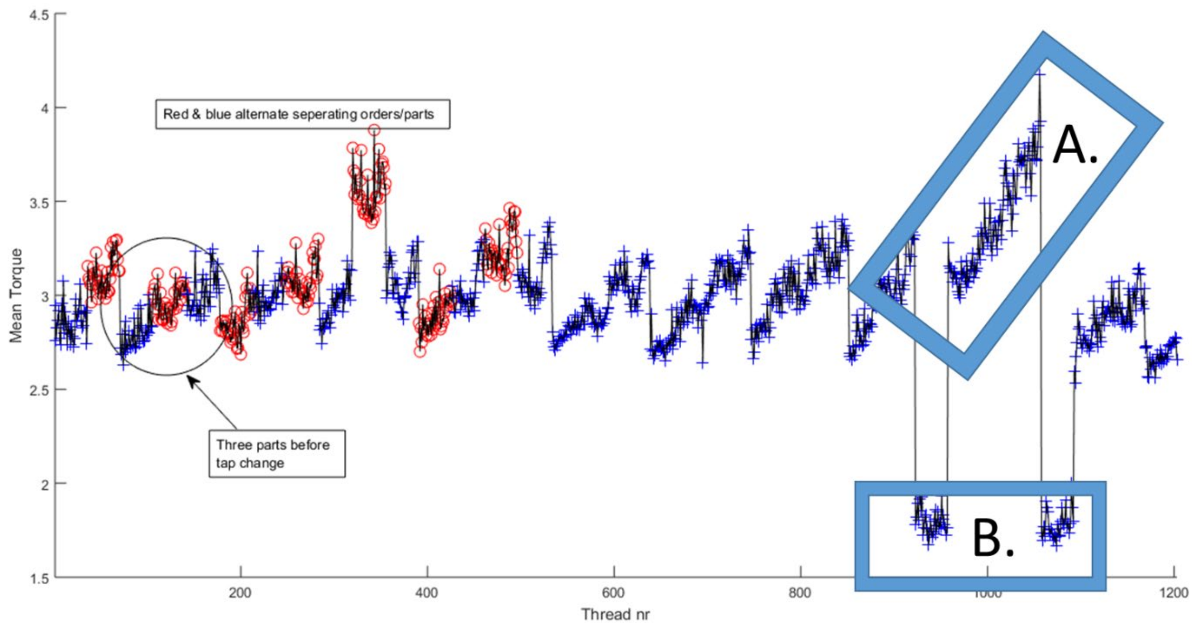

Figure 24 - The linear increase shows a repeating pattern after three parts processed, this correlates to tap change.

This yielded further clarification and strengthened the initial hypothesis that tool wear could be seen in the increase of mean torque. In Figure 24 different orders/parts are denoted by alternating red and blue markers. However, the structure in which the measurement system saved order numbers changed and the techniques used by the team to separate and alternate colour no longer worked after the initial 500 threading operations however the alternation can still be seen after the initial 500 threading operations if the reader is attentive. Figure 24 shows a repeating structure of three orders of increasing mean torque followed by the scheduled tool change, and such reset the slope. Please note that the production cell consists of five machines that share the same tool stock, and a tool used in the observed machine could have been used in different machines before, as described in *4.1.1 Production Unit*. This creates a traceability problem as the tool could have been run in other machines. However, the tool in Figure 24 had only been run in MTC 5 which allows for full traceability of the tool. This was investigated using the complementary program ATMS to track the tool. This is however done through a proactive program to understand the traceability described further in chapter 4.4.4

The step increase marked as A. in Figure 24 depicts the last three runs before tool breakage, further strengthening the hypothesis that tool breakage can be prevented and be seen long before the final thread. This tap had a significantly higher initial torque than the norm, this could have several explanations and provokes further questions. But the fact remains that from the start this tap was a clear candidate for tap breakage and should have been discarded after completing the threads of the first or second part.

The torque means marked B. in Figure 24, corresponds to the previously described cold stripes in the mesh plot.

4.4.3 Prolonging life length of tools

Given the linear regression and the apparent safe margins, the team calculated that the average tap could be used safely for 2 more parts before reaching working torques that risk breakage. Due to the uncertainty from lack of observed thread tap breakage this is highly speculative and needs to be cross checked with the final quality of the thread tap. However, during discussions with people responsible for manufacturing and tools it was discovered that they had previously decreased the tool life of the thread taps, as a last resort to decrease tool breakage. After presenting the findings it was concluded that with this system and prolonging the tool life for an additional part would be possible. This would represent an increase of tool life by 33%, but given that some would get changed earlier it was concluded that a reasonable representation of increase in tool life would instead be 25%.

4.4.4 Automatically identify when new or different tools are used

The next part was to further test the theory of tool wear translating to linear increase in mean torque. Script was written in MATLAB that automatically attempts to divide the 1200 operations after changing linear slope and displaying these as seen in Figure 25.

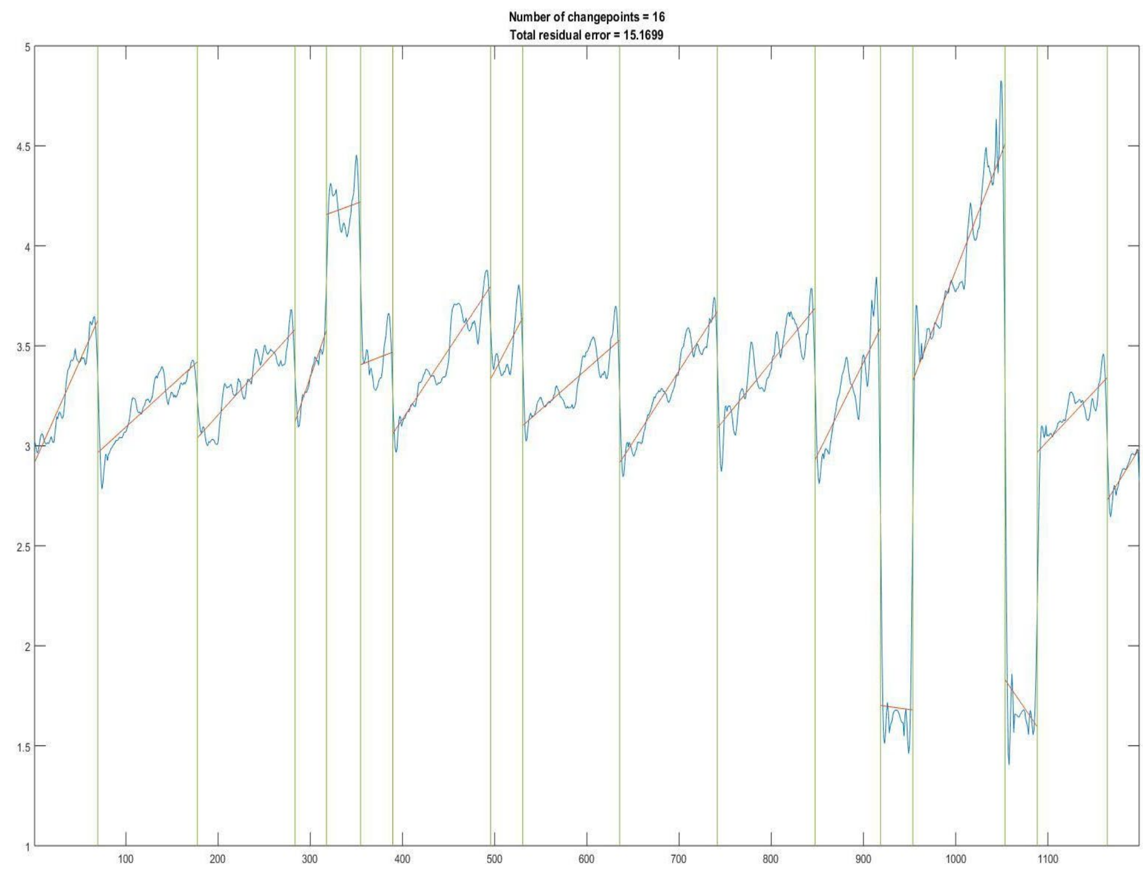

Figure 25 - The linear pattern is highlighted and perfectly splits the graph in to sections after tool change.

This proved to be highly effective and the script successfully identified when a new tool was used. The script identified when a tool was changed after three parts, as well as, tools that had previously been used in different machines that were not observed by the measurement system before. This was all done by calculating the regression line for varying section sizes and identifying when abrupt changes happened. This was additionally confirmed by backtracking and checking all sections order number and what tool and tap combination had been used by cross checking in the ATMS.

4.4.5 Automatically creating control limits

Given that the tool wear was detectable and predictable, an attempt was done to develop control limits for the threading operation, seen in Figure 26. The ones used by the measurement system did not detect the tool breakage, the control limits automatically set by the measurement system were too high. The underlying inspiration for how the control limits were created stemmed from the readily used control charts (Montgomery, 2013). Therefrom the mean for each point was calculated from the 1200 runs as well as the corresponding standard deviation (sigma, σ). In accordance to Montgomery 2013, the warning limit was set to two sigma's from the mean and the control limit was set to three sigma from the mean.

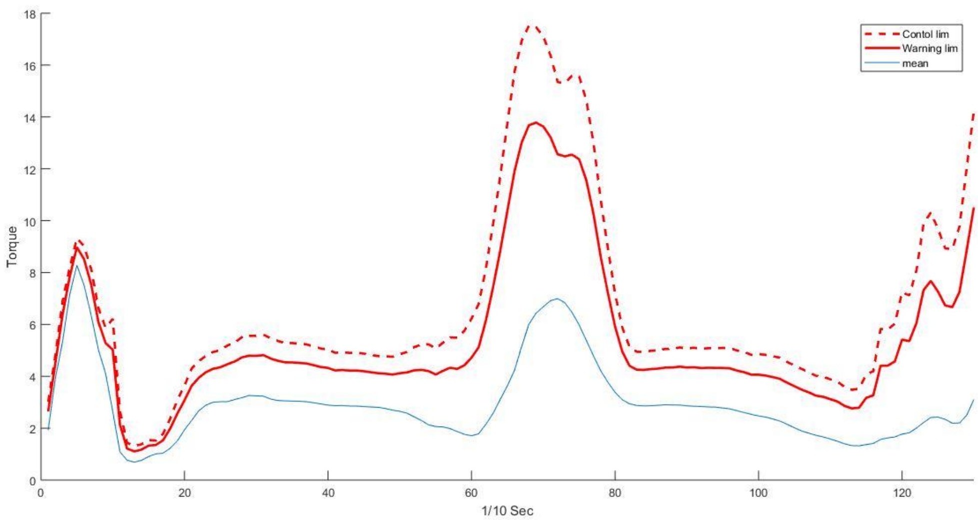

Figure 26 - The control chart showed where deviation was the greatest and where the control limits could be useful.

The result of the control chart development can be seen in Figure 26. There are several interesting features that need to be expanded on. Firstly, the lack of deviation or spread before the tap enters the material, this is the previously identified zone A. In this zone the tap is above the material and the only deviation should be that of the machine itself and measurement errors. The close to no deviation indicates that the machines internal servers are stable, and any measurement errors are negligible.

In contrast the deviation is significantly higher in the end of the process (after 11 sec), this is due to how the NC programming is setup. Since the measurement system calculates the torque through the electrical current in the servos, the movements of the entire working arm will cause faulty readings. This should not be a problem if the NC program is set to start the measurement system at the start of threading and turn it off after completion, however the current NC program at points include a few seconds extra when the machine is moving from one hole to the next. This causes the exceedingly high torques measured, however it is no torque that the actual tool experiences.

Please note as well the double peaks in the control and warning limits. The reason for these are currently unknown. The current working theory is that worn thread taps get distorted due to them getting stuck in the process of breaking the residual chip. The astute read might have noticed that the initial small peak in the deceleration of the tool in the hole is missing this is most likely due to the misalignment and lack of second peak in the operations with worn tools. This was shown in the previous peak analysis.

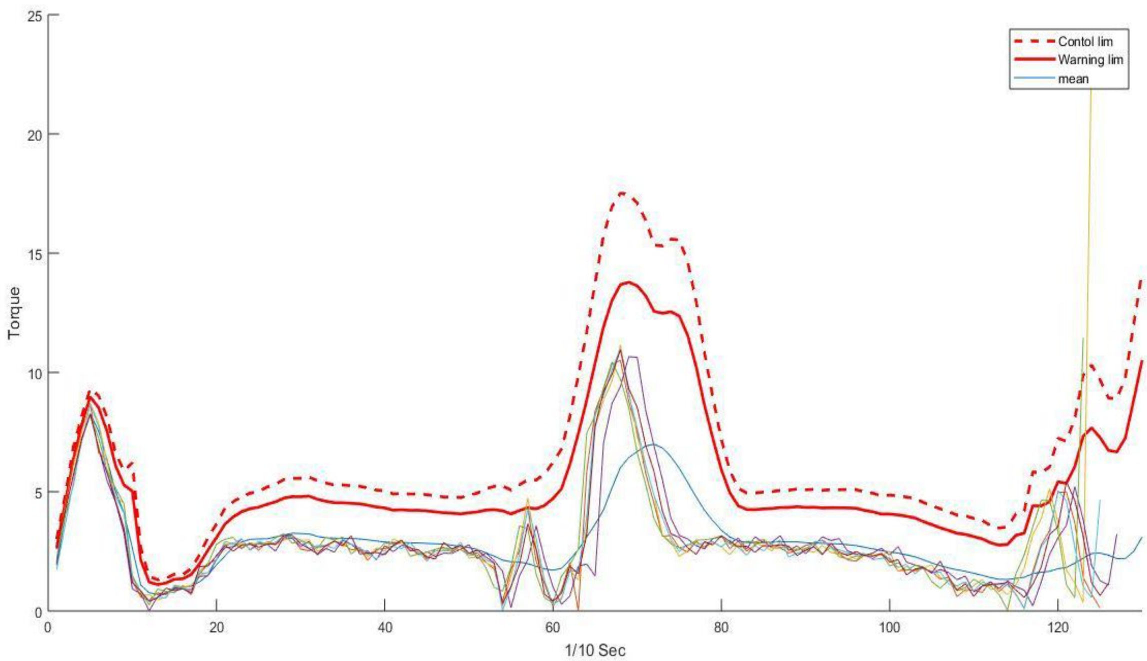

Figure 27 - The five random runs almost perfectly stayed within the warning (2σ) and control limits (3σ).

The result of inserting five random runs to Figure 26 can be seen in Figure 27. Inserting five random runs into the control chart show how well the runs are conforming to the mean, the exceptions are the lack of first peak and the erratic behaviour at the end of the process. Comparing this to the last five before thread tap breakage and failure run, see in Figure 28 below. They are all significantly further from the mean and almost all are above the warning limit. The final run, highlighted as the thicker red line in the graph, is at almost exclusively over or on the control limit. In the case of this thread tap, ample warning was given ahead of time to stop and change the tap. In basis of SPC as described in the theoretical framework, rules are generally applied for understanding in taking action, if the first rule of Western Electric, one measurement over the control limit, was applied the threading operation would have requested an action three cycles before the failure (Montgomery, 2013).

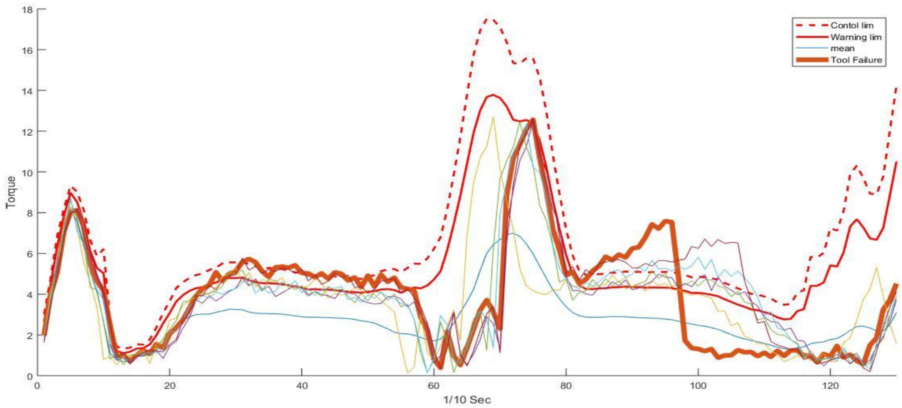

Figure 28 - The runs leading to failure are all above the warning limits and last runs break the control limit.

4.5 Findings from analysis of measurement data

The objective of the analysis of the measurement data was to explore the data and to try and show that tool wear and tool breakage is detectable and predictable. The tool wear showed to be so predictable that out of a set of 1200 runs the team could identify when new taps had been introduced to the process without any other information than the mean torque for each run. Hence, RQ1 can safely be answered and the findings used to strengthen the validity of the cost model. The team was also able to create a control chart that if implemented would have prevented tool breakage and stopped the process before the last part would have been processed, in accordance to the rules described by Montgomery (2013). It is important to note that the root cause of the thread tap breakage is unknown, since the traceability of the individual tap to a specific batch is currently impossible. The list of potential causes is as followed:

- **Operator misuses**, the tap could have been damaged during tap change or an old tap could have been accidently used by the operator during change or when shift ends.
- **Supplier escape**, the thread tap could have suffered from internal quality issues undetected by the supplier.
- **Part material**, the working material is cast titanium, the tap could have struck a casting defect damaging the tap in the first part.

After interviews with tool and manufacturing experts within the company the first seem to be the most likely cause. The experts stating that shift change during tap change or simply the tap rolling of the workbench hitting the floor and getting damaged, as the likely reasons. This, or the supplier escape is the more likely explanation than material defect, since the tap started off with a higher mean torque than its counterparts.

After interviews with experts and the result of the study the team is confident that even though only one tap breakage was observed the norm showed such predictability that future breakage would be identifiable and preventable if the proposed control limits were implemented in production.

It was also identified that the life length of the tools could be prolonged. By analysing the broken thread tap breakage it was seen that the breakage occurs at a significantly higher momentum than the torque which is reached when tool change is done. This shows on the potential to increase the current life length of the tools by at least one additional detail. As the amount of operations vary depending on the tool, the percentage increase for the tools vary. This potential increase of the life lengths is strengthened by interviews with tool and manufacturing experts within GAS who strengthens that the life lengths can be safely increased by at least 25 percentage. The potential for this is additionally strengthened by interviews claiming that the life length of the tools had earlier been higher but had been decreased due to a sequence of increased thread tap breakage. However, if the real-time SPC system is used by setting appropriate control and warning limits according to Montgomery (2013) the life length of the tools can be increased by making the system act if the tool is reaching critical working torque levels.

5. Cost Model for Thread Tap Breakage

In this chapter the potential cost reduction, which can be achieved by predicting thread tap breakage and identifying tool wear is calculated. RQ2, RQ3 and finally RQ4 are answered in this chapter. Based on the findings from chapter 4, it was found that thread tap breakage and tool wear can be predicted. The calculations carried out in this chapter, should not be limited to the threading operation. The same calculations can be applied to other production processes, as the cost and cost saving elements are similar. The handling of quality discrepancies is the same for all processes. The calculations are based on the number of thread tap breakages during the production year 2018. This is due to having access to data for the entire production year. However, the same calculation for upcoming years can be done by changing the variables, e.g. the amount of thread tap breakages (Q3/Q4) or the hourly wage for various departments. These are variables which are commonly changing over time. The cost for implementing the measurement system is compared with the potential savings of installing such system. The depreciation is set to two years at GAS, however for simplicity the depreciation time of one year was used in the calculations. This further strengthens the potential cost savings which can be achieved. The cost elements and cost savings which are considered can be seen in the scale model in Figure 29. The cost elements of having such system are categorized to implementation of measurement system and handling of output data from the measurement system. The savings are instead shown in form of:

- fewer tool breakages which reduce the amount of quality discrepancy reports,
- prolonged tool life by running additional operations before tool change,
- avoiding rework,
- decreasing the inventory,
- avoid losing production time by having more robust processes.

However, not all costs can be quantified but instead some advantages and disadvantages with the measurement system and the associated real-time SPC system can be motivated qualitatively.

The profitability of the measurement system is calculated through Equation 1 and lays the foundation for the cost model.

$$Profitability = Savings_{total} - Cost_{total} \quad [1]$$

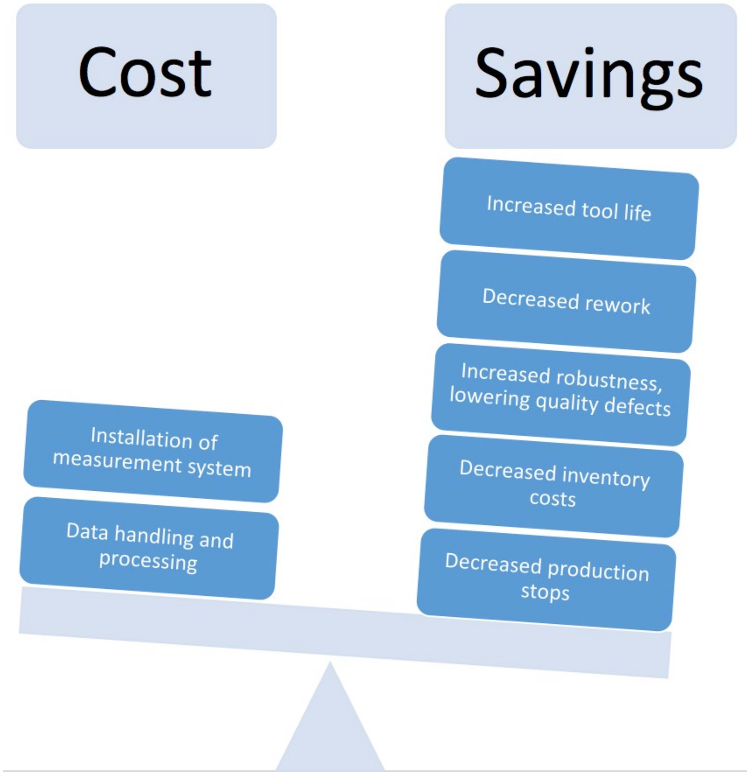

Figure 29 - Identified cost elements for installation of measurement system versus the cost savings of having such system.

5.1 Map of the cost and cost saving elements

The breakdown of the different costs and cost saving elements can be seen in Figure 30. The cost and cost saving elements have been derived from internal interviews and internal documents. The two different cost categories which are considered for this thesis are commissioning and handling cost. The commissioning cost is divided into two cost elements, purchase cost for the system and installation of the system involving several departments at GAS. The handling cost for the system is the cost for storing the data output from the measurement system. This is the only cost which has been accounted for handling of the system for this thesis. The savings are instead divided into quality discrepancy, what are the savings if thread tap breakages can be avoided? This results in avoiding unnecessary rework and reducing scrap of detail. Increased tool life, what is the savings if the tool life of the thread taps is increased? Reduced inventory, what is the cost for reduced inventory due to not awaiting customer conformation. Avoiding production stops due to avoiding quality discrepancies and for not having enough thread taps to run the operation.

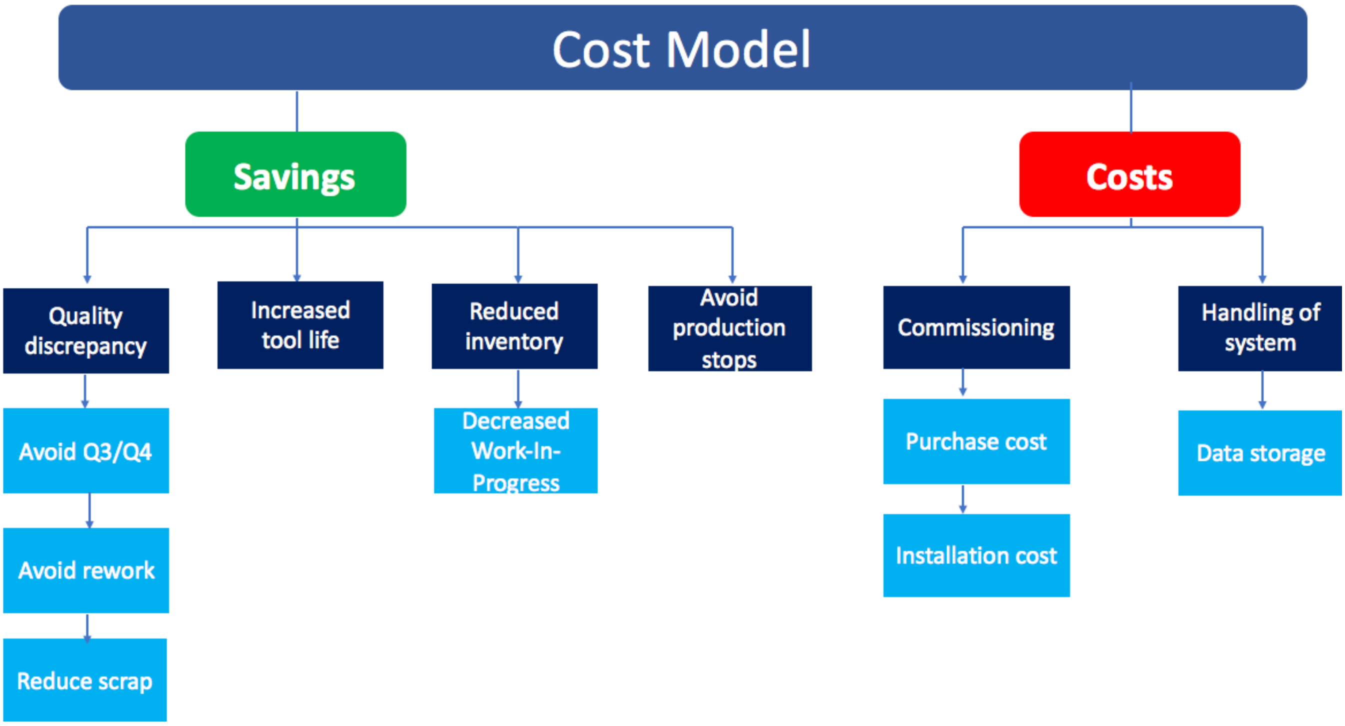

Figure 30 - The figure shows the cost elements that were evaluated in the cost model.

The various cost and cost saving elements can be grouped into two major categories. Costs related to production and administration. The administrative costs are the costs for handling the quality discrepancies and awaiting confirmation between different customer sites. This is explained in chapter 5.2. Please note the breakdown for potential savings and system costs, in Equation 2 & 3 respectively.

$$Profitability = Savings_{total[2]} - Cost_{total[3]} \quad [1]$$

$$Savings_{total} = Savings_{Q3\&Q4} + Savings_{Rework} + Savings_{Scrap} + Savings_{Tool\ life} + Savings_{Inventory} + Savings_{Production\ stop} + (Savings_{WIP}) \quad [2]$$

$$Cost_{total} = Cost_{Purchase} + Cost_{Installation} + Cost_{Data\ Storage} \quad [3]$$

$Savings_{WIP}$ was not quantified in this cost model however it is an element worth considering as it can provide great benefits in terms of productivity to the organization if the WIP is decreased.

5.1.1 Primary assumptions

The assumptions which are used for the calculations is presented in this subchapter. Please note that all costs are assumed by the team and assumptions are made based on plausibility and magnitude of cost, so the cost do not accurately depict the costs at GAS. Detailed description of the calculations can be found in the chapters specific for each cost or cost saving element.

One example of primary assumptions for the cost model is the cost per hour for various departments at GAS. For the purpose of the report the hourly wage was estimated to 500 SEK/hour for all departments. The potential cost savings can therefore differ depending on the actual wage cost for the various departments. Additionally, it was assumed that approximately 25% of the reported tool failures (Q3s) have sustained lasting damage and needed extended rework (Q4s), based on the ratio between Q3 and Q4s seen in Table 2 in chapter 5.2.1.

The cost model will be evaluated by calculating the potential breakeven point of the investment, the hopes expressed by GAS is that the breakeven point for this type of system should be around two years. It is clear, that measurement system like these are instrumental for GAS to retain its competitive edge in manufacturing, however receiving funding can be hard without clear short-term payoffs.

5.2 Cost savings

As seen in Figure 30 major categories of cost elements were identified that showed great promise for cost savings by the new measurement system. Costs related to production and costs related to additional administration. The summary of this potential savings answers RQ2.
The first category, **production** can be divided into following cost savings:

- Rework, if it is rework for Q3 (Operation 600) ~1.4h, Q4 >50h
- Thread taps not being used with maximum efficiency grade due to changing tools after a few cycles to avoid thread tap breakage. Potential cost saving of increasing the efficiency grade (25-33%)
- Loss of production time due to downtime of MTC
- Lead time to customer increased due to Q4 → Inventory costs
- Risk of scraping part due to thread tap breakage, for the purpose of this report probability of (1/1000) was set, *(Worst case scenario)*.

The second category, the costs related to **administration** can instead be divided into following costs:

- Administrative handling of Q3 or Q4 depending of there is a sustained damage on the thread or not
- Awaiting confirmation between customer site and GAS if it is Q4
- Awaiting confirmation between different departments at GAS

5.2.1 Identification of cost savings due to avoiding quality discrepancy

The process of dealing with a thread tap breakage is heavily structured, and a Q3 or Q4 report needs to be written depending on severity. The process can be avoided by successfully predicting thread tap breakage, a potential cost reduction emerges from this cost element. In Figure 31 the process of handling a Q3 is found and the process of handling a Q4 is seen in Figure 32. The process is taken from the internal documentation at GAS. There is a significant difference in the time required for fulfilling the different quality discrepancies, mainly due to Q4 requiring technical review, repair plan and conducting repair and waiting for customer disposition. This in comparison to a Q3 which can be closed rapidly if it can be concluded that no sustained damage is found on the detail.

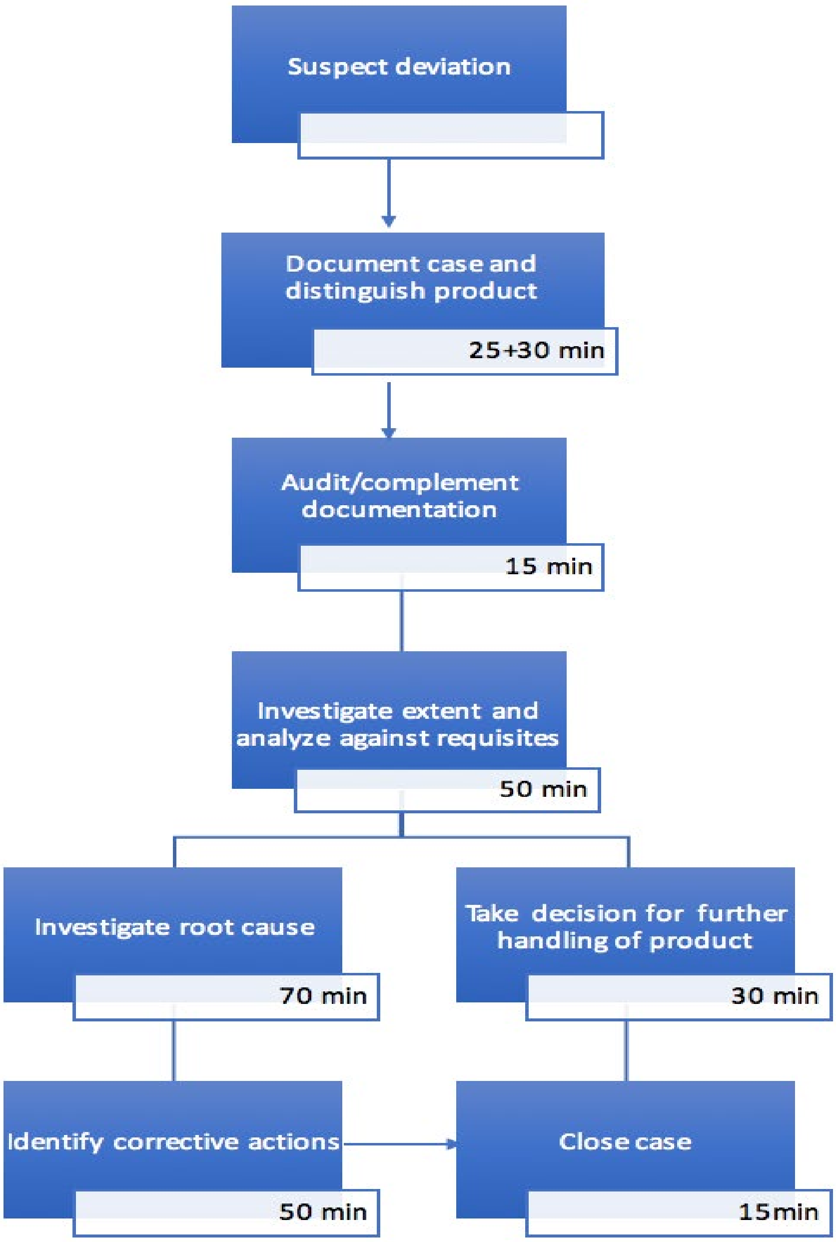

Figure 31 - The process of writing a Q3 report – if there is no sustained damage.

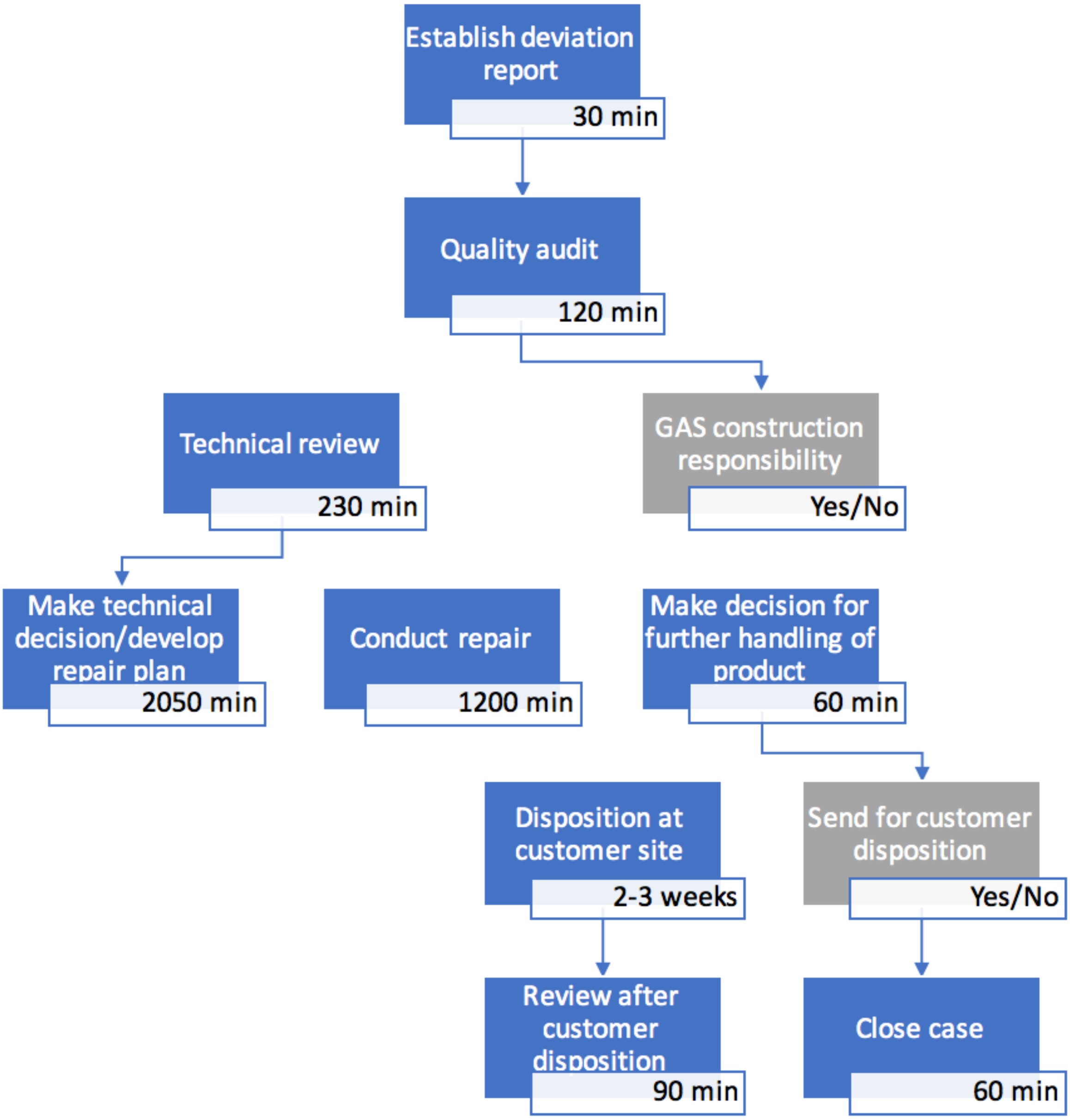

Figure 32 – The process of writing a Q4 report – if there is a sustained damage.

The times seen in Figure 31 and Figure 32 for the various actions, are based on interviews held with the concerned departments – technical and quality, for handling the quality reports. However, the numbers which could not be obtained through the interviews were obtained by internal documents based on a previous cost calculation for Q3 and Q4s at GAS and the identified numbers from the interviews were verified with previous cost calculation. (Sjöberg, 2008).

The costs for a Q3 respective Q4 can therefore be calculated as seen in Equation 4 and 5.

$$Savings_{Q3\&Q4} = Savings_{Q3} + Savings_{Q4}$$

$$Savings_{Q3} = Time_{Q3} * Wage_{Hourly} \; [4]$$

$$Savings_{Q4} = Time_{Q4} * Wage_{Hourly} \; [5]$$

If the times for handling a Q3 are summarized:

$$\sum 285 \, min = 4.75h$$

$$Cost_{Q3} = 4.75 * 500 = 2345 \, SEK$$

If the times for solving a Q4 instead are summarized:

$$\sum 3840 \, min = 64h$$

$$Cost_{Q4} = 64 * 500 = 32\,000 \, SEK$$

5.2.1.1 Process for dealing with thread tap breakage

To investigate the various costs and cost savings the process for dealing with thread tap breakages needs to be understood. Figure 33 depicts an overview of how thread tap breakage needs and is handled at GAS. If a thread tap breakage occurs the operator identifies the damage, changes the tool to make the process continue and writes a quality discrepancy, Q3 report. If there is no sustained damage on the product and the thread conforms to the given tolerances the thread tap is taken out in the manual deburring process in operation 600, to extract the remaining, which takes approximately 1.4 hours if the mean time is considered. If the thread is nonconforming and there is a sustained damage the Q3 turns into a Q4 and the customer becomes alerted of the issue.

Depending on if GAS or the customer have the design responsibility as determined in the contract, the outcome for dealing with thread breakage is different. If GAS have the design responsibility as seen described in Figure 33, a repair plan needs to be produced based on analysis of the non-conformance and communication is carried out with the customer to get the repair plan approved. When the customer approves the repair plan, the repair is carried out and the result is sent to customer site for final confirmation. The rework is now done and the Q4 can be successfully closed.

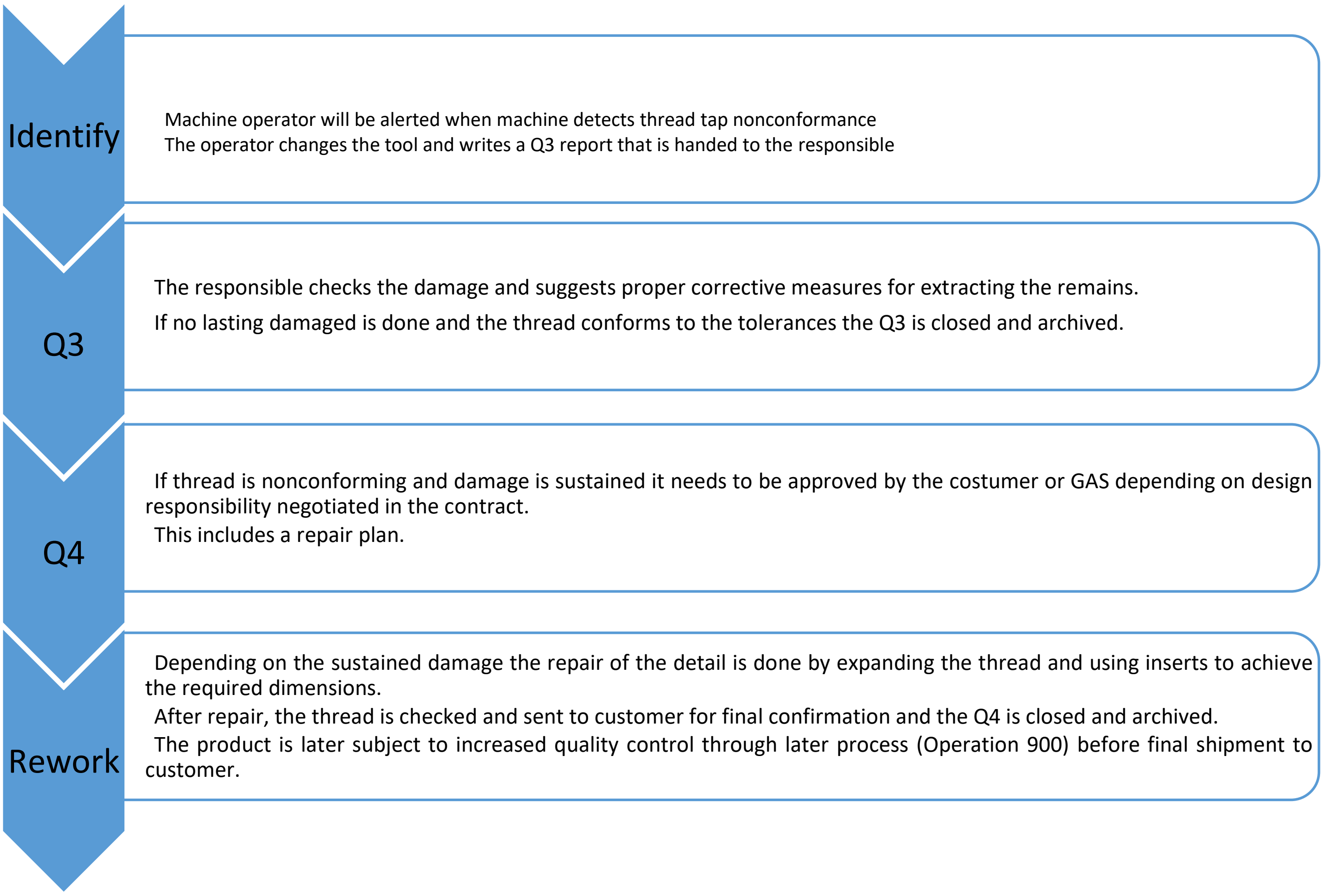

Figure 33 - The process for dealing with threading tap breakage from identification to rework.

5.2.1.2 Identification of number of thread tap breakages

When reviewing the business administration system SAP at GAS, it was possible to identify the number of thread tap breakages which have occurred in the different MTC (MTC1 to MTC5) during the year of 2018. 26 notifications were reported during the production year 2018. Based on the ratio between Q3 and Q4s in Table 2, it was identified that approximately 24% of the Q3s become Q4s.

Table 2 - During 2018, 26 thread tap breakages occurred and for 6 of those extended repairs were needed.

Row Labels	**Count of Notification during 2018**
Q3	26
Q4	6
Grand Total	**32**

5.2.2 Identification of cost savings due to avoiding rework in groove operation

If a Q3 occurs the parts of the thread tap needs to be taken out of the drilled hole. This is done in the groove operation, operation 600, where the operator spends an additional 1.4 hours according to internal documents. This is the next operation after the detail has been processed in the MTC. The additional time for the manual deburring operation was found by investigating internal documents containing times for operation 600. and comparing the orders where thread breakage have occurred against a standardized list of times when there is no thread breakage. This made it possible to understand the additional time for the manual deburring operation, to take out the broken thread tap from the hole. These times could vary according to interviews between one to three hours, therefore according to the mean time of 1.4 hours from the manual deburring operation which was found in the internal document, it should be a good approximation and representation of the actual time for the operation. To calculate the cost for this operation the calculations for the manual deburring operation is calculated by multiplying the mean time for the operator by 500 SEK/hour that was assumed for this cost model. This calculation is seen in Equation 7.

During an interview with a Chief Manufacturing Engineer (CME) it was mentioned that there is an additional cost for the operation, as stifts are necessary to take out the remaining of the thread tap from the hole. According to the interview, two shifts are approximately used with a cost of approximately 100 SEK/each as seen in Equation 8. The combined saving is calculated in Equation [6].

$$Saving_{deburring} = Manpower + Cost_{D-tools} \text{ [6]}$$

$$Manpower = Time_{Extraction} * Wage_{Hourly} \text{ [7]}$$

$$Cost_{D-tools} = Cost_{stifts} * Amount_{stifts} \text{ [8]}$$

$$Cost_{deburring} = 1.4 * 600 = 840\, SEK \;:\; Cost_{stifts} = 2 * 100 = 200\, SEK$$

$$Saving_{deburring} = 840 + 200 = 1040\, SEK$$

5.2.3 Identification of cost savings due to prolonged tool life

There are twelve different thread taps being used to carry out the threading operation. The thread taps vary in size and the amount of details the thread taps complete also vary. It is however according to interviews usually the thread taps with a smaller diameter which are suffering breakage and it usually occurs in the gentler, operation 200. Examining the twelve taps tool cost in the tool list in Table 3. Please note that these are old numbers and does not accurately reflect the current cost. The prices for the thread taps range from approximately 700 SEK to the most expensive thread tap which costs approximately 2500 SEK. The tool cost for each part is calculated according to Equation [10], i.e. the sum of the tool cost divided by tool life. The findings from the threading study motivates that the life length of the thread taps can be prolonged by at least 25-30%. This is further confirmed by two interviews held with experts within tool manufacturing at GAS where it is agreed upon that the life length of the twelve tools can be safely increased by 25% without risking breakage. The thread breakages can most likely be increased by more than 25%. However, this is a number which is strengthened by two interviews therefore the calculations will be carried out based on potential prolonging of the life tool by 25%. The new tool cost is calculated in Equation 11, the sum of the tool cost divided by the increased tool life. For the purpose of this report it is assumed that, 800 numbers of engine parts are manufactured annually, this would be equivalent of 400 smaller jet airliners or 200 larger. If it is assumed that 800 engine parts are manufactured, and the lifetime of the tools can be increased by 25%, then the cost savings are calculated to approximately 346 366 ~ 350 000 SEK annually, as seen in Table 3. It is calculated by comparing the new cost/part with the old cost/part and multiplying by the amount of details manufactured annually, 800, as seen in Equation [9].

$$Saving_{Tool\,life} = Manufactured_{annually} * \left(Cost_{\frac{Tool}{part}} - Cost_{\frac{NewTool}{part}} \right) \quad [9]$$

$$Cost_{\frac{Tool}{part}} = \sum \frac{Cost_{tap}}{Parts_{tap}} \quad [10]$$

$$Cost_{\frac{NewTool}{part}} = \sum \frac{Cost_{tap}}{(Parts_{tap} * Life_{\%})} \quad [11]$$

Table 3 - Showing the approximate tool costs for threading and how drastic savings can be managed by increasing tool life.

Cost Thread tap	Parts/tap	Kr / Part	Increased tool life by 25%	New Cost/Part	Cost savings per Part
1288	20	64,40 kr	25	51,52 kr	423,92 kr
749	9	83,22 kr	11,25	66,58 kr	
749	25	29,96 kr	31,25	23,97 kr	
722	4	180,50 kr	5	144,40 kr	
928	4	232,00 kr	5	185,60 kr	
1179	17	69,35 kr	21,25	55,48 kr	
1547	3	515,67 kr	3,75	412,53 kr	
946	3	315,33 kr	3,75	252,27 kr	
2320	65	35,69 kr	81,25	28,55 kr	
899	3	299,67 kr	3,75	239,73 kr	
749	3	249,67 kr	3,75	199,73 kr	
750	17	44,12 kr	21,25	35,29 kr	
Total		**Total**		**Total**	
		2 119,58 kr		1 695,66 kr	

$$Saving_{tools} = 800 * 432{,}92 = 346\ 366\ SEK$$

5.2.3.1 Cost savings if one additional detail per tool is run

Previous calculations were carried out based on the findings from the threading process and interviews that confirmed the tool life could be increased by 25%. However, the issue with this approximation is that preferably, tools should be used for entire part operations, the tool life would not be set to 3.75 parts, instead it would be rounded up to 4 parts. In other cases, it can instead be the other way around and 11.25 runs should be 11 runs. If it is assumed, that all the twelve tools in the tool list, can run an additional operation then this is the minimum increase which can be done, but still having great impact on cost savings. The new tool cost is calculated in accordance with Equation 12. If all the details run in minimum one more detail the cost saving is estimated to: 357 575 ~ 360 000 SEK. This can be compared to 346 366 SEK. Therefore, there is a cost saving difference seen in Equation 14, 11 209 SEK.

$$Cost_{\frac{Tool}{part}} = \sum \frac{Cost_{tap}}{(Parts_{tap} + Life_{Nr-Increase})} \ [12]$$

$$Cost_{diff} = Cost_{\frac{Tool+1}{part}} - Cost_{\frac{Tool+25\%}{part}}] \ [13]$$

$$Cost_{diff} = 357\,575 - 346\,366 = 11\,209\ SEK \ [14]$$

The reason for the cost savings being greater when running an additional operation, is because the thread taps which complete fewer amount of details before the tool is changed are more expensive per detail compared to the thread taps which complete a greater number of details. However, if the tool which completes 25 details is increased by 25 percent it is instead completing 6 details more however if it is increased to only one more run it completes 26 details. Due to the number of details completed varying with the tool a rather small difference in cost difference is to be expected.

5.2.4 Cost savings due to reduced inventory

Due to the extensive protocols followed in the instance of thread tap breakage a part can be on standby for several months. Consequently the inventory is as such increased, the increased inventory carries a resulting cost. The inventory cost can be estimated by the material cost and rate of interest. For the purpose of this report it was assumed that, the material price of the engine part is estimated by, multiplying an approximate weight by an estimated price on titanium. The weight of the part is approximately 100kg and the approximate price of a kg processed titanium is $400/kg. According to Equation 15 the material cost for the engine part is 40 000 USD.

$$Cost_{enginepart} = Kg * {}^{Price}/_{Kg} \ [15]$$

$$Cost_{enginepart} = 100 * 400 = 40\,000\ USD$$

The inventory cost for the engine part is calculated by multiplying the cost of the engine part which is approximately 40 000 USD by the cost of capital. The cost of capital used at GAS is 12% according to interview held with the department of finance at GAS. Conversion rate between USD and SEK is taken as of May 10^{th} to 9.62. The duration which the details are idle due to waiting for conformation varies heavily in time as seen in Figure 1. These times are based on previous cost calculation carried out at GAS (Sjöberg, 2008). However, it is assumed to still be representative for understanding how long a detail is idle in average as it is awaiting confirmation from customer. Details are in average stored one month according to Figure 1, therefore the rate of interest is divided by twelve in Equation 16 as the rate of interest is based on an annual basis. The monthly inventory cost is calculated by the inventory cost multiplied by the cost of capital divided by 12 (months), in order to calculate the inventory cost for each month, as seen in Equation 16.

$$Savings_{Inventory} = \frac{(Cost_{Material} * c)}{12} \text{ [16] : } c = cost\ of\ capital$$

$$\frac{(40\,000 * 9.62 * 0.12)}{12} = 3848\ SEK\ [16]$$

The cost of storing is therefore 3848 SEK for each engine part which is not delivered to the customer immediately as this is a loss of profit for GAS is in tied capital. In 2018 six out of these deliveries were classified as Q4s as seen in Table 2. This leads to six details having to be stored in wait for confirmation from customer and between departments before repair is conducted. This leads to an inventory cost for the six details. Therefore, the inventory costs for year 2018 can be summarized in Equation 17 to 23 088 SEK.

$$Cost_{inventory,month} = 3848 * 6 = 23\,088\ SEK\ [17]$$

Table 4 - Representation of time the parts have been stored, interval displaying the time the part has been idle in days and the corresponding amount of details are shown.

Interval	Total
1–2	2
3–7	1
8–14	1
15-30	1
31-60	1
91–180	1
Grand Total	**7**

5.2.5 Cost savings due to increased production time

When thread tap breakage occur the machine stops, and several steps are needed to clear and prepare for continued production in the MTC. This cost of loss of production can be de approximated by dividing sales with total number of hours worked, for the purpose of this cost model it has been assumed that $Cost_{\frac{production}{hour}} = 800\ SEK$.

Depending on how long the MTC is stopped there will be a loss in production. The loss of production does heavily depend on *when* the thread tap breakage occurs. If it occurs during the nightshift the stop can last for several hours, but if it happens during the dayshift it can be solved within 15 minutes. For ease of calculation it was estimated that the machine stands still one hour per breakage.

$$Savings_{Production\_hour} = Cost_{\frac{production}{hour}} * Time_{hour} [18]$$

$$Savings_{Production\_hour} = 800 * 1 = 800\ SEK$$

5.2.6 Cost saving due to reducing scrapping

The worst-case scenario is worth considering even if the probability of it occurring is low. This scenario occurs if the detail is scrapped due to thread tap breakage. The probability of this occurring was set to 1/1000, this was approximated by the thesis team (extreme case). The material price of the engine part is approximated to ca 400 000 SEK, by estimating the weight and the price of titanium. Please not that this is not the standard price of the part, and for a more correct assumption the processing cost needs to be added to the material cost.

This means that approximately 400 000 SEK is lost due to potential scrapping of the detail. The rate of scrapping was set to 1/1000 details, this means that with the current production estimates of 800 engine parts, one product is scrapped every 15 months of production. The annual scrap risk is calculated in Equation 20. Annually 320 000 SEK is lost in scrap costs due to this probability if it is assumed that 400 000 SEK is multiplied by the annual scrap risk. This is shown in Equation 19.

$$Saving_{scrapp} = Risk_{\%} * Value_{part} \ [19]$$

$$Risk_{\%} = \frac{Manufactured_{annually}}{Manufactured_{\ failure\ rate}} [20]$$

$$Savings_{Scrap} = \frac{400\ 000}{1000} * 800 = 320\ 000\ SEK$$

5.2.6 Cost savings due to avoiding loss of thread taps

It is mentioned in one of the interviews with Chief Manufacturing Engineer, during periods with a high frequency of thread tap breakage, there is a risk that GAS will run out of tools. This has happened before and caused a standstill in the production. This needs to be valued in the same way as cost due to loss of production time, as seen in Equation 18 for calculating the loss of production time. This could not be put in the cost model but is crucial to increase the manufacturing robustness.

5.2.7 Cost savings due to decreased Work In Progress

During interview with the production leader and the person responsible for the specific engine part programme, it was mentioned by the interviewees that the Work In Progress (WIP) can be reduced by predicting thread tap breakage. By reducing thread tap breakage, the over al lead-time would be decreased, as well as increasing the predictability of manufacturing process. By increasing manufacturing predictability, it would be possible to reduce buffers and increasing supply chain efficiency. The cost savings for decreasing the WIP was not included in the cost model, due to the complexity of calculation and time restrictions of the master thesis.

5.3 Measurement system commissioning and data costs

The benefits and cost savings possible with the measurement system, must outweigh the commissioning and implementation cost of said system. There are several different costs that occur besides the purchasing of the system. Time needs to be spent by the different functions of GAS and the data need to be stored somewhere. The following costs were identified and calculated and so answering RQ3:

- **Costs due to storage of data:** The system produces a lot of data and requires storage space on which it can be saved.
- **Cost due to IT systems:** GAS complex IT system needs to be checked to allow the implementation of a new third-party device.
- **Cost due to implementation of measurement system:** The maintenance and CAM function at GAS are directly affected and need to be involved in ensuring that the manufacturing systems can interact with the measurement system.
- **Purchasing cost of measurement system:** The fixed cost for the measurement system.

5.3.1 Costs due to storage of data

The measurement system is sending data from the production server to the internal server at GAS where it is later saved and used. This data is requiring storage space on the server. However, storage space is not free of charge as it is requiring servers for the data to be stored on. Currently the cost for 1 Gigabyte is around 1 SEK (Mott, 2019), by including some server maintenance, software license cost etc., we will assume a total cost to 3 SEK/Gigabyte and an additional 1 SEK for backup of the data for each Gigabyte. The total cost for each Gigabyte is therefore 4 SEK. During an interview with a representant from the IT department it was concluded that the measurement system stores approximately 50 Gigabyte annually based on the current rate of data save from the measurement system. The cost can therefore be calculated as seen in Equation 21.

$$Cost_{storage} = Cost_{Gigabyte} * Gigabyte_{Total} \quad [21]$$

$$Cost_{storage} = 4 * 50 = 200 \frac{SEK}{year}$$

This cost for storing the data is in comparison to the total cost of the measurement system negligible. However, the cost is still worth having in mind as it will quickly grow over time and the addition of new measurement systems. The reason this cost is not higher is due to only taking the hardware costs into account, the costs for electricity and cooling of the servers are not considered in this calculation.

5.3.2 Cost due to implementation and installation of measurement system

The cost for the measurement system to be installed was 175 000 SEK for the hardware and for the installation of the system to be completed on the machine by the supplier of the system.

$$Cost_{purchase} = 175\,000\ SEK$$

However, additional costs emerged due to the work different departments at GAS conducted to make the system compatible with internal standards and with the machines. The ingoing hours for the project vary depending on the department. The IT-department spent approximately 80 hours for making the measurement system compatible with GAS IT-system, according to interview held with IT department. The maintenance department spent 24 hours for installation. According to the questionnaire asking two different CAM engineers being responsible for the implementation of the measurement system one engineer spent 60-70 hours and an additional 5 hours meeting time and the other allocated 40 hours. This is confirmed, by an interview with the responsible for implementing the measurement system, which the CAM department allocated 100 hours towards implementing the software onto the MTC. The sum of the different times for the various departments which have been identified during interviews are seen in Table 5. The additional cost for the implementation of the system can be seen in Equation 22. The time cost per hour for the different departments is approximated to 500 SEK/hour as described in 5.1 This cost is added to the cost for the system and is all together summarized as the implementation cost.

Table 5 - The time requirement differed between the functions but all state that next implementation would be drastically less time consuming.

Maintenance Department	IT Department	CAM Department
24 Hours	80 Hours	100 Hours

$$Cost_{installation} = \sum_{Departments} Time_{Department} * Wage_{Department} \quad [22]$$

$$Cost_{installation} = (24 + 80 + 100) * 500 = 102\ 000\ SEK$$

5.4 Result of Cost Model

Calculations have been carried out below for the production year 2018. The calculations are carried out based on 26 Q3s and 6 Q4s, the number of Q3s and Q4s as seen in Table 2.

The calculations are assuming a prolonged tool life of 25% and that all the quality discrepancies could be avoided using real-time SPC.

5.4.1 Summary of costs and cost savings

The calculations which can be potentially reduced are summarized in the Table 6.The size of the potential cost savings is shown for each cost saving element.

$$Savings_{total} = Savings_{Q3\&Q4} + Savings_{Rework} + Savings_{Scrap} + Savings_{Tool\ life} + Savings_{Inventory} + Savings_{Production\ stop} + Savings_{WIP} \quad [23]$$

$$Savings_{Q3} = 2375 * 26 = 61\ 750\ SEK$$

$$Savings_{Q4} = (32000) * 6 = 192\ 000\ SEK$$

$$Savings_{Rework(deburring)} = 1040 * 26 = 27\ 040\ SEK$$

$$Savings_{Scrap} = \frac{400\ 000}{1000} * 800 = 320\ 000\ SEK$$

$$Savings_{tool\ life,25\%} = 346\ 366\ SEK$$

$$Savings_{Inventory} = 23\ 088\ SEK$$

$$Savings_{Production\ stop} = 800 * 26 = 20\ 800\ SEK$$

Table 6 - Summarized cost saving elements for 2018.

Return from prolonging tool costs by 25%	343 366 SEK
Return from avoiding all Q3s due to avoiding thread tap breakage	61 750 SEK
Return from avoiding all Q4s due to avoiding thread tap breakage	192 000 SEK
Return from avoiding additional time in manual deburring operation	27 040 SEK
Return from avoiding the MTC to stop due to avoiding thread tap breakage	20 800 SEK
Cost due to avoiding Q4s and the product to be idle waiting for conformation from customer	23 088 SEK
$\sum_{total\ cost\ savings\ system} 343\ 366 + 61\ 750 + 192\ 000 + 27\ 040 + 20\ 800 + 23088 = 671\ 044\ SEK$	671 044 SEK

In Figure 34 in the pie chart the different categories are shown based on the potential cost savings. It is found that the great savings can be done in increasing the tool life and avoiding quality defects. The quality defects stand for 38 percent of the cost savings (29+9) which can be done, while increasing the tool life stands for most of the savings, 52 percent.

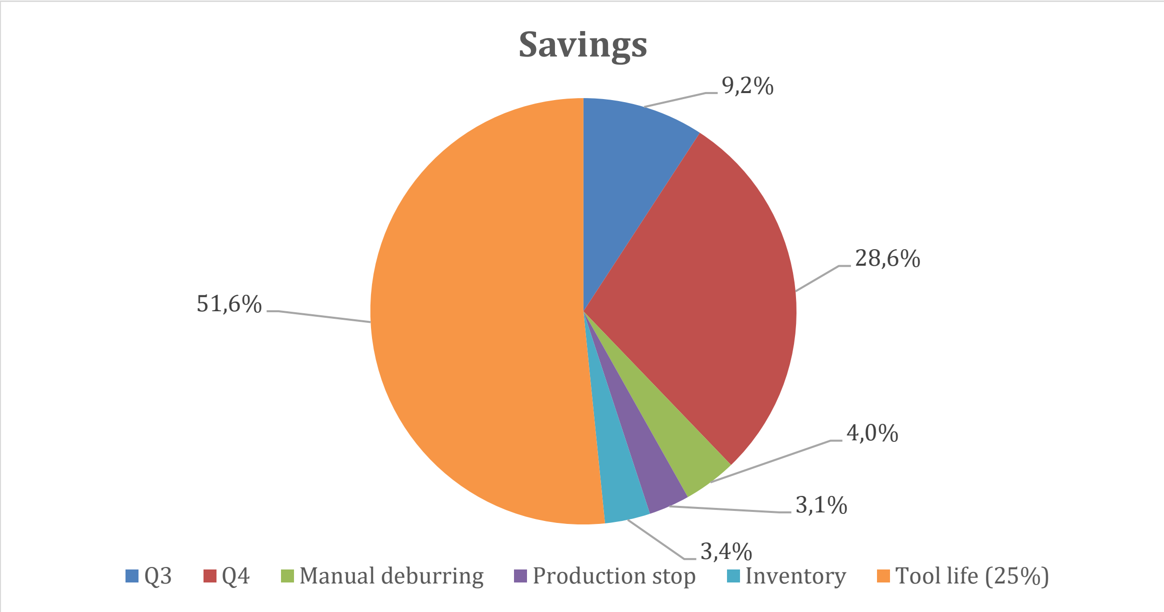

Figure 34 - Savings from tool life and administration are the main savings.

The cost elements for having the measurement system is shown in Table 7 and the total cost is calculated through Equation 24.

$$Cost_{total} = Cost_{Purchase} + Cost_{Installation} + Cost_{Data\ Storage} \quad [24]$$

$$Cost_{purchase+installation} = 102\ 000 + 175\ 000 = 277\ 000\ SEK$$

$$Cost_{handling} = 200\ SEK$$

$$Cost_{total} = 102\ 000 + 175\ 000 + 200 = 277\ 200\ SEK$$

Table 7 - Summarized measurement system cost elements for 2018.

Cost including the cost for the system, installation from supplier and the various departments at GAS (Purchase cost + installation)	277 000 SEK
Cost for data storage	200 SEK
$\sum_{total\ cost\ system} 102\ 000 + 175\ 000 + 200 = 277\ 200\ SEK$	277 200 SEK

5.4.3 Winnings of installing a real-time SPC system

The potential return for year 2018 is calculated by subtracting the measurement system cost of the potential savings. The return for 2018 would be 393 844 SEK ~ 393 000 SEK, as seen in Figure 35.

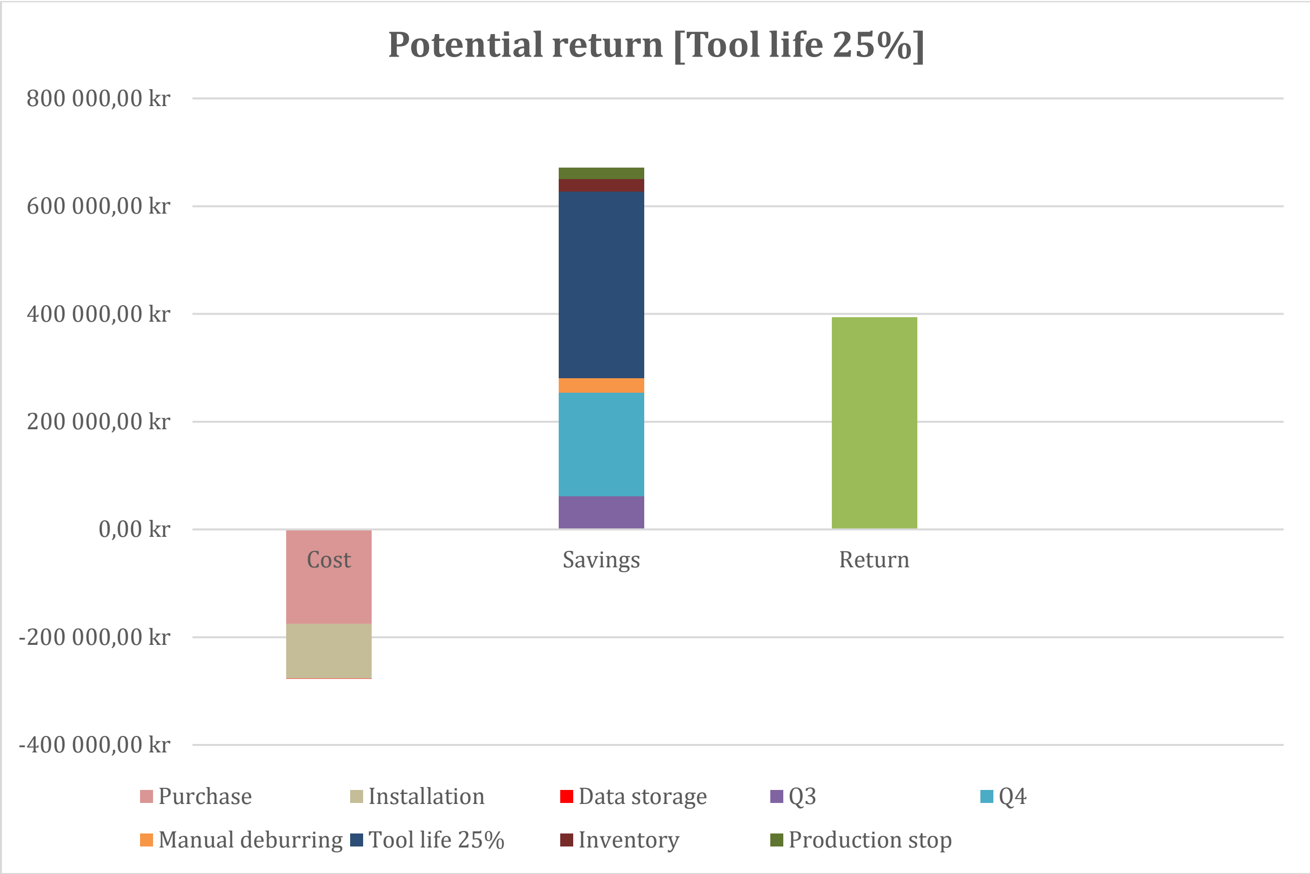

Figure 35 - The cost savings after one year are greater than the commissioning cost for one system

If the calculation above is carried out taking the scrap cost into consideration, then an additional 320 000 SEK can be saved by avoiding scrap costs.

If this is taken into consideration, then the net profit of installing the measurement system is instead 710 000 SEK as seen in Equation 25 and is visualised in Figure 36.

$$Potential\ reduction = 393\ 000 + 320\ 000 = 713\ 000\ SEK \quad [25]$$

‘

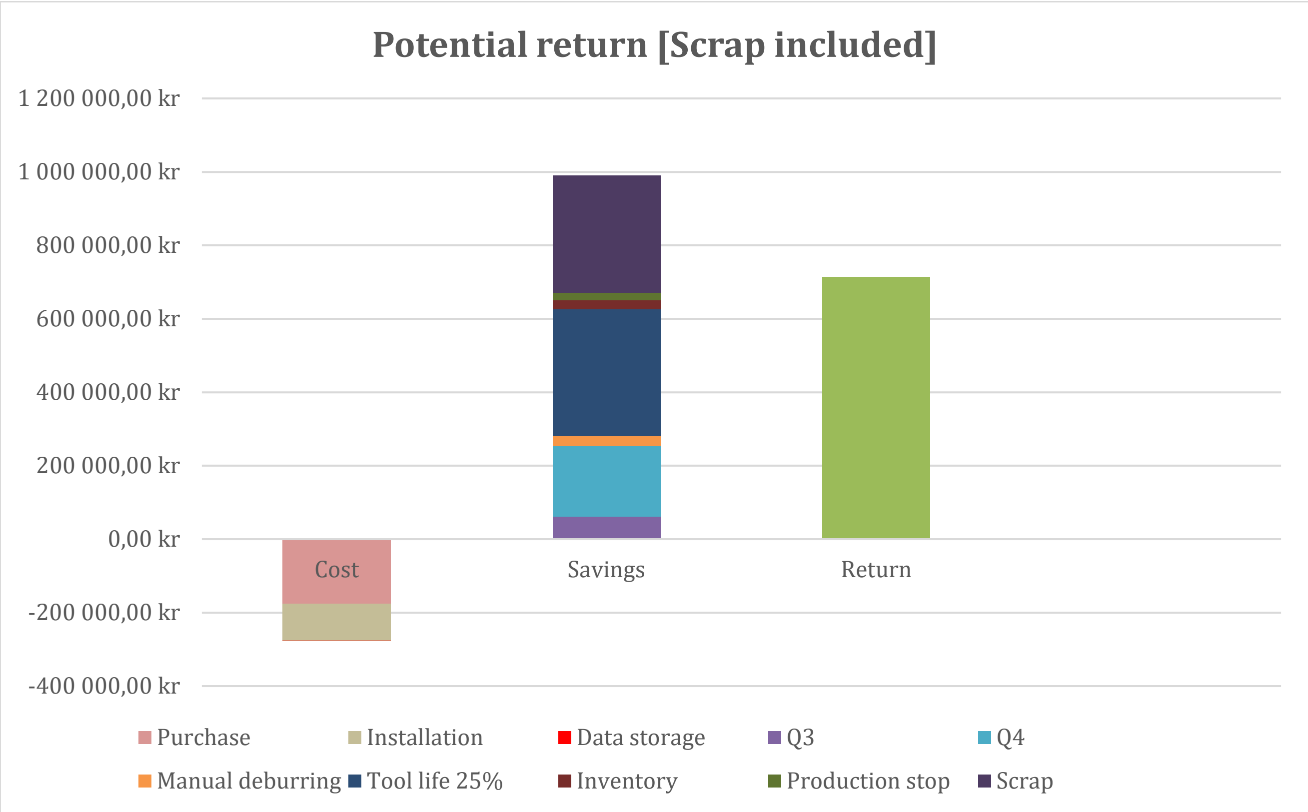

Figure 36 - By reducing the possibility in scraping one in a thousand parts even greater savings could be made.

The winnings of a real-time SPC system need to be put in relation to the investments. GAS have a depreciation time of 2 years on their production equipment. If it is assumed that the system was installed on all five machines, then the investment would be 175 000 SEK multiplied by five units for the purchase cost. If we assume that the process is standardized for installation after the first unit, it is a fixed cost of 102 000 SEK. This gives us the investment cost of:

$$Cost_{investment} = 175\,000 * 5 + 102\,000 = \sim 975\,000\ SEK$$

The potential return if the life length of the tools is extended by 25% is however approximately 710 000 SEK, this in comparison with the investment gives that the breakeven point for the investment is approximately 1,4 years. This is without considering the possible cost for scrapping a detail. These calculations show that the investment fulfills the standard depreciation time of 2 years at GAS, therefore the result of the cost model is that the investment is worth it.

5.5 Sensitivity analysis

Sensitivity analysis is required to validate and verify the result of the cost model. The calculations which have been conducted are based on more or less optimal conditions. The calculations above are valid if **all** the thread tap breakages can be prevented by implementation of real-time SPC. However, the conditions are not always optimal and therefore the calculations need to be carried out based on varying the value of the parameters and the assumptions which the calculations are based on. There are some cost elements which can be assumed to be constant therefore these will not be considered in the sensitivity analysis. The different cost elements are categorized in Table 5.

It is necessary to perform a cost sensitivity-analysis on a cost model. This because there are always parameters which vary, and which are made upon assumptions. Numbers are always changing, for example the rate of interest is a parameter which often varies and which can affect the result. Therefore, a sensitivity analysis is in this chapter performed based on varying the biggest assumption - the amount of Q3/Q4s which can be prevented. Manual deburring, production stops, inventory costs are all in correlation with the number of quality discrepancies, therefore these are also lowered by the same number as the quality discrepancies as seen in Figure 37.

If it is assumed that *at least* 50% of the thread tap breakages can be avoided by predicting tool wear and using real-time SPC to prevent the tool to exceed the control limit the potential cost reduction can be seen in Figure 37.

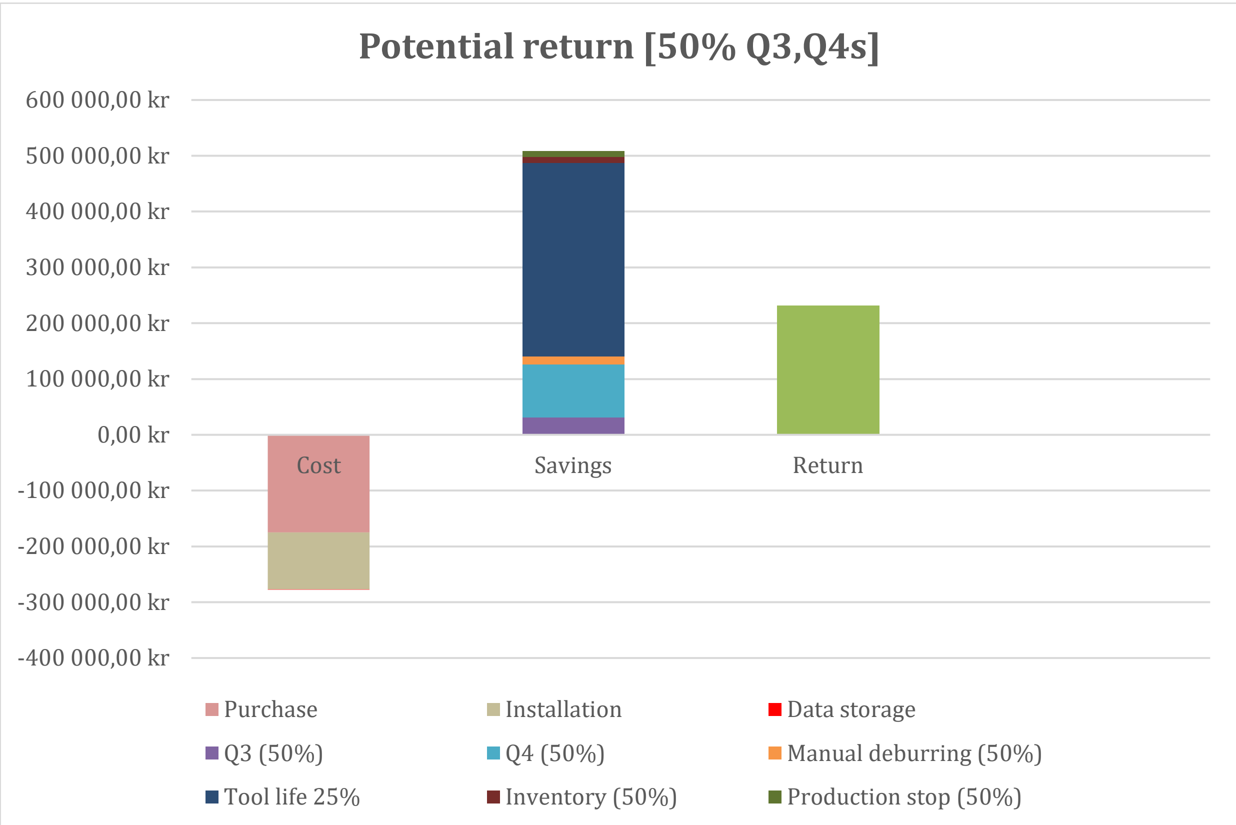

Figure 37 - By assuming that the system will only catch half of all errors, the savings are still substantial even without considering the scrap savings.

When test and verification plan is done at GAS, it is calculated that the equipment should be depreciated within 2 years otherwise the equipment is not purchased in first place. This is important to take into consideration when showing the profitability of the measurement system to place it in relation to the investment. If only the life length of the tools is extended by 25% the measurement system is paid off within less than a year. Based on the findings from the study it identified that the life length of the tools could be extended to two more parts. However, this puts higher pressure on that the real-time SPC feedback is functioning accurately, as it needs to be able to stop the operation if it is abnormal. This due to tools working closer to the set control limits.

6. Discussion

In this chapter the implications from the thesis are discussed and the study credibility of the study is evaluated along with proposal for future research within the subject of the thesis.

6.1 Evaluation of credibility

The credibility of the thesis is dependent on the data which was collected from the measurement system in the threading study. The credibility here is risked by basing the analysis only upon one thread breakage. During an interview held with a professor within signals and systems at Chalmers it was mentioned that in order to expect more credible results more thread breakages are needed; it cannot be circumvented in any way. It was stated that it was mandatory for GAS to run the thread taps to failure to have sufficient data to conduct an analysis. The current analysis was made upon solely one thread tap breakage. To have more credibility more thread taps would be needed to be able to base the analysis on several thread tap breakages. For adjusting the fit of the control chart with appropriate warning and control limits more data from thread tap breakages is mandatory. The issue is the measurement system is only installed within one MTC, MTC 5, therefore it requires the thread tap to break in this machine to be able log the data for the breakage. There were several thread tap breakages in other machines, however only one in the MTC 5 since the installation of the measurement system. One thread tap breakage is not significant to draw any conclusions on what underlying factors are, a sample of approximately 20 thread tap breakages would be needed to have a representative sample. In chapter 5, some costs were approximated by assumptions. This is something which can affect the credibility of the result. For this reason, the assumptions which were made were motivated clearly. To show that the result of the thesis is credible even if all costs are not correctly estimated a sensitivity analysis performed on the cost model.

6.2 Implications of the study

There were interesting findings from the study conducted at GAS. By following the implementation phase of the measurement system, the progress has been clear. From not being able to retrieve any data from the threading process without forcing the machine, to now having real-time data on the process and being on a good way towards predicting thread tap breakage. It is now possible to visualize tool wear and there is an increased knowledge in preventing thread tap breakage. Not to mention the overall knowledge in the threading process has increased drastically as there is now data in form of torque, position and rotations per minute for every operation which is performed. Chapter 4 showed the potential of predicting thread tap breakage and tool wear, and chapter 5 presented the potential cost savings which can be managed by predicting thread tap breakage and tool wear.

However, there are external parties hindering the development towards enabling real-time SPC. There are laws which GAS needs to follow from e.g. The International Air Transport Association (IATA) and their customers. Some parameters according to interviews at GAS must be frozen, therefore this is a hinder to the development of a real-time SPC system towards predicting and avoiding thread tap breakages.

It was also noted during the study especially during the conducted workshop that there seems to be a residual reluctance to implement new measurement systems within the organization. However, this was not analysed further, but the working theory is that manufacturing managers are too preoccupied with firefighting as their KPIs are related to the number of products that get processed. If manufacturing managers were given KPIs that reflected improvement in data and analytics, there would be stronger incentives to invest time and money in measurement systems that would pay off greatly in the future as the study has shown. During one interview, it was mentioned, that previous investments in measurement systems had resulted in data which was hard to read and to understand the value of the data. This indicates that it is not only a matter of KPI priority but also how the value of the data is presented. Storytelling is a term that has been thrown around lately and this only strengthens the notions that data is only as valuable as what can be seen and learned from it, and need to directly be correlated to tangible improvements for the organization.

The threading process was a suitable case to study as thread tap breakages were identified to be an issue for the process. The findings from the threading process can however be applied to additional processes. The study has shown that machine data is something worth storing and can be used for operations improvement. By installing measurement and real-time SPC system for additional machines the understanding and knowledge for the specific process will increase. The implementation cost will decrease heavily with additional installations as the installation on the MTC 5 can be seen as a test installation therefore it is natural to cost more for the first machine the system is installed on. This is additionally strengthened by the empirical findings, from interviews where it is confirmed that the cost would decrease for additional installations in the machine park. IT department has e.g. stated that the installation process is not standardized and that not more than an hour or two would be required to make the machine compatible in comparison to the 80 hours which were used for installing the system on MTC 5.

6.3 Future research

The result from the threading study and cost model show that there is potential for cost savings within the threading process. However, it has been understood that there is interest in additional processes for storing process data and allowing for decision making based on this data. The issue is that for some processes it is hard to characterize the parameters to monitor which is typical for e.g. welding process. The study on the threading process have shown that thread tap breakage can be predicted and when it is predicted there are big cost categories which can be reduced using real-time SPC. The same measurement and real-time SPC system can be applied for several processes within GAS. If it is assumed that quality defects can be avoided, and tool life length can be extended and if the process is in statistical control as described by Montgomery (2013) then there is great potential for a real-time SPC system. The advantages are many, not only for reducing the cost related to the process but to effectives the process. For future research, other processes could be investigated but the analysis should also be redone when there is more thread tap breakages to rely on. Therefore, if the analysis would be repeated on new data there could be interesting findings to expect. Having bigger amount of data on thread tap breakages is a key step for setting warning and control limits. This is a prerequisite for preventing thread tap breakages as seen in chapter 4. This thesis has shown that there is potential with storing machine data and basing decisions on this data. The question is no longer *if* the data is useful but rather *how* should it be used to improve the production processes at GAS. What this study discovered which could not be accomplished due to time restriction is that the quality of the threads can be cross referenced with the process characteristics of the MTC cell. This would create prerequisites for adaptive machine processing and be a great step towards the work of reaching Industry 4.0 which is an internal aim at GAS. This is something which should be studied closer in the future. Further research could also be done on the treading characteristics, the peaks and valleys analysis presented in the threading study show some interesting properties. Nonetheless, by taking inspiration from ECG and cross referencing the peak analysis against the different types of tool wear, this could further increase manufacturers' ability to lengthen tool life, while maintaining a high reliability and finished product quality. Worth mentioning is this could be an instrumental tool for tool manufacturers in designing better tools.

7. Conclusions and recommendations

From the result of the threading study in combination with the cost model the thesis concludes that with the current measurement system on MTC 5, GAS has the capability to drastically reduce costs from manufacturing. The possibilities presented for GAS are not limited to reduction in production errors and tool costs, the long term benefits the data will provide is crucial for automating and implementing a successful Industry 4.0 solution. Though the thesis only investigated the threading process, all metal cutting processes suffer from the same type of wear and should in theory be detected with the same type of system.

From the theoretical framework, it has become ever clearer that data is an untapped resource, data is the fuel for any Industry 4.0 solution (Marr, 2015). Without it no matter how powerful tool or system GAS implements, data collection needs to form the base. The obliqueness of Industry 4.0 and the many theories and tools developed lets one get confused and overwhelmed. The thesis proved that though the end goal of Industry 4.0 is far from achieved, only by taking small steps and starting to measure and analyse new sets of data, value and quality can be derived.

7.1 Answer of research questions

RQ1: Can thread tap breakage and tool wear be predicted?

This research question was answered in chapter 4, in the threading study. In this study, it was concluded that it was possible to predict thread tap breakage and tool wear. This was possible by using real-time SPC for setting appropriate warning and control limits to prevent the thread tap to reach higher torque than predefined by the system. It was also seen that tool wear is predictable, it was clear when the thread tap had been worn out and was about to experience breakage. If the process had been stopped before the high torque was reached the tool tap breakage could have been avoided. It was seen that the life length of the tools could be increased by at least 25 percentage based on the torque of the broken thread tap. Characteristics of the thread tap breakage were identified and the process could have been stopped by recognising the negative trend which was clearly seen since the thread tap was used in the first operation.

RQ2: What are the current costs for thread tap breakage and tool life at GAS?

The threading costs which were identified can be divided into two categories, costs related to production and costs related to administration. The cost elements which emerged from these two categories and which were considered in the cost model were alternative costs due to changing tools early, cost for Q3 and Q4, cost for manual deburring operation, cost for MTC cell stopping and cost for inventory due to waiting for conformation from customer if Q4 occurs. These costs can be reduced by implementing a real-time SPC system. These costs have great opportunity to be prevented and reduced by the utilization of real-time SPC. It could be identified in chapter 5 that the cost for the thread tap breakages and short tool life is approximately 670 000 SEK/annually.

RQ3: What was the cost for implementing the real-time SPC system?

The cost of implementing the measurement and real-time SPC system which is currently in use in MTC 5, has according to the empirical findings and cost model cost the organization approximately 300 000 SEK. The cost elements which are considered into this amount are cost for the system, implementation and cost for handling the data storage. The costs are due to buying the system from the supplier and the costs are for implementing the system. This required time by various departments. The IT department invested 80 hours into the installation of measurement system, for making the machine and the standards at GAS compatible with the system. The maintenance department invested approximately 24 hours for installing the measurement system and the CAM department invested approximately 100 hours for making the NC program compatible with the system.

RQ4: Do the benefits of a real-time SPC system for threading outweigh the cost of implementation and handling?

This research question is answered by combining the result from the second and third research question. The second question investigates the potential cost savings by using real-time SPC and the third question corresponds to the costs of the real-time SPC.

There are great benefits from using a measurement and real-time SPC system as this thesis has shown. The benefits of using this system can be visualized in Figure 38. Here the costs are compared with the potential returns that can be achieved by predicting thread tap breakage and tool wear. The cost savings and the current costs show on the potential cost reduction which can be achieved by installing this system. This is answering the purpose of the thesis and showing the potential cost reduction of utilizing machine data. There are different scenarios which lead to different cost savings. The different calculations which were carried out were if the tools life was prolonged by 25%, if the tools instead were running an additional operation, if half of the quality discrepancies could be avoided (50%) by predicting tool breakage and if scrap cost was included into the calculations. It is clearly shown that the benefits of having a measurement/real-time SPC system outweighs the cost of the system by visualizing the different costs and cost savings along with the potential return as seen in Figure 38 below. It is seen in the cost model that the breakeven point is reached within 1,4 years if the system is installed on all MTCs. This in comparison with the depreciation time of two years for production equipment at GAS motivates further that it is an investment worth fulfilling and that the benefits of a real-time SPC system does outweigh the cost of implementation.

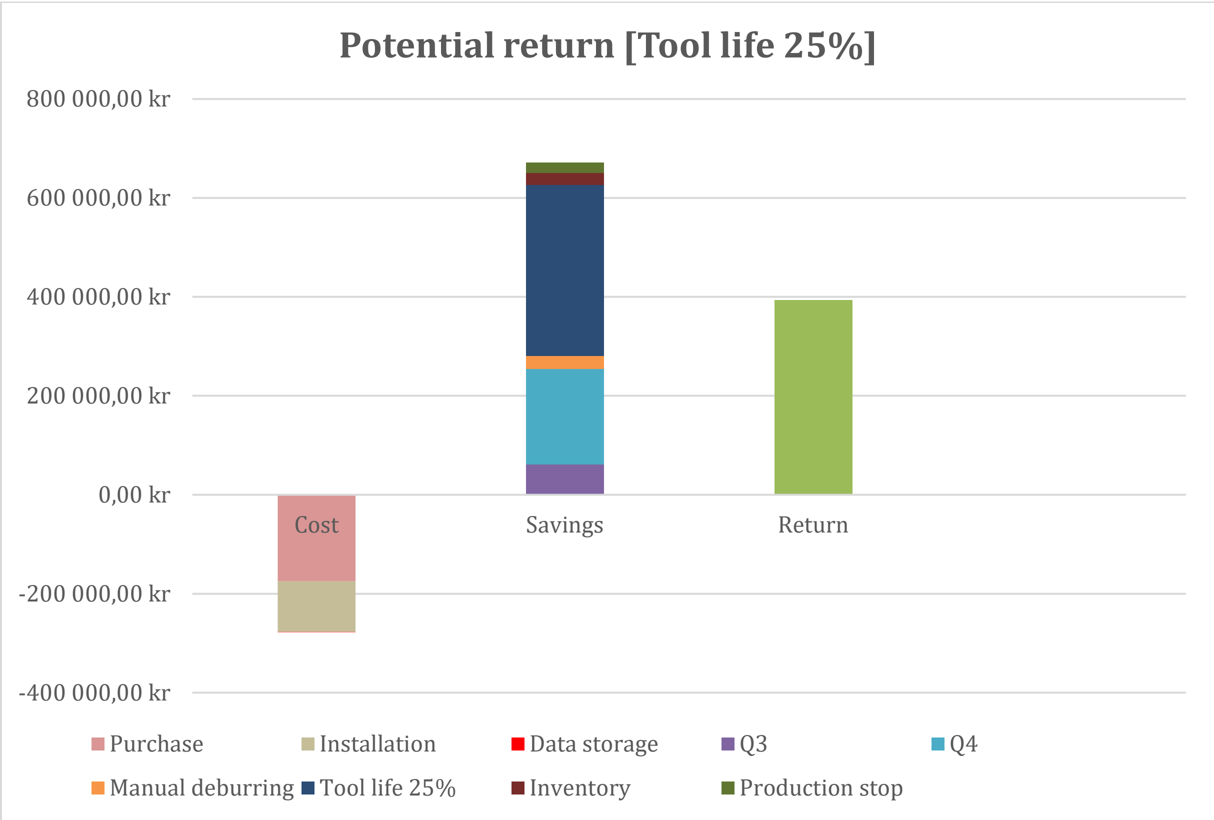

Figure 38 - The potential returns are extraordinary and show how valuable data can be.

7.2 Recommendations

The measurement system which was installed on MTC 5 showed to be significantly useful, installing the same or similar systems for additional machines should be of high priority as it would then allow traceability for the entire threading process. What should additionally be of high priority is to try and run the thread tap breakages to failure to gather data which can be used to soon implement warning and control limits for the MTC park. This will allow GAS to take the next big step words machine adaptivity and the world of real-time SPC.

The thesis did not investigate how the process characteristics result in the end quality of the thread. However, by cross referencing tolerance measurement with the process characteristics which were analysed in the threading study, it would be possible to create predictive models for adaptive manufacturing. For instance, with the data now available, it would be possible to utilize machine learning or neural networks. The only parameter which is missing is that additional thread tap breakages are required to identify the characteristics to a better extent. It is additionally recommended for GAS to continue working with the machine data and explore other parameters which are stored, such as the position. This will allow for further understanding by analysing the measurement data from a different perspective.

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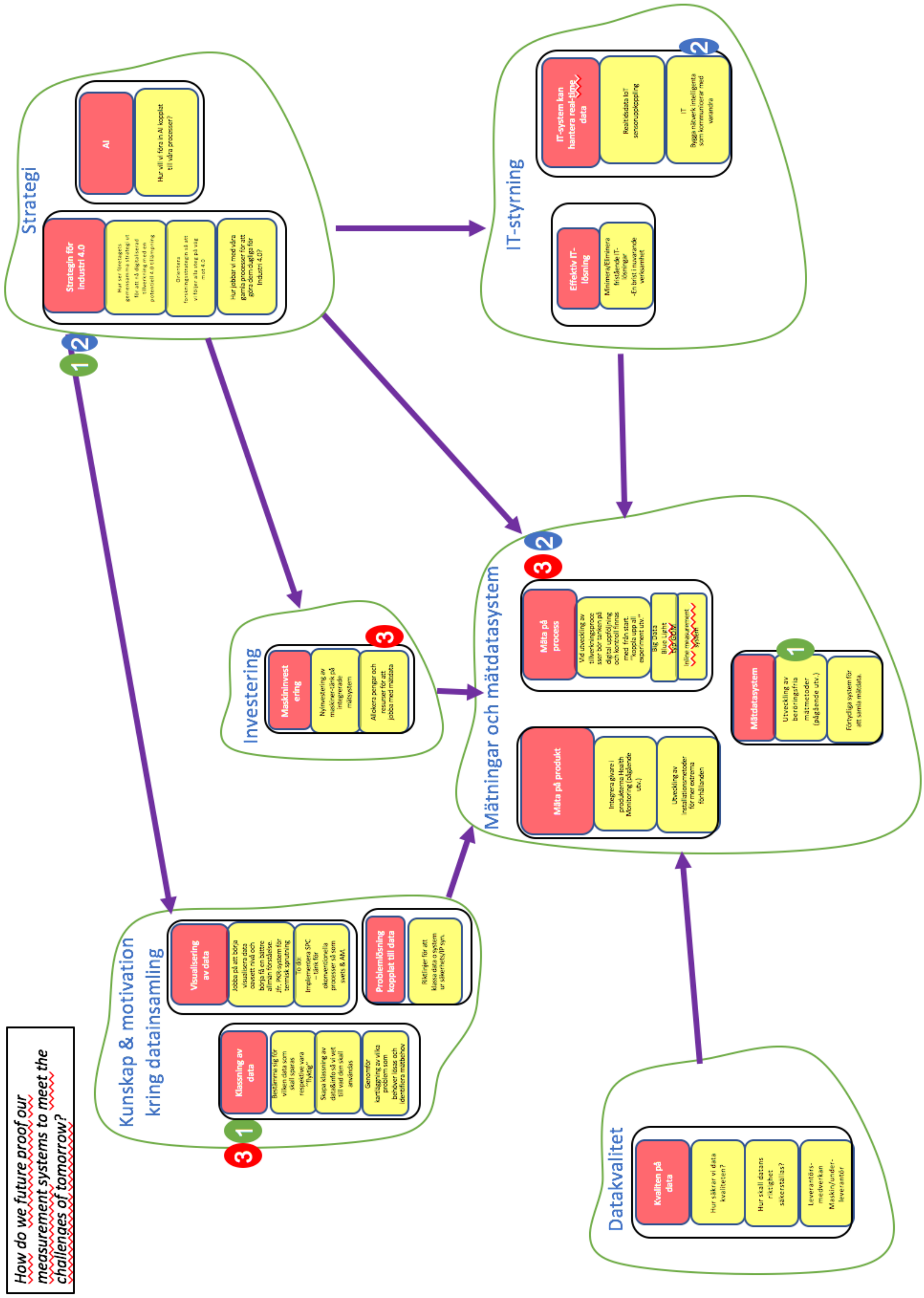
Appendix

Appendix A - AIM



Appendix B - Interview questions

<u>Introduction</u>

- Greetings & short summary of who we are and what we are doing
- Address ethical considerations (e.g. anonymity)
- Years worked at GAS?
- Position at GAS & responsibilities?

<u>Understanding how robustness is measured and how it is implemented</u> (Warm up)

How do GAS translate robustness in its core operations?
How do you control/measure robustness?
How has this been implemented in production?
How will GAS deal with robustness in the next decade?

<u>Identifying if thread tap breakages and tool wear can be predicted</u> (Investigation of the opportunities to use real-time SPC for preventing thread tap breakages and tool wear)

Is there a correlation between the number of defects and the machine characteristics/properties?
What does the production systems need to look like to enable an implementation of Real-Time SPC?

<u>Identifying costs and value of the installed measurement system</u> (Investigation of the various costs for the measurement system and the threading process)

How are the advantages and disadvantages compared of a measurement system?
Which costs do you identify in the threading process?
What benefits do you see data providing the production processes?
Which cost categories do you think are the biggest?
What do you think access to more data could contribute?
Do you think access to more data provide opportunities to reduce costs in the threading process or more general, production processes?
If you could hypothetically invest into the production process with endless funds, what changes would you make?
Which costs could be potentially reduced in the production? (Rework, scrap..)
How does GAS use machine data today?
How do you compare the benefits with the costs of data?
How does GAS use machine data to control production processes?
What costs do you see with using machine data? Or which costs do you see with not using

machine data?
Can these costs be avoided by using machine data and real-time SPC?
What cost does GAS consider when investing into measurement systems?
How does GAS motivate investments in measurement systems?
What cost do you associate with measurement systems?
What benefits do you associate with measurement systems (MS)?
How does the idea to implementation process look like for MS?
How would you like to see GAS handle data in 10 years?
Why would you like to see these changes?
What do you think is stopping these changes from happening?
In general, how do you feel about the way GAS uses data analytics?
How does the idea to implementation process look like for MS?
How long does this implementation phase take?
How do you handle data? Physical storage, digital storage?
What is the cost of this handling?

<u>Additional questions</u>

Where do you see GAS in 10 years in its way of handling data?
How would you like to see GKN handle data in 10 years?
    Why would you like to see these changes?
    What do you think is stopping these changes from happening?

Is there something else that you would like to add or expand on from this interview or is there something we have missed that we should take in to account when trying to understand how thread tap breakage and tool wear can be predicted and the understanding of costs in the threading process?

Would you like to see the notes which we have taken during the interview? (To verify)