

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Predictability – an enabler of weld production development

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Process stability illustrated as a dartboard.

Further description is found in 2.2.1

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To Krister and Alma

Abstract

Predictability enables proactive control of the production instead of reactive inspection. The research presented in this thesis provides insights and tools to enable predictability in weld production. The research shows that sufficient use of process information facilitates predictability and can support the reduction of unnecessary and costly safety margins in production. This will, in the short term, affect the productivity of the company. Even more influential is the effect predictability can have on product and process development in the long term, enabling welding companies to reduce weight of their fatigue loaded structures. The result can be lower fuel consumption and increased payloads, which will increase the companies' competitiveness.

Knowledge of the process is the key to evolve towards predictable weld production. To understand variation and how the evaluation process should be designed is therefore important. A model describing evaluation process development is presented. It emanates from the internal customer's need for information about the product or the process. Several aspects are decided on before the evaluation method is chosen, such as what information is needed and suitable ways to present that information.

Understanding the variation occurring in all parts of the process is necessary to achieve predictability. Tools long known in the quality society have proven to be useful. MSA, measurement system analysis, has shown to be a useful tool to understand the variation stemming from the evaluation process. Control charts seem to be effective to visualize variation and facilitate improved decision making by creating a common understanding. To have a critical mass of people sharing the same nomenclature and definitions is also necessary. The studies show that soft issues are often as important as technical solutions.

Implemented results from the research indicate a significant financial effect. The research could have a bearing in a wider context, which has been demonstrated by interview studies including companies in the welding industry.

Keywords: predictability, variation, proactive, process control, weld, production, quality

Sammanfattning

Förutsägbarhet möjliggör proaktiv styrning av produktionen i stället för reaktiv inspektion. Forskningen som presenteras i denna avhandling ger insikter och verktyg för att åstadkomma förutsägbarhet i svetsproduktion. Genom att använda processinformation på ett bra sätt åstadkoms en förutsägbarhet vilket kan möjliggöra en minskning av onödiga och kostsamma säkerhetsmarginaler i produktionen. Detta kommer, på kort sikt, påverka produktiviteten i företaget. På lång sikt kan effekten på produkt- och processutveckling bli ännu mer betydelsefull. Svetsföretagen kan minska vikten på sina utmattningsbelastade konstruktioner. Det leder till lägre bränsleförbrukning och ökade nyttolaster, vilket ökar företagets konkurrenskraft.

Kunskap om processen är nyckeln till att utvecklas mot en förutsägbar svetsproduktion. Att förstå variation och hur utvärderingsprocessen bör utformas är därför viktigt. En modell som beskriver hur en utvärderingsprocess bör utvecklas presenteras. Den utgår från den interna kundens behov av information om produkten eller processen. Flera aspekter beaktas innan utvärderingsmetoden väljs, såsom vilken information som behövs och lämpliga sätt att presentera informationen.

Att förstå variationen som finns i alla delar av tillverkningsprocessen är nödvändigt för att uppnå förutsägbarhet. Flera verktyg som sen länge är kända inom kvalitetsområdet har visat sig vara användbara. En MSA, mätsystemanalys, är användbar för att förstå varifrån variationen i utvärderingsprocessen härrör från. Styrdiagram är effektiva för att visualisera variation och förbättrar beslutsfattande genom att skapa en gemensam förståelse. Att en kritisk massa av människor delar samma nomenklatur och definitioner är också nödvändigt. Studierna visar att mjuka frågor ofta är lika viktiga som tekniska lösningar.

Resultat från forskningen som implementerats tyder på en betydande ekonomisk effekt. Forskningen kan vara relevant också i ett större sammanhang, som har påvisats genom intervjustudier med företag inom bland annat svetsindustrin.

Nyckelord: förutsägbarhet, variation, proaktiv, processtyrning, svets, production, kvalitet

Acknowledgements

Now it is already time for me to write an acknowledgement again. Last time, for the licentiate thesis, I dedicated it to Krister and to, at the time unborn, baby “Pyret”. “Pyret” is now 3 years old and more commonly known as Alma. Time really flies...

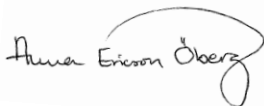
The work would not have been such a pleasure without help from a lot of people and organizations. I would like to start by thanking Volvo Construction Equipment for deciding to invest in the industrial doctoral student position and letting me perform research at the company. Vinnova should be thanked for financing the research projects I have been involved in. The organizers of the research schools ProViking and Production 2030 also deserve many thanks for excellent courses and possibilities of networking with other PhD-students. All doctoral students I have met – thank you for everything!

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Thank you all!

A handwritten signature in black ink that reads "Anna Ericson Öberg". The signature is written in a cursive style with a large, sweeping loop at the end of the last name.

Anna Ericson Öberg
Arvika, August 2016

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals. The contribution of the authors differed between the papers.

- I** Öberg A, Johansson, M, Holm, E, Hammersberg, P, and Svensson L-E. *The Influence of Correct Transfer of Weld Information on Production Cost*. In *Proceedings of the 5th Swedish Production Symposium, SPS12*, 6–8 November 2012, Linköping, Sweden, pp. 295–302.

Öberg initiated the paper, did the literature review and writing. Öberg, Johansson and Holm jointly conducted the data collection and data analysis. Hammersberg and Svensson reviewed and quality assured the paper.

- II** Ericson Öberg, A. *A Different View of Quality Assurance for Fatigue Loaded Structures*. In Barzoum, Z (Ed.) *Proceedings of the 2nd Swedish Conference on Design and Fabrication of Welded Structures*. 9–10 October 2013, Borlänge, Sweden, pp. 130–137.

Ericson Öberg initiated the paper, performed the literature review, data collection, data analysis, and writing.

- III** Ericson Öberg, A, Wikstrand, S, and Mattsson, V. *Impact of Gaps on Resource Efficiency in Heavy Welding Industry*. Paper presented at the 6th Swedish Production Symposium, 16–18 September 2014, Gothenburg, Sweden.

Ericson Öberg initiated the paper, performed the literature review, data analysis, and writing. Wikstrand and Mattsson assisted with data collection and proofreading.

- IV** Ericson Öberg, A and Hammersberg, P. (2016) Facilitating decision-making by choosing an NDT method based on information need. *Welding in the World* 60(5): 979-985. DOI 10.1007/s40194-016-0355-3.

Ericson Öberg initiated the paper, planned the structure and did the main part of the writing. Part of the data collection and analysis as well as proofreading was done in cooperation.

- V** Ericson Öberg, A and Åstrand, E. *Improved productivity by reduced variation in heavy welding industry*. Paper under first round of peer-reviews in international scientific journal.

Ericson Öberg initiated the paper, planned the structure and did the main part of the writing. Data collection and analysis as well as proofreading was done in cooperation.

- VI** Ericson Öberg, A, Andersson, C, Hammersberg, P, and Windmark, C. *The absence of variation in key performance indicators*. Paper presented at the PMA Conference, 26–29 June 2016, Edinburgh, UK.

Ericson Öberg initiated the paper, conducted the literature review, and did the main part of the writing. Part of the data collection and analysis as well as proofreading was done in cooperation.

- VII** Ericson Öberg, A, Hammersberg, P, and Fundin, A. Factors influencing control charts usage of operational measures. Paper submitted to international scientific journal.

Ericson Öberg and Hammersberg initiated the paper. Ericson Öberg planned the structure of the paper, performed the literature review, and did the data collection as well as the main part of the writing. Data analysis as well as proofreading was done in collaboration between the three authors.

- VIII** Ericson Öberg, A and Sikström, F. Barriers for industrial implementation of in-process monitoring of weld penetration for quality control. Paper has been accepted for publication in The International Journal of Advanced Manufacturing Technology.

Ericson Öberg initiated the paper, planned the structure, and did the main part of the writing. The literature review, data collection and data analysis were done jointly by Ericson Öberg and Sikström.

- IX** Ericson Öberg, A. The Journey from Standard Change to Implemented Assessment. Paper presented at the International Conference IIW 2016, 14–15 July 2016, Melbourne, Australia.

Ericson Öberg initiated the paper, planned the structure, and did the writing.

Additional publications by the author not included in the thesis

- I** Ericson Öberg, A. (2013) Svetsinformation kan spara miljoner [in Swedish]. *Svetsen 1/2013*, pp 16-19.
- II** Öberg, A, Hammersberg, P, and Svensson L-E. (2012). Selection of Evaluation Methods for New Weld Demands: Pitfalls and Possible Solutions. Paper presented at the 18th World Conference on Non-destructive Testing, 16–20 April 2012, Durban, South Africa.
- III** Ericson Öberg, A, and Åstrand, E. (2013) *The Subjective Judgement of Weld Quality and its Effect on Production Cost*. In Jármai, K and Farkas, J (Eds.) *Design, Fabrication and Economy of Metal Structures: International Conference Proceedings 2013, Miskolc, Hungary*, 24–26 April 2013, pp. 621–626.
- IV** Ericson Öberg, A, Hammersberg, P, and Svensson, L-E. The Right Evaluation Method – an Enabler for Process Improvement. Paper presented at the International Conference on Joining Materials, 5 – 8 May 2013, Helsingør, Denmark.
- V** Åstrand, E, Ericson Öberg, A, and Jonsson. *Cost Affecting Factors Related to Fillet Joints*. In Jármai, K and Farkas, J (Eds.) *Design, Fabrication and Economy of Metal Structures: International Conference Proceedings 2013, Miskolc, Hungary*, 24–26 April 2013, pp. 431–435.
- VI** Sikström, F and Ericson Öberg, A. (2016) In-process monitoring of weld penetration in fillet welds – an experimental study. Paper submitted to international scientific journal.
- VII** Landström, A, Almström, P, Winroth, M, Andersson, C, Windmark, C, Shabazi, S, Wiktorsson, M, Kurdve, M, Zackrisson, M, Ericson Öberg, A, and Myrelid, A. Present state analysis of business performance measurement systems in large manufacturing companies. Paper presented at the PMA Conference, 26–29 June 2016, Edinburgh, UK.
- VIII** Ericson Öberg, A, Braunias, S, Andersson, C, and Hammersberg, P. (2016) Changing from watermelon measures to real decision support: including information about variation in performance measurements. Paper presented at the 5th World Conference on Production and Operations Management P&OM Havana 2016, 6–10 September 2016, Havana, Cuba.

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Abbreviations

HVM	high value manufacturing
VCE	Volvo construction equipment
LOST	lightweight optimized welded structures
WIQ	weight reduction by improved weld quality
RQ	research question
Lightstruct	lightweight high performance welded structures
FaRoMonitA	fast and robust optical in-process monitoring for welded automation
SuReBPMS	sustainable and resource efficient business performance systems
NDT	non-destructive testing
GMAW	gas metal arc welding
ARC	areas of relevance and contribution diagram
MIG	metal inert gas
MAG	metal active gas
WPS	welding procedure specification
TIG	tungsten inert gas
UIT	ultrasonic impact treatment
QA	quality assurance
NDE	non-destructive test and evaluation
VI	visual inspection
DT	destructive testing
DMAIC	define, measure, analyze, improve, control
MSA	measurement system analysis
DOE	design of experiments
TQM	total quality management
TQ	total quality
BPMS	business performance measurement systems
AIM	affinity-interrelationship method
KPI	key performance indicator
WIA	weld impression analysis
ONWELD	new online method for quality assurance of welded structures
IR	infra-red
CMOS	complementary metal-oxide-semiconductor
MA@L	material availability at line side
SPC	statistical process control

CHAPTER 1 - Introduction

This chapter introduces the research presented in this thesis regarding predictability in weld production. The background to the research will be described from an industrial as well as an academic perspective. The current challenges are narrowed down to an objective of the thesis, conceptualized in two research questions. Thereafter, the scope and delimitations of the research are specified. Finally, the disposition of the thesis is presented and the appended papers are summarized.

1.1 Challenges

The manufacturing industry is very influential on society at large. Fifty percent of Swedish export is connected with manufacturing industries, creating direct employment for more than 550 000 (Teknikföretagen, 2011). Several initiatives have been launched over the years in order to empower the manufacturing industry. The vision of Manufuture (European Commission, 2004) was to ensure the future of manufacturing in Europe. European manufacturing has great potential but its success will depend upon continuous innovation in products and processes. High value manufacturing (HVM) was an initiative from the United Kingdom (Technology Strategy Board, 2014). The HVM strategy wanted to ensure that high value manufacturing is a key driver of UK economic success, by doubling direct investment in high value manufacturing innovation and directing the investment towards the most attractive technologies and market sectors. An initiative that has received much attention is Industrie 4.0. This is a German initiative from 2011 that refers to the fourth industrial revolution (following the three previous ones, mechanization, electrification, and digitalization) and is supported by extensive governmental funding (Drath and Horch, 2014). Sweden's innovation agency Vinnova responded by launching Produktion 2030 (Myrehed, 2015). It is a Swedish production vision, recommending long term efforts that are necessary to strengthen innovation, development, and production of goods and services in Sweden. The research agenda by Teknikföretagen from 2008 pointed out that Swedish industry needs to develop its ability to adapt to fast changes, with reduced cost, towards reduced environmental influence to be able to take a global lead (Teknikföretagen, 2008).

This is the reality to consider when developing new generations of products subjected to fatigue in equipment such as agricultural machinery, cranes, and construction equipment. There is a continuous striving towards reduced environmental impact and increased profitability. An incessant increase in payload with reduced fuel consumption and reduced production cost is therefore required. One way to go is to reduce the structural weight, as illustrated in Figure 1, since up to as much as 60–80 % of the vehicle weight comes from complex, welded structures made from steel or steel castings in construction equipment machineries (Samuelsson et al., 2008).



Figure 1: Illustration of benefits of reduced structural weight.

Figure 2 illustrates the connections between environmental impact, lightweight structures, requirements, and production performance. If the weight reduction is achieved by using thinner plates (as Figure 2 illustrates) the requirements on the welds increase because of increased stress. According to Marquis and Samuelsson (2005), higher operating stress increases the susceptibility to fabrication defects and weld geometry variation, e.g., penetration, throat thickness, and weld profile. Therefore, it becomes more important to have stable and predictable processes with known variation.

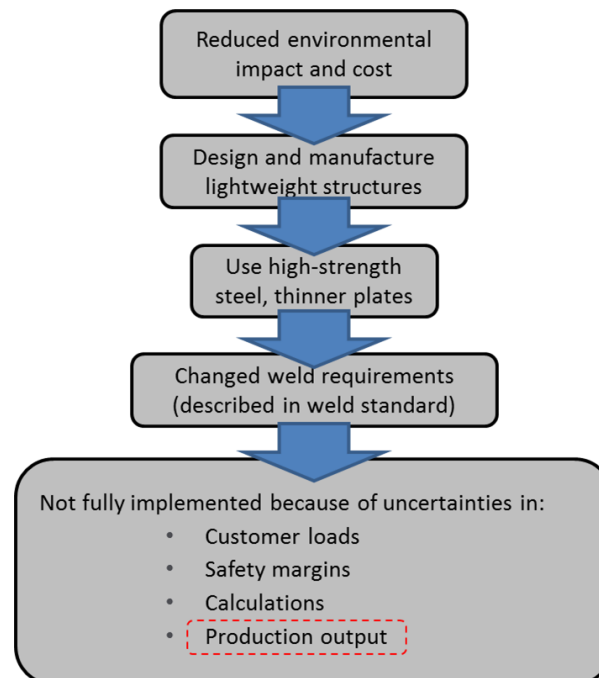


Figure 2: Illustration of connections between environmental impact and production uncertainties.

Experience from Volvo Construction Equipment however indicates a gap. Design innovations from previous research projects such as LOST (lightweight optimized welded structures) are not fully implemented because of uncertainties in the manufacturing process. One innovation is the introduction of weld toe radius as a requirement, since the connection between fatigue life and the smoothness of the transition between weld and plate has been established. The requirement is described in the weld class system in the Volvo weld standard (Volvo Group, 2008). The WIQ (weight reduction by improved weld quality) project (Samuelsson, 2012) started as a way to find how this standard should be implemented in engineering and production, enabling a structural weight reduction by at least 20 %. Many issues had already been identified (like “how to measure the weld toe radius”).

The production difficulties identified could be divided into mainly two areas, the difficulties to evaluate the weld toe radius and the difficulties to always fulfil the requirements in the production.

Since the new requirements were based on a company-specific standard, there was a need for research in close cooperation with the company and therefore an industrial doctoral research project was initiated to address the research gap. According to Teknikföretagen (Teknikföretagen, 2008), one of the strengths of Swedish industry is exactly this interdisciplinary research conducted by universities, institutes, and industry in close cooperation. At this point the solution of implementing the standard was thought to be found in a new inspection method, which would illustrate the lowest level in Figure 3. Figure 3 illustrates the development from reactive inspection towards proactive control.

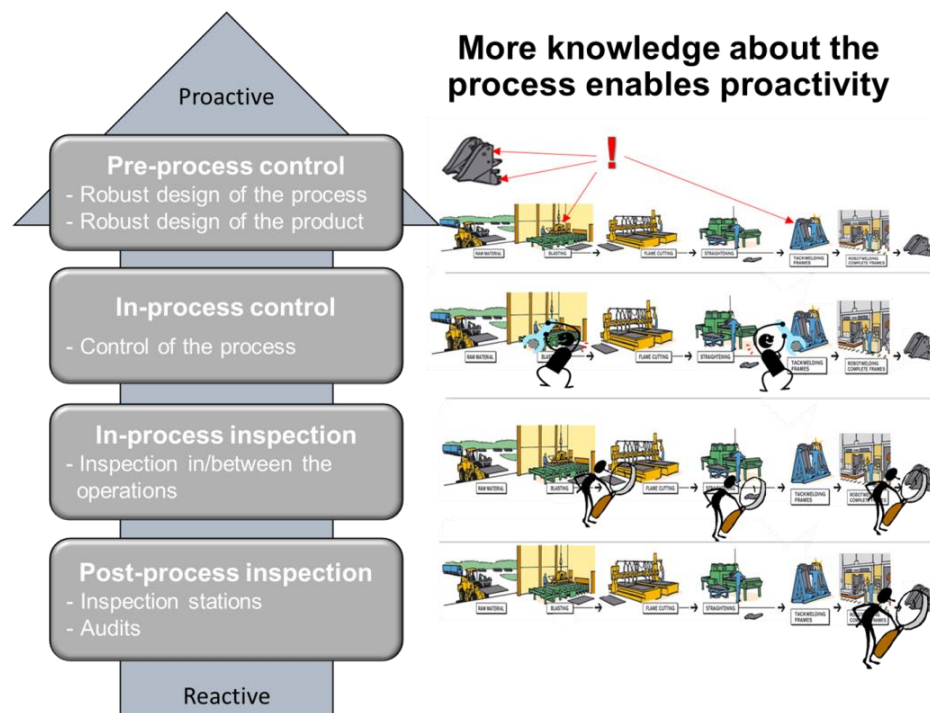


Figure 3: Illustration of development from reactive inspection towards proactive control.

New approaches were discovered and the scope was somewhat widened from only finding an evaluation method for weld toe radius. A new evaluation method would not solve the issue of fulfilling the requirements. It was rather necessary to find a product and manufacturing process design that enabled the creation of the intended lightweight structure, as the highest level in Figure 3 illustrates. At that stage the connections between process parameters and product quality are known. That in turn requires deep knowledge of the process and related process elements. The steps between the reactive inspection and proactive control first involve understanding when, what, and how to inspect. The next step is to understand how these properties could be controlled.

To be able to control the output of the process, the initial focus therefore needs to be on understanding the process. That requires a wider approach including more perspectives than solely the inspection of a certain property. Much research in welding is, however, conducted in specialized areas like non-destructive testing but not in the cross-section between fields of quality, production, welding, and change management.

There is also a lack of practical cases described in the literature. That makes this a unique opportunity to be able to follow the development towards lightweight structures. Björk et al. (2008) state that research in manufacturing technology, inspection techniques, fatigue design, etc., cannot be conducted in separate research fields. Therefore, a holistic approach to this research is necessary.

Even though the organization studied is successful in its business and has significant knowledge in the fields of design, welding, and quality assurance, the awareness of the influence of variation on quality and productivity can be improved. The research challenges to address are several; they are, however, very influential on the entire business if addressed properly.

1.2 Objective and research questions

To be able to realize lightweight solutions a deeper understanding of what enables implementation of design innovations is necessary. There is a need to get wider and deeper knowledge of the process itself, its interdependencies, and how it can be evaluated. A holistic view is necessary in order to grasp the influencing perspectives enabling a predictable and thereby proactive process. This can be summarized into the following objective:

The objective of this thesis is to provide insight and tools to enable predictability and thereby facilitate proactive process control in welding towards lighter fatigue loaded products.

The difficulties identified at the WIQ project start-up led to the thesis objective. The answer to the research questions should support the achievement of the objective. Therefore, the research questions are based on the two initial difficulties, to evaluate the weld toe radius and to always fulfil the requirements in the production.

RQ 1: Evaluation process: How should the process for evaluating properties critical to weld quality be designed?

A suitable evaluation process for properties critical to fatigue loaded structures is lacking. This was first identified as a lack of inspection method for weld toe radius but in order to be able to generalize and support the development from inspection towards control, a more holistic approach is necessary. The first research question is framed to describe the evaluation process and not a specific method.

RQ 2: Understanding variation: How should the process variation be described and managed?

To reach predictability and thereby the possibility to control the process and establish whether the requirements can be fulfilled, the influencing variation needs to be understood. The starting point is therefore to describe the current situation in an understandable way. This research question will then investigate what factors to consider when improving how variation can be managed.

1.3 Academic and industrial relevance

The result presented in this thesis will have relevance from both an academic and an industrial perspective.

1.3.1 Academic relevance

It is of academic relevance to get improved understanding of what it takes to get new and upgraded requirements in place. Knowledge about how variation influences the business and

how it can be evaluated, presented, and handled systematically in an industrial context of welding is also relevant. It is also important for academia to understand what prevents organizations in this context from implementing already existing solutions. Research in the interface between several fields like quality, production, and management adds cross-functional perspectives. There is a strong connection with industrial applicability that normally could be difficult for academia to access.

1.3.2 Industrial relevance

Even though the organizations studied are successful in their business and have significant knowledge in the fields of welding and quality assurance, several improvement areas still exist. The awareness of the influence of variation on quality and productivity is the first step towards managing variation. Understanding variation and the correct countermeasures on all organizational levels in the company provides a competitive advantage (Wheeler, 2000).

The costs of unimplemented solutions and opportunities lost are huge, and an increased understanding of what affects the implementation success is very valuable to the industry.

The research is a part of several research projects, like WIQ (Samuelsson, 2010), Lightstruct (Samuelsson, 2012a), FaRoMonitA (Sjöstedt, 2012), and SuReBPMS (Andersson, 2015). The project objectives include enabling weight reduction, robust monitoring, and a sustainable performance measurement system, all with significant financial potential.

1.4 Scope and delimitations

This thesis will have a production perspective focusing on issues relevant in this type of industry. The scope is therefore not to understand the underlying psychological aspects like, e.g., how decisions are made based on mental processes but rather the context that is necessary to get to that stage. Except when stated otherwise the studies were conducted at Volvo Construction Equipment with its common weld method GMAW (gas metal arc welding).

1.5 Thesis outline

The thesis consists of two parts, (1) a frame describing the research undertaken and (2) 9 appended papers. The frame connects the research described in the papers and summarizes their main points.

Part 1 comprises six chapters. The introduction chapter gives the background of the research as well as objective and research questions. Chapter 2 presents the frame of reference. In Chapter 3 the research methodology used is introduced. Thereafter the studies conducted are presented in Chapter 4 including the empirical findings from these studies. In Chapter 5 the studies are analysed and results based on theory and empirical findings are presented. Finally, in Chapter 6 the result is discussed and concluded before future research is suggested.

Part 2 comprises the papers included in the thesis. The content of each paper is described briefly below.

Paper I: The Influence of Correct Transfer of Weld Information on Production Cost

The paper investigates the causes of deviations between actual and theoretical weld weight. The common factor for observed deviations seems to be the ability of correct information transfer between different functions within the organization.

Paper II: A Different View of Quality Assurance for Fatigue Loaded Structures

The paper identifies a need for a different view of quality assurance. A model with a pull approach has been developed based on the internal customer's need for information about the product or the process.

Paper III: Impact of Gaps on Resource Efficiency in Heavy Welding Industry

This paper reviews the current situation of gaps in welded structures at a case company. The result showed signs of large variations of gaps, concerning both the size of gaps and the presence of an extra weld. A large improvement potential was identified.

Paper IV: Facilitating decision-making by choosing an NDT method based on information need

This paper analyses the choice of an NDT (non-destructive testing) method from an information-need perspective. It bridges the gap between the technical methods, monitoring procedures, and the need for information occurring in the industrial application.

Paper V: Improved productivity by reduced variation in heavy welding industry

The paper presents the variation occurring in each step of the manufacturing process from customer requirements to final assessment. The financial consequences are exemplified.

Paper VI: The absence of variation in key performance indicators

The paper provides a literature review and empirical case studies investigating the display of variation in key performance indicators. The research conducted shows a very limited presence in both literature and practice.

Paper VII: Factors influencing control charts usage of operational measures

This paper describes the possibilities connected with the use of control charts as a mean to visualize strategic measures. A case study is presented in which factors influencing the implementation of control charts are evaluated in relation to change management literature.

Paper VIII: Barriers for industrial implementation of in-process monitoring of weld penetration for quality control

The paper discusses identified barriers to introducing technical solutions for monitoring weld penetration. The paper is based on a research project using cameras during welding as well as interviews at the participating companies.

Paper IX: The Journey from Standard Change to Implemented Assessment

This paper provides a case study of a company's journey from change of weld standard to implemented assessment. The obstacles encountered have been not only technical but rather organizational with a cross-functional characteristic.

CHAPTER 2 – Frame of reference

This chapter gives an overview of the frame of reference related to the research topic. The topics that have been taken into account when conducting the research will be presented and briefly discussed. At first, variation will be described. Thereafter, welding of fatigue-loaded structures and quality assurance of welding will be introduced. Further, theories concerning Lean Six Sigma and production are presented. A summary of the frame of reference will conclude the chapter.

2.1 Frame of reference related to the topic

The topic of research could be viewed from several perspectives and integrates several areas. A suggestion of the position of the research is shown in Figure 4. It is described as an ARC diagram (Areas of Relevance and Contribution diagram) in accordance with Blessing and Chakrabarti (2009).

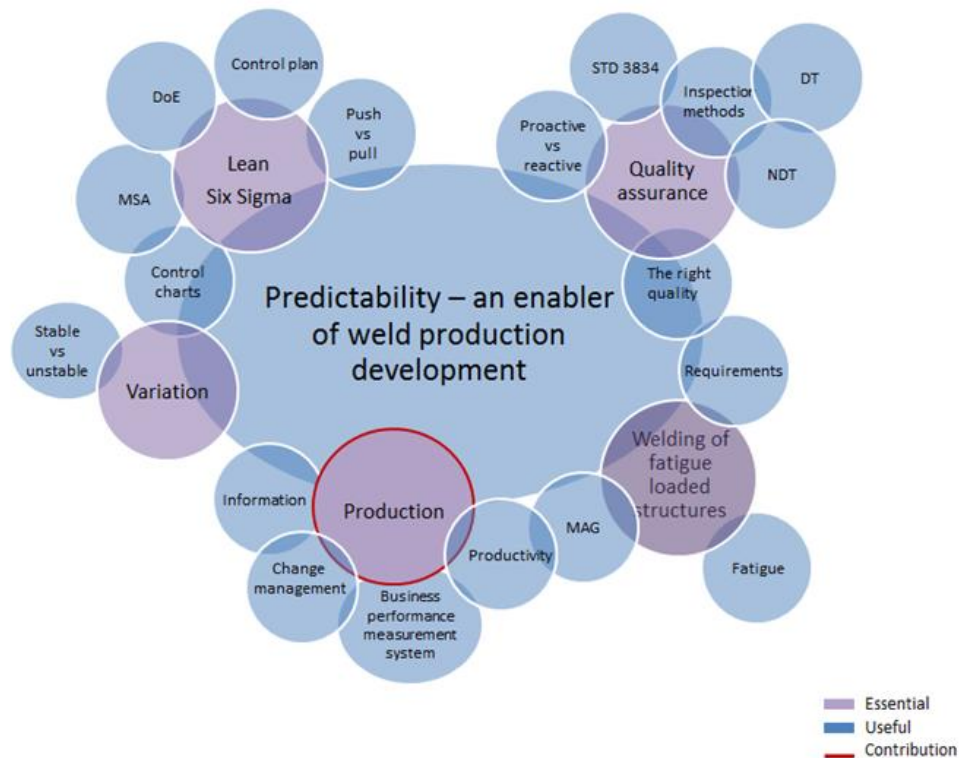


Figure 4: Areas of relevance and contribution diagram of the research area.

The conclusion is that variation, welding of fatigue-loaded structures, Lean Six Sigma, quality assurance, and production are useful areas for the research. The main contribution will

however be made mainly in the production area. Björk et al. (2008) state that research on manufacturing technology, inspection techniques, fatigue design, etc., cannot be performed as separate research fields and the research will therefore be conducted in the intersection between the fundamental research areas as illustrated in Figure 5.

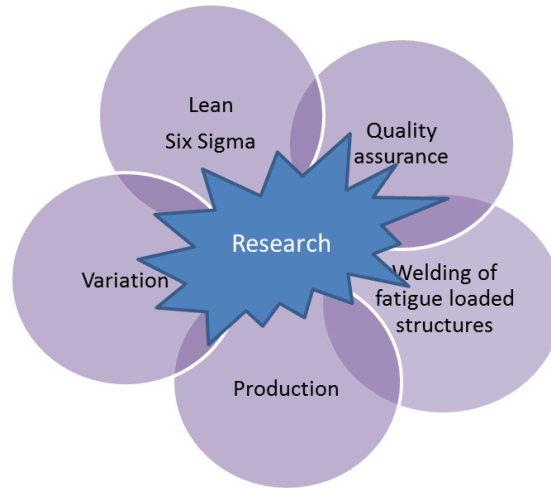


Figure 5: The research is conducted in the intersection between research areas.

The areas of most relevance to the research will be further introduced in the following sections.

2.2 Variation

Of course there is a variation in how to define variation. It can be considered as a different form of something or a degree of change. According to Wheeler (2000), variation can be considered as a random and miscellaneous component that undermines simple and limited comparison. Two types of variation exist depending on what is causing it, assignable causes of variation and chance causes of variation (Shewhart, 1931). Assignable-cause variation can also be termed special-cause variation, and chance-cause variation can be called common-cause or non-assignable cause variation (Deming, 1994). There are, according to Bergman and Klefsjö (2010), two types of mistakes that are often made in this context, reacting to chance-causes and not reacting to assignable causes.

2.2.1 Process stability

If a process only contains natural noise, that is, common causes of variation, it is said to be a *stable* process. The process is predictable within limits. If the process instead contains assignable causes of variation, it is defined as *unstable*. Then there are often one or a few unpredictable, but traceable, causes of variation. It is important to be able to distinguish between a stable and an unstable process, illustrated in Figure 6, since they require totally different actions to be addressed at different management levels (Deming, 1994).

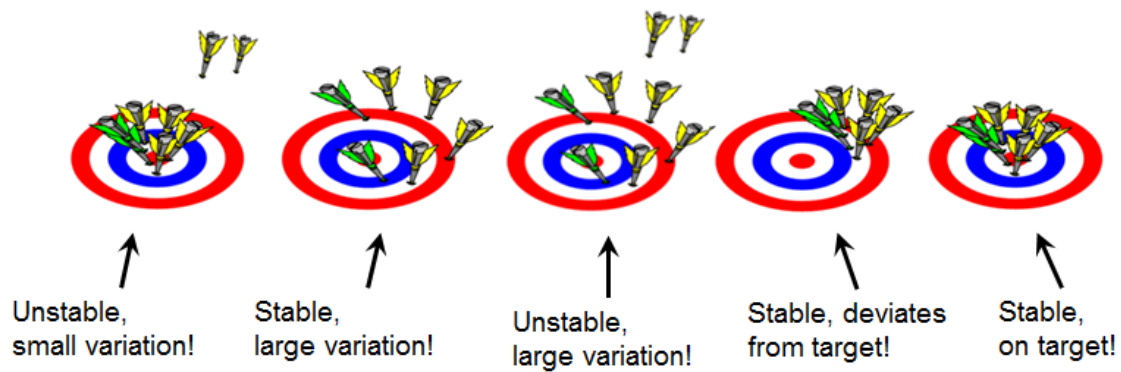


Figure 6: Illustration of stable and unstable processes with differences in variation.

In the case of an unstable process, the assignable causes of variation are usually easy to detect and could be rectified directly on the shop-floor level. Improvements of a stable process, i.e., reducing the level of chance-cause variation, can only be realized by a redesign or update of equipment or methods. As an example, if the tool in a machining centre breaks, a sudden change of the machined surface occurs. That could be easily detected and handled by the operator. If instead the process is stable and only contains variation stemming from vibrations, wear, and temperature differences etc. an improvement requires a change of the process. That could involve changing the type of tool, refurbishing the axles, or buying a new machining centre. Those decisions, however, need to be made on a higher management level. Therefore, suitable actions and functions involved are dependent on whether the process is stable or not.

2.3 Welding of fatigue-loaded structures

The industry strives at reducing the weight of welded structures. The benefits of lower structural weight are several: reduced fuel consumption, increased payload, and reduced production costs. However, according to Marquis and Samuelsson (2005), a 10 % increase in loads and 10% improvement in utilization may increase the number of structural failures per year by a factor of five. They thereby demonstrate the need to improve design and manufacturing processes for welding.

2.3.1 MAG welding

Gas Metal Arc Welding, GMAW, is the dominant method of welding in most industrial countries (Weman, 2003) and is the weld method mainly considered in this thesis. GMAW can also be referred to as MIG (metal inert gas) and MAG (metal active gas), depending on the type of shielding gas used.

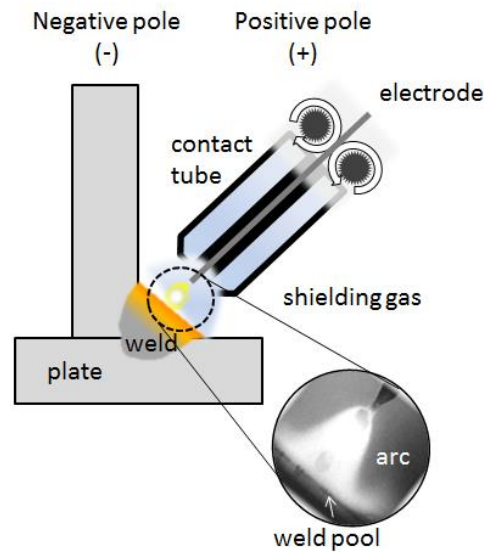


Figure 7: Principle of MAG welding illustrated for a fillet weld.

The main principle of MAG welding is to produce an arc between the plates to be joined and the electrode, the weld wire. The electrode is fed into the arc as Figure 7 shows. Electrical energy is passed through the contact tube to the wire. When the positive pole on the contact tube and the negative pole on the work piece are connected, an arc is created. The shielding gas protects the weld pool and arc from being contaminated by the surrounding air and thereby oxidation.

The main parameters are wire feed speed/current and voltage. Different levels and combinations of current and voltage change the arc character and the weld process behaves differently. The welding process is however also influenced by a number of other welding parameters such as welding speed, inductance, wire type, wire stick-out, wire diameter, shielding gas type, gas flow rate, torch angles, joint position, weaving frequency, and weaving width. The welding process itself is very complex with interdependent parameters and is also highly affected by other sources of variation in the manufacturing environment, such as fit-up between plates. A WPS, welding procedure specification, is a document defining parameters to be used for a specific application in order to assure repeatability (Weman, 2003). The fillet weld is, according to Cozens (2013), the most common weld, accounting for around 80 % of all joints made by arc welding.

2.3.2 Fatigue

Lee et al. (2005: 57) define fatigue as “a localized damage process of a component produced by cyclic loading”. Fatigue is the result of a cumulative process consisting of three phases; crack initiation, propagation and final fracture of a component. When a structure is subjected to fluctuating stress, contrary to static stress, it is said to be a fatigue-loaded structure. There are several examples of areas where fatigue needs to be considered, like bridges, cranes, and construction equipment. This thesis considers fatigue-loaded structures only.

Fatigue cracks often start from the weld since the welding process can leave small discontinuities from where cracks can start to grow. That means that the initiation phase can be regarded as having passed as Figure 8 shows. The crack propagation phase starts instantly contrary to the static load case.

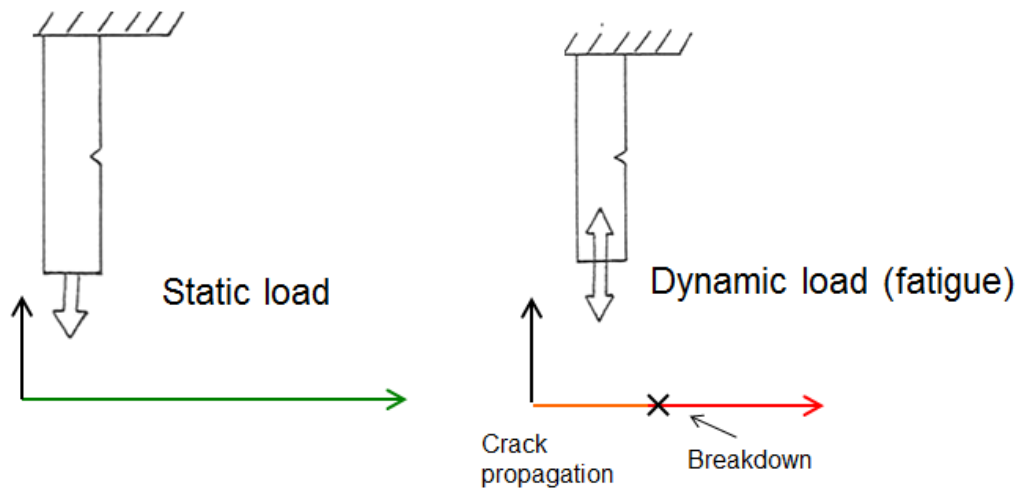


Figure 8: Crack propagation comparison between static (left) and dynamic load (right).

The static strength of the parent metal is of less importance since once a fatigue crack has started, it will grow at the same speed irrespective of material grade (Weman, 2003). Especially sensitive are the areas close to the weld toe and weld root. These points cause local stress concentrations that make the cracks grow faster. Critical points of high stress concentrations are therefore sometimes treated to obtain smoother transitions between the weld and the parent material. This can be achieved by post treatment like TIG (tungsten inert gas) dressing, grinding, or UIT (ultrasonic impact treatment). If the weld toe region is sufficient, the weld penetration can instead become a problem (Marquis and Samuelsson, 2005).

2.3.3 Requirements

The quality levels of the welds are often specified as weld classes with certain imperfection levels (Swedish Standards Institute, 2004; Volvo Group, 2008). Jonsson (2012) states that the imperfection levels described do not well reflect the fatigue situation. Karlsson and Lenander (2005) as well have shown that the connection between weld class and fatigue life is weak. Marquis and Samuelsson (2005) state that weld acceptance limits generally have been based on what is considered good workmanship and easily observed physical characteristics. According to Jonsson et al. (2011) the type of defect plays a greater role than the quality level itself and some imperfection types are more important than others with respect to fatigue life. Weld defects and properties often mentioned in relation to fatigue-welded structures are toe radius, throat size, and penetration, see Figure 9.

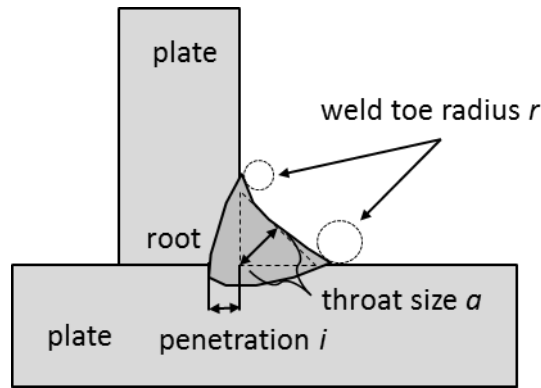


Figure 9: Toe radius, throat size, and penetration on a fillet weld.

Toe radius has historically not been considered in many standards except when “even transition” should be achieved (Swedish Standards Institute, 2004; Volvo Group, 2005), even though the weld toe profile is one of the most important measures regarding fatigue (Jonsson et al., 2011).

The *throat size* is defined as the height of the largest inscribed triangle having equal leg length. Jonsson et al. (2011) show that the influence of the throat size differs depending on the load condition. For non-load-carrying structures the stress level is almost independent of the throat size. For load-carrying welds the throat size is influential.

When the root side is critical, weld *penetration* is influential. The penetration is not described in the standard but is instead expressed as a requirement on the drawing.

The philosophy of the new Volvo weld class system (Volvo Group, 2008) is that the acceptance limits for the defects should be characterized based on their impact on fatigue strength (Jonsson et al., 2011). That standard has introduced different weld toe radii as a requirement.

2.4 Quality assurance of welding

Quality is a very broad issue. Björk et al. (2008: 35) define *weld quality* as “that a weld is able to perform its required function during the life of the structure”. The initiatives to achieve this include quality assurance, control and inspection. *Quality assurance (QA)* can be defined as “all those well planned and systematic actions taken by a manufacturing or service organization to instil confidence in the mind of the buyers that the product or service is made as per standard and it serves the purpose well” (Raj et al., 2000: 234). Control and inspection are parts of the QA. *Control* can be said to imply “the steps that are taken on the basis of developed practices so that a welded joint is made to serve the designed objectives” (Raj et al., 2000: 9). An even more reactive approach is *inspection*, which can be defined as “[t]o examine carefully and critically, especially for flaws” (American Heritage, 2009).

SS-EN ISO 3834 1-5:2005 (ISO, 2005) is a standard describing how the quality assurance of welding can be implemented. It contains the following five parts: criteria for choice of appropriate requirement level, comprehensive requirements, standard requirements, elementary requirements and references for which compliance is necessary. The requirements cover areas like approval of welding procedures, approval of welders and NDT staff, handling of consumables and base material and testing. The standard refers to other international standards, such as qualification of welders and procedures.

2.4.1 The right quality level

Achieving the right quality means not only to fulfil requirements but also not to exceed demands, creating unnecessary costs. Raj et al. (2000) state that specifying high quality can lead to high costs with no benefits while low quality leads to high maintenance costs. The aim should therefore be to specify an optimum quality level that leads to “fitness for purpose”. Björk et al. (2008) state that under-quality can lead to serious safety or cost consequences. They see over-quality as harmless and something that does not increase production costs. Making a weld larger than necessary could, however, be an example of how over-quality or over-welding can influence cost. According to Stenbacka (2009) a deviation from the weld throat size could have a substantial financial impact.

Miller (2011) names three potential sources of over-welding, designer, welder, and parts fit-up. The designer, because he or she can select a weld design that is larger than necessary, welder, because he or she can weld larger than stated, and parts fit-up because wider root openings require over-welding. Miller also states that the supervisor has some influence on the over-welding. Safety factors applied by the designer, welder or inspector are also mentioned by Cozens (2013). Those safety factors could lead to as much as twice the volume of a correctly sized fillet weld according to Cozens, significantly affecting cost, productivity, weight, and distortions.

2.4.2 Inspection methods

According to Kihlander (2006), welding can be seen as a special process because all quality properties cannot be verified by inspection and testing. However, great effort is put into improving this situation.

Prasad and Nair (2008: 1) state that “*Non-destructive test and evaluation* (NDE) is aimed at extracting information on the physical, chemical, mechanical or metallurgical state of materials or structures”. They describe *non-destructive testing* (NDT) as “the entire range of methods used to determine the soundness of materials and structures, without impairing their serviceability”.

Destructive testing (DT), contrary to NDT, makes the part unusable. The part is cut, bent, or pulled apart to see internal imperfections or mechanical properties. The parts are often specially prepared samples that are produced with similar process conditions as in production. Destructive testing is often costly and time consuming.

The method mainly considered in this thesis is visual inspection. *Visual inspection* (VI) is probably the most widely used test since it is simple, quick, and cheap (Raj et al., 2000). It can reveal surface defects like undercut, cracks, and spatter.

2.4.3 Proactive and reactive approaches

Kihlander (2006) stresses that condition, execution, and follow-up are important parts of the welding production that requires controlled procedures and knowledge. It is therefore necessary to control the weld process and the activities around it already from the beginning to reach the right quality of the finished product. This implies that a proactive approach should be used.

Raj et al. (2000) divide the measurement of various parameters into pre-weld parameters (like bevel angle), welding parameters (such as current) and post-weld parameters (e.g. material composition). Prasad and Nair (2008) also state that NDE fits into various stages and divide these into design and product development, manufacturing and life-cycle management. In this thesis four stages are instead suggested: *pre-process control*, *in-process control*, *in-process inspection* and *post-process inspection*, of which the first two are proactive and the last two are reactive (see Figure 3).

2.5 Lean Six Sigma

Lean is developed based on the Toyota Production System. The existing definitions of lean are countless. Modig and Åhlström (2011: 96) suggest that: “*Lean* is a business strategy focusing on value stream efficiency”. This means that lean is shifting the focus from efficient use of resources towards an efficient value stream to satisfy the customer need. This is done by, e.g., reducing different types of waste, that hinder the flow in the value stream.

Six Sigma was introduced in the 1980s as Motorola’s improvement program, focusing on reduction of unwanted variation (Bergman and Klefsjö, 2010). According to Berger et al. (2002: 640) it can be defined as “a quality philosophy; a collection of techniques and tools for use in reducing variation”. The process improvement methodology called DMAIC is divided into five steps: define, measure, analyse, improve, and control, described by, among others, Magnusson et al. (2003). At each step, several tools and techniques are available to support the work.

2.5.1 Pull and push

One important principle in Toyota’s production system, described by, among others, Liker (2004), is the customer focus and pull approach. By having a *pull* system means producing only when there is an actual need for it. The customer only receives items when demanding them. That also counts for the internal processes, meaning that the different process steps in the company should also be related to customers and suppliers, but internal (Modig and Åhlström, 2011). The opposite to pull is *push*. In that case the supplier pushes parts onto you, whether you need them or not, which creates waste in the form of inventory.

2.5.2 Measurement system analysis (MSA)

The reliability of the inspection methods is also influenced by variation. Prasad and Nair (2008) mention seven major factors: human factors, testing method, test object, nature of defect, knowledge base, facilities, and risk factors. Dickens and Bray (1994) instead argue that a measurement system consists of intrinsic and extrinsic factors. Intrinsic factors could be operator experience and motivation while extrinsic factors are the method used and the measurement tool.

To be able to trust the measurement system it needs to be investigated to see if it is good enough for the intended purpose. *Accuracy* and *precision* are important characteristics to consider and have been defined by Berger et al (2002). *Accuracy* is the degree of agreement of measurements with an accepted reference value or level. *Precision* is how well identically performed measurements agree with each other. A measurement system analysis (MSA) is performed to see the precision, that is, *repeatability* and *reproducibility* of a measurement system. *Repeatability* shows the agreement of measurements performed on the same part under the same conditions. *Reproducibility* shows the degree of agreement between several appraisers measuring the same part under the same conditions. In this thesis Gauge R&R has been used for performing measurement system analyses on continuous data. Previous research has shown that commonly used evaluation methods have poor precision. Hammersberg and Olsson (2010) performed MSA on throat-size gauges, showing significant variation originating from the measurement system itself.

It is also possible to investigate the measurement system when there are only attribute data. The attribute agreement analysis can then be used. When there are ordinal data, Kendall’s coefficient of concordance is suitable. It measures the associations between ratings and does not treat misclassifications equally. If the data are not ordinal, Fleiss’ Kappa can be used instead, which treats misclassifications equally.

2.5.3 Control charts

Control charts have been used since the 1920s, when they were initiated by Dr. Walter Shewhart (1926) at Bell Laboratories. A control chart consists of a central line, upper control limit, lower control limit, and plotted data points, as Figure 10 shows. The control limits are statistically calculated and should not be mixed up with tolerance limits which are set by the customer need. When a data point falls outside any of the control limits, or an unnatural pattern is shown, it is a sign of an assignable cause and an unstable process. A control chart can detect process deviations before they get out of tolerance. Depending on the type of data, different control charts can be used.

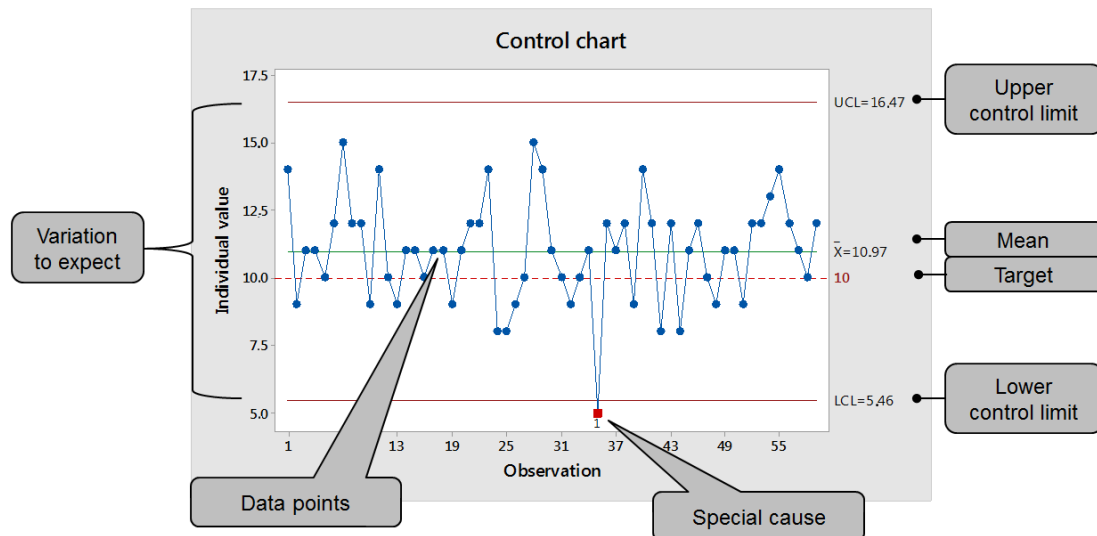


Figure 10: Example of control chart indicating an unstable process.

Raj et al. (2000) state that control charts are only useful for the regulation of manufacturing processes. Danielsson and Holgård (2010), Deming (1994) and Wheeler (2000) have shown that control charts could be very useful also for other types of information in a company, for example, key performance indicators on management level.

2.5.4 TQM and principles, practices, and tools

Bergman and Klefsjö (2010: 37) define total quality management (TQM) as “a constant endeavour to fulfil, and preferably exceed, customer needs and expectations at the lowest cost, by continuous improvement work, to which all involved are committed, focusing on the processes in the organization”. According to them improvement work shall rest on a culture based on the values illustrated in Figure 11.

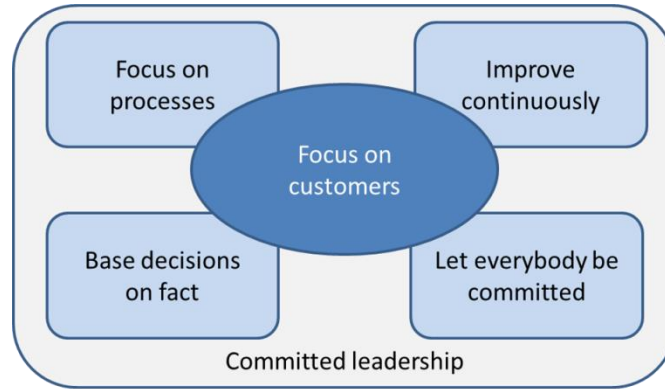


Figure 11: The Cornerstone Model describing the basis of TQM (Bergman and Klefsjö, 2010).

A central aspect in the model by Bergman and Klefsjö (2010) is the *focus on the customers*, internal as well as external. Another important element is to *base decisions on facts*. That requires knowledge about variation and an ability to distinguish between natural variation and variation due to identifiable causes. Most activities can be regarded as a *process*, i.e., “a network of interrelated activities that are repeated in time, whose objective is to create value to external or internal customer” (Bergman and Klefsjö, 2010: 42). *Continuous improvements* are also vital. There is always a way to achieve improved quality using less resources. For the work to be successful it is essential to create conditions for participation, e.g., removing obstacles to *commitment* and delegating responsibility. Last, but certainly not least, *committed leadership* is important to create this quality culture by supporting activities regarding quality financially, morally, and with management resources.

Dean Jr and Bowen (1994) see total quality (TQ) as a philosophy or approach to management that can be characterized by its principles, practices, and techniques. Each principle is implemented through a set of practices, which are in turn supported by techniques. Hasenkamp et al. (2009) apply this thinking to robust design methodology but use the word “tools” instead of “techniques”. They connect the levels to questions. Principles describe “why”, practices “what”, and tools “how” as illustrated in Figure 12.

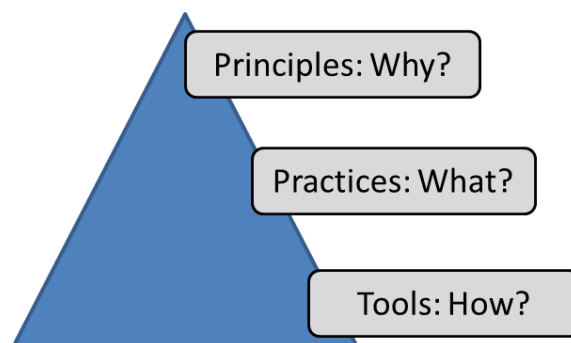


Figure 12: Illustration of principles, practices, and tools as described by Hasenkamp et al (2009) and Dean Jr and Bowen (1994).

2.6 Production

Global competition drives production towards shorter time to market, increased flexibility, and reduced production cost. The production of welded components is no exception. To stay competitive requires continuous improvement and being able to use the available resources in

the best way possible is necessary. The production of a welded component involves several functions in the company, from analysis and design to fabrication and assessment. The challenge is to overcome functional barriers to avoid sub-optimization and use the information available.

2.6.1 Information

According to Daft and Lengel (1986), organizations process information to manage uncertainty and equivocality. Uncertainty has to do with absence of information while equivocality rather includes multiple and conflicting interpretations of a situation.

Cohen and Levinthal (1990) argue that the ability of a firm to recognize the value of information, assimilate it, and apply it to commercial ends is critical to its innovative capabilities. They call this the firm's absorptive capacity. Kehoe et al (1992) say that an organization may be depriving itself of a major competitive advantage if it does not manage its information processing resources effectively. They state that the effective use of information in manufacturing operations, to support the decision-making processes of the organization, is a prime factor in the achievement of business goals. Danielsson and Holgård (2010) also showed that by changing the presentation of managerial data into control charts, the support for decision-making was improved. According to Hammersberg (2010) there are differences between the traditionally separated functions for product development, production and quality inspection in their language and approach to robustness and reliability. These variations can be hidden by over-dimensioning and broad margins but need to be clarified and explored to develop cost-effective NDT, according to Hammersberg (2010).

2.6.2 Performance measurement systems

Measuring performance is a de facto standard in the manufacturing industry. Business performance measurement systems (BPMS) are intended to give information about the business and provide data for making improvement decisions. According to Neely et al. (1995), a performance measurement system is a set of metrics used to quantify both efficiency and effectiveness of actions. The field of performance measurement research seems to have evolved through a number of phases, productivity management, budgetary control, integrated performance measurement, and integrated performance management, according to Bititci et al (2012). Since the 1990s, the concept of the balanced score-card has been influential (Kaplan and Norton, 1992). Despite the extensive research performed, there still seems to be a lack of research on implementation and use of performance measures (Bourne et al., 2000).

2.6.3 Productivity

To use limited resources in the best way possible is essential for a company. Productivity can be described as output divided by input (Almström et al., 2012) or how much and how well we produce from the resources used (Bernolak, 1997). The productivity potentials have shown to be substantial in the Swedish industry and with a relatively small work effort great improvements can be created by starting with the low-hanging fruits (Almström et al., 2012).

2.7 Summary of the frame of reference

Welding is a complex process affected by many parameters. In the industrial context of the research conducted, fatigue is important. This means that the quality at the weld toe and weld root is of extra interest. There are, however, weaknesses in commonly used standards when it comes to connecting the weld classes with the actual fatigue life. The Volvo welding standard created in 2008 (Volvo Group, 2008) aims at taking this into consideration by having a

connection between quality levels and fatigue life. Toe radius, throat size, and penetration are defects and properties of special interest when it comes to fatigue-loaded structures.

Quality assurance can be of a proactive or reactive type, using destructive or non-destructive testing methods. Lean Six Sigma helps to improve the customer-focused value stream flow by reducing waste and unwanted variation. A pull approach means producing with the customer need in focus.

To be able to understand and manage variation could improve decision-making, having a vast impact on profitability. The control chart is an important tool to facilitate understanding of the variation of the process and distinguish between assignable causes and common causes. The presence of assignable causes differentiates between stable and unstable processes. Since appropriate measures are different depending on whether the process is stable or not, it is essential to be able to see the difference. Measurement system analysis can be used to understand the variation in the evaluation system used and make sure the chosen method is suitable for the intended purpose.

There is a potential for improved productivity in the industry. Several sources indicate that an improved use of process information would affect the company's performance. Welding at the right quality instead of over-quality or under-quality would affect productivity and consequently profitability.

CHAPTER 3 – Research method

In this chapter, the research methods used will be described as well as the reasoning behind the choice. First, the research approach is presented, followed by a description of chosen methods and techniques for collecting and analysing the data. Finally, the validity and reliability of the research methods chosen are discussed.

3.1 Research approach

The research topic is related to several research areas such as quality, welding, production, and change management. The different research areas also come with different research traditions in terms of approach and methods used. Welding and non-destructive testing research often uses a positivistic approach in which the research method also could be implied. In that area it is common to have a deductive approach and use Popper's hypothesis testing and falsification (Williamson and Bow, 2002). Production research on the other hand has a research tradition of empirical case studies. The research tradition in quality can be divided into two sections, statistical and organizational. Statistical research uses a positivistic approach whereas organizational research more often has a case-study or even action-research approach.

The intended approach for the research conducted in this thesis can best be described as abductive or, as Dubois and Gadde (2002) define it, systematic combining. Dubois and Gadde (2002: 555) state: "the researcher, by constantly going 'back and forth' from one type of research activity to another and between empirical observations and theory, is able to expand his understanding of both theory and empirical phenomena". This is illustrated in Figure 13. Dubois and Gadde suggest that abductive research is closer to an inductive than a deductive approach. There is emphasis on theory development rather than theory generation. Empirical fieldwork parallels theoretical conceptualization. Since the research conducted in this thesis should have a holistic view, connecting both academic and industrial aspects as well as rather developing than generating theory, it is believed that systematic combining is a suitable approach.

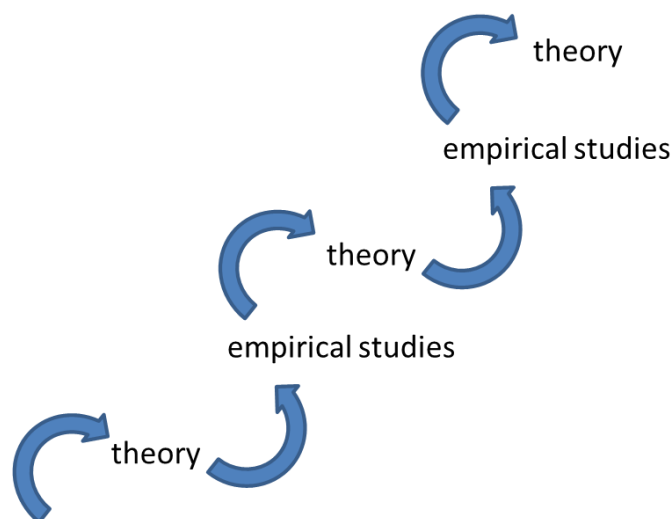


Figure 13: Illustration of the abductive research approach used.

The research includes a combination of qualitative and quantitative data. The choice of method was dependent on the purpose of the study in question. The risk of this choice could be a mix-up of different methods leading to wrong conclusions (Wallén, 1996). However, if made with awareness and consistency, through triangulation (Williamson and Bow, 2002; Yin, 2009) it can improve the validity of the research.

3.2 The role as industrial doctoral student

The author's role as a researcher has been that of an industrial doctoral student. That means being employed by Volvo Construction Equipment but having academic supervision from Chalmers University of Technology. Such a set-up naturally has its pros and cons. It is necessary to consider objectivity when conducting research on the organization one belongs to. However, when applying suitable research methods and techniques the result should not be negatively affected. The academic supervision needs to be effective to assure that the research is of both academic and industrial relevance, to avoid the risk of providing consultancy work of interest only for the company. The major advantages are access to data and study objects as well as validity. Having knowledge of the organization and contacts makes it possible to ask for data of which an outside researcher would be unaware.

Since the company invests in the research, it is assured that the research is relevant to society. By choosing research methods wisely, the bias can be turned into an advantage. When the researcher has been working close to the people involved in studies, the result could be influenced. However, it could be of benefit to be able to influence the participants when performing, for example, action research. The literature disagrees on this matter. Wallén (1996) on the one hand states that the researcher needs to be independent of the employer, while Coughlan and Coughlan (2002) say action research done from within the organization is increasingly common.

3.3 Research methods and techniques

The research methods chosen have varied depending on the purpose of the study as well as the type of data to be analysed. The studies addressing research question 1 (Evaluation process) are in general quantitative while the investigations linked to research question 2 (Understanding variation) and the potential in a wider context are more often qualitative. According to Yin (2009), different research methods are preferable depending on the type of research question, control of behavioural events, and focus on contemporary events.

Table 1 shows the connection between the studies, the research questions, as well as in which paper the findings from the studies are described. The number of organizations and unique companies studied is displayed. The method or technique chosen for each study performed is also presented, as well as whether the main characteristic has been quantitative or qualitative. In some cases, like interviews, there are both qualitative and quantitative elements, but the dominant approach has been included in the table. The methods used for each study are also described in Chapter 4.

Table 1: Connection to research question, papers, and chosen method/technique of studies.

Study	Research question	In paper	No. of organizations studied [unique companies]	Type of method/technique	Characteristic mainly quantitative	Characteristic mainly qualitative
Obstacles to quality assurance	-	IX	1[1]	Affinity-interrelationship method		X
Assessing weld toe radius	1	IV	3[2]	MSA	X	
Currently used methods	1	IX	13[2]	Questionnaire	X	
Precision of visual inspection	1	V	12[1]	Attribute agreement analysis	X	
Weld weight deviation	2	I	3[2]	Interviews Observations Archival analysis MSA Experiment	X X X	X X
Workshops control charts of KPIs	2	VII	4[1]	Action research Interviews Questionnaire Archival data Observations Control charts Affinity-interrelationship method	X X X	X X X X
Barriers to monitoring	1	VIII	3[3]	Experiment Interviews	X X	
Influence of gaps	2	I, III, V	1[1]	MSA Experiment Observations	X X	X
Standardized evaluation methods	1	IX	2[1]	MSA	X	
Reactive/proactive evaluation in industry	-	-	22[12]	Interviews		X
Weld toe radius variation	2	IV	1[1]	MSA Experiments Affinity-interrelationship method	X X	X
Control charts of KPIs literature study	-	VI	N/A	Systematic literature review Traditional literature review	X	X
Empirical distribution of control charts of KPIs	-	VI	7[6]	Interviews Observations Archival analysis	X	X X

3.3.1 Literature review

Focused literature reviews were mainly done on specific topics for each study or paper. For the study “Control charts of KPIs literature study” a thorough review was conducted in two parts, first a systematic literature review and second a traditional review (Jesson et al., 2011). The boundaries of the research area were not completely clear from the start, which hampered a complete literature study from the beginning. The literature studied was normally found by using both systematic and traditional review, e.g., search queries in databases, journal alerts for certain keywords, recommendations from research colleagues, or specialized collections for certain topics. Scopus, Emerald and Web of Knowledge were the most frequently used general databases.

3.3.2 Archival analysis

Archived data have been used when applicable and available. The data have been in the form of, e.g., performance indicators, product specifications, quality result, and process descriptions. Because of the researcher's previous role it has been possible to get access to the data. With an outside researcher, it would have been difficult to know about the existence of the data as well as to get access to them.

3.3.3 Questionnaire

Questionnaires have been used several times, mainly in cases of long distance study objects but also when quantitative data were desired. The type chosen had semi-open questions and the number of participants was limited. That made it possible, if necessary, to get back to the respondents for further clarification. The limited number of participants also facilitated achieving a high response rate. The method was inexpensive in comparison to face-to-face meetings with such a wide geographical spread. The limitations of the chosen method are the risk of misinterpretation of the questions, lack of possibility to acquire supplementary data, and limited complexity of the data collected. The advantages of using a questionnaire in the research outweighed in this case the disadvantages.

3.3.4 Observations

Direct observations were used to collect data, as part of a triangulation described by Williamson and Bow (2002) and Yin (2009). A drawback of this method could be the objectivity. There is a risk that the observer is looking for confirmation of theories instead of being open to other causes. No suitable alternatives to observations were identified. Observations were, however, not used as a standalone method, but rather as a supplement to interviews and archival data.

3.3.5 Six Sigma methods

The research conducted has to a large extent been based on DMAIC from Six Sigma. DMAIC is a well-defined process improvement methodology divided into five steps, define, measure, analyse, improve, and control, described by, among others, Magnusson et al. (2003). In each step, several tools and techniques are available to support the work. The most frequently used tools during the research have been measurement system analysis gauge R&R, attribute agreement analysis, time series plots, design of experiments, affinity and interrelationship analysis, also referred to as AIM (Alänge, 2009), and control charts, further described by Brook (2010) and Bergman and Klefsjö (2010). Depending on the type of data there are different choices of measurement system analysis as well as control charts. The choices are further justified in each study.

3.3.6 Interviews

One frequently used data collection method is interviews. The interviews were based on the methodology described by Lantz (2007). The interviews were recorded, transcribed, and validated before analysis. Depending on the way the questions were formulated they could be used either for quantitative or qualitative analysis of the phenomena studied. One issue to consider is the interviewer's previous position as value stream manager at one of the companies studied. There was a risk that the respondents tried to give what they believed was the "right" answer. For that reason other interviewers were involved in some of the studies.

3.3.7 Action research

The study “Workshops control chart of KPIs” had an action research approach. The difference from “ordinary” qualitative research is that action research is done together with practitioners instead of about them. The researcher affects the situation, prompting an action. Williamson and Bow (2002) describe the intention of action research to bring about a change of practice while at the same time creating knowledge. Bradbury-Huang (2010: 93) states that “theory without practice is not theory but speculation”. According to Coughlan and Coughlan (2002) action research comprises three types of steps:

1. Pre-step for understanding
2. Six main steps including to gather, feedback and analyse data and to plan, implement, and evaluate the action
3. Meta-step to monitor, which is the academic focus

This research approach was chosen for several reasons. First of all, the intention of the research is twofold: it should be of use both academically and industrially. Second, to test the theories it was necessary to actually influence the situation. Otherwise nothing would have happened right then, meaning nothing to study. The third reason was the background of the researcher. Since the researcher had been working closely with some of the practitioners earlier, the result might be influenced. The choice was therefore to turn this into an advantage and benefit from the ability to influence. Wallén (1996) states that the researcher needs to be independent of the employer. Coughlan and Coughlan (2002) on the other hand say it is increasingly common for action research to be from within the organization.

Interactive research could have been chosen instead. Interactive research differs from action research mainly in to what extent the practitioners are involved in the different steps. According to Aagard and Svensson (2006), there could be joint responsibilities in problem definition, selection of methods, analysis, and dissemination of results. Based on the current situation at the companies it was believed that the right level of involvement for the practitioners instead was in line with an action research set-up.

3.4 Reliability and validity

In order to evaluate the quality of the research its *reliability* and *validity* need to be considered as described by, among others, Yin (2009) and Williamson and Bow (2002). *Reliability* is the consistency of results, which means that when repeated the same result should be achieved. *Validity* is the method’s capacity to investigate what it was intended to investigate. Validity can be further divided into *internal*, *external*, and *construct validity*. *Internal validity* describes the possibility to establish causal relationships distinguished from unknown factors. *External validity* refers to how generalizable the research findings are. *Construct validity* describes to what extent the method actually investigates what it was intended to investigate.

3.4.1 Reliability

In the case of quantitative data, measurement system analysis has been used to see the variation caused by the measurement process. Repeatability and reproducibility have been investigated. Repeatability indicates whether the operator gets the same result when evaluating the same sample several times. Reproducibility instead shows if different appraisers get the same result when evaluating the same parts using the same equipment.

In qualitative studies reliability can instead be achieved by collecting and storing the data in a clear way according to Yin (2009). Thereby other persons could conduct the same study and arrive at the same findings. Stenbacka (2001), on the other hand, considers reliability not to be relevant to qualitative research. She suggests, however, to give a thorough description of

the whole process enabling conditional intersubjectivity, which could be interpreted as the same intention as Yin's description of reliability in qualitative research.

In this reliability section it is also relevant to discuss the researcher's role. The researcher is always a part of the study, whether quantitative or qualitative, even though more evidently when performing qualitative research. As mentioned before there are both opportunities and drawbacks regarding the researcher's role. Opportunities were that the researcher in question had connections to the people involved, by previous work arrangements. It was therefore possible to get easy access to data, events, and constellations that otherwise would have been impossible. This is crucial since the intention was to investigate the phenomena in their actual context. Stenbacka (2001) considers pre-understanding as an important quality aspect. However, there is a risk of affecting the scene. The way the researcher was approached could be affected by the fact that the people involved had an earlier connection to the researcher. Sometimes this connection was utilized intentionally (action research).

3.4.2 Internal validity

Internal validity describes the possibility to establish causal relationships distinguished from unknown factors. This is inapplicable to descriptive or exploratory studies but of high importance for explanatory studies. In the research conducted the level of internal validity differs depending on the extent of "laboratory" settings. In the quantitative studies it was easier to gain control of the different influencing variables compared to the qualitative studies. In the internal validity it is also necessary to consider the investigator's interference.

3.4.3 External validity

External validity describes how generalizable the research findings are. There are two different types of generalization; analytical and statistical according to Yin (2009). Analytical generalization means how well the result can be generalized to some broader theory. The findings can then be replicated to see if the application of the same theory gives the same result. Statistical generalization is instead affected by the sampling measures and response rates (in the case of surveys).

3.4.4 Construct validity

Construct validity refers to the extent to which the method actually investigates what it was intended to investigate. Yin (2009) suggests three ways to improve construct validity: first to use multiple sources of evidence, second to create a chain of evidence, and finally to have the report reviewed by key informants. Multiple sources of evidence can be addressed by using triangulation as described by Williamson and Bow (2002) and Yin (2009). This can then be further divided into different types of triangulation: data, investigator, theory, and methodological triangulation.

CHAPTER 4 – Empirical findings

In this chapter the connection between research questions and empirical studies will be shown. The empirical studies will be described and the findings from the research will be presented.

4.1 Empirical studies

In the following sections the different empirical studies will be presented. Figure 14 shows the connections between research studies conducted, papers, and research questions. Depending on the type and delimitation of the research questions, they are covered to various extents in several studies. The research questions are both well covered. Research question 1 (Evaluation process) is covered in five of the 13 studies. The second research question (Understanding variation) also has high coverage, four studies. An additional four studies were conducted, investigating the potential in a wider context than the research questions. The study “Weld toe radius variation” was run as a separate Six Sigma project but was influenced by and affected the research. The papers appended are based on results from the research studies.

	PAPER	RQ
Obstacles to quality assurance	IX	-
Assessing weld toe radius	IV	1
Currently used evaluation methods	IX	1
Precision of visual inspection	V	1
Weld weight deviation	I	2
Workshops control charts of KPIs	VII	2
Barriers to monitoring	VIII	1
Influence of gaps	I, III, V	2
Standardized evaluation methods	IX	1
Reactive/proactive evaluation in industry	-	-
Weld toe radius variation	IV	2
Control charts of KPIs literature study	VI	-
Empirical distribution of control charts of KPIs	VI	-

Figure 14: Connection between research studies conducted, papers, and research questions.

The studies were conducted during six years' time with a one-year recess due to parental leave as shown in Figure 15. Many of the studies were carried out concurrently.

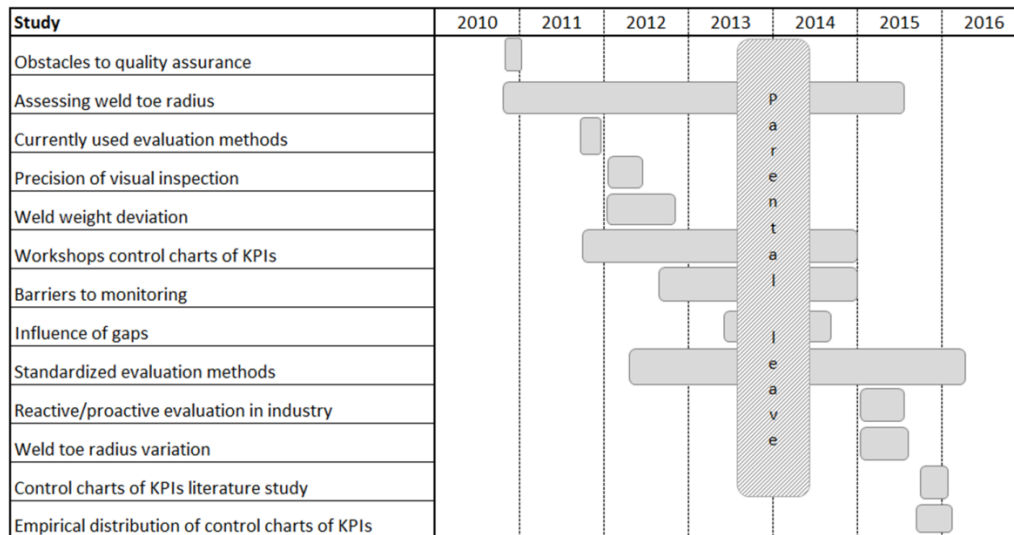


Figure 15: Time extension of performed studies.

A more detailed description of methods and techniques used in each study can be found in Chapter 3 of the thesis and in the published papers. The connections between the objective, research questions, and studies conducted are illustrated in Figure 16. The first study, obstacles to quality assurance, was conducted before the research questions were formulated and was done to understand the issues of the implementation of the weld standard.

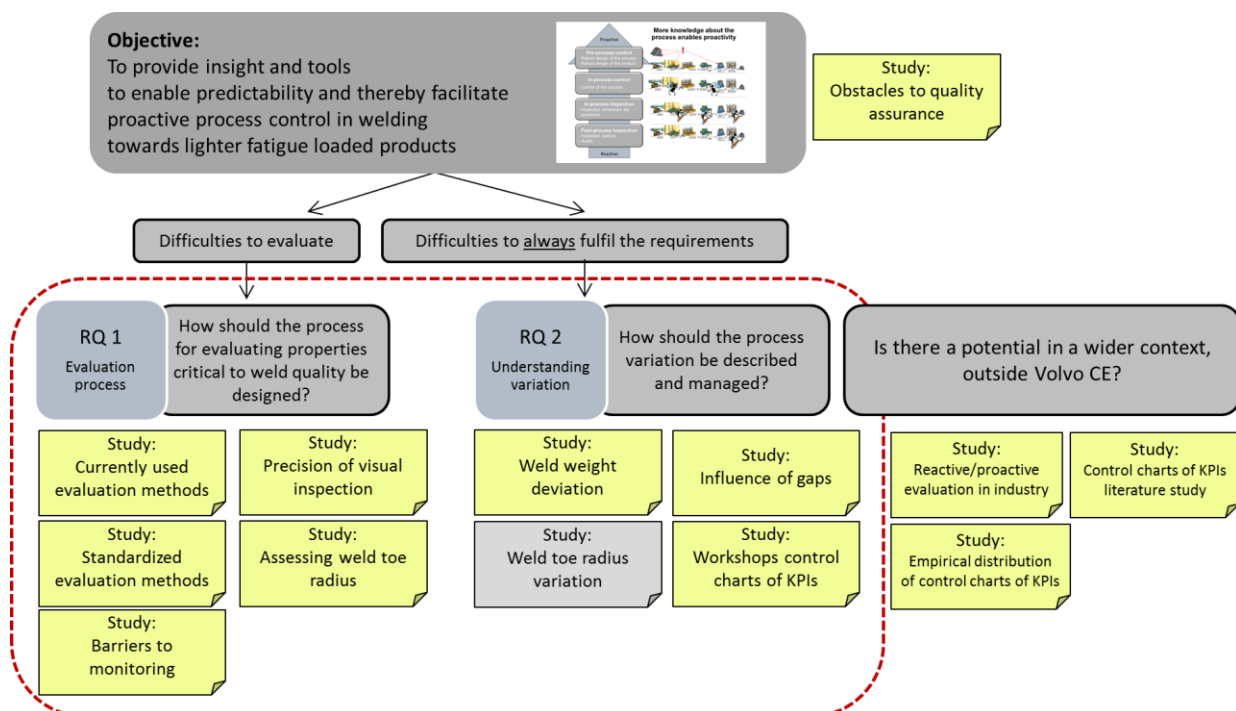


Figure 16: Illustration of connections between objective, research questions, and studies conducted.

The WIQ research project (Samuelsson, 2010), which was the starting point for these

doctoral studies, aimed at finding a way to implement the Volvo weld standard (Volvo Group, 2008) in engineering and production, enabling a structural weight reduction by at least 20 %. The difficulties identified concerned with production could be divided into mainly two areas, the difficulties of evaluating the weld toe radius and the difficulties of always fulfilling the requirements in the production. Based on those difficulties, the research questions were formulated. Studies were conducted to try to find answers to the questions.

For research question 1 (Evaluation process) the first step was to understand the current situation regarding evaluation methods used throughout Volvo Construction Equipment. From that study it was clear that visual inspection was the most common method and therefore needed to be further studied. It was evident that there was a need of standardized evaluation methods, in particular for assessing the weld toe radius. Finally, barriers to monitoring were studied since they were believed to be a prerequisite for being able to control the process.

In the case of research question 2 (Understanding variation) it was also necessary to understand the present situation regarding variation in order to be able to manage it. At first, weld weight deviations were studied. That was followed by a study of the influence of gaps. The weld toe radius variation was also studied, however in a separate Six Sigma project, not run as part of the research. It was clear that these issues could not be solved on shop-floor level only but it was necessary to spread the understanding of variation throughout the entire organization. Therefore workshops about control charts of KPIs were conducted.

Most of the studies were conducted in the Volvo CE organization. The issues studied and conclusions drawn are however believed to be relevant for other companies and contexts as well. Therefore additional studies were conducted to investigate the potential in a wider context. Reactive/proactive evaluation in industry was studied by interviewing representatives from 22 welding plants. The empirical distribution of control charts of KPIs was studied at seven Swedish manufacturing companies. The empirical study was supplemented by a literature study on control charts of KPIs.

First, the study “Obstacles to quality assurance” will be presented. That will be followed by the studies connected with research question 1 (Evaluation process). Then the studies linked to research question 2 (Understanding variation) will be presented. Finally, the studies that put the research into a wider context will be described.

4.2 Obstacles to quality assurance

The background, method, result and findings from the AIM (Affinity-interrelationship method) workshop held in the last quarter of 2010 will be presented in the following sections. The study is included in Paper IX.

4.2.1 Background

As a part of the research project WIQ the opinions about obstacles preventing quality assurance in accordance with the weld standard (Volvo Group, 2008) were investigated. The same type of exercise had been done in the previous research project LOST described by Hammersberg (2010). The research questions had not been formulated at the time of the study.

4.2.2 Method

The method used was KJ Shiba, also called AIM (Affinity-interrelationship method) (Alänge, 2009). The study was carried out with cross-functional team members from management, welding, production engineering and quality department at the same plant. The choice of participants was made to cover the departments concerned. The study was conducted during three sessions from late September until early November 2010. Before the exercise, several of

the participants expressed their opinion that the problem had to do with the cooperation with the design department or a lack of test methods.

The theme of the exercise was to find a common answer to the question “What are the main obstacles preventing quality assurance in accordance with the weld standard?”. The participants could discuss this theme freely before each member was asked to jot down possible answers to the question on post-it notes. All notes were then discussed to make sure everyone understood their content. All notes were then grouped and headings were created by the participants jointly. This step was repeated twice. Finally, interrelationships between the groups were indicated by arrows. The participants then voted for the groups they thought were the most influential. A joint opinion of the group was formulated as an answer to the initial question.

4.2.3 Result

The group with the highest score was “Lack of competence” followed by “Lack of standardized work” and “Method is not followed”. This was summarized into: “We lack enough competence and insight into why it is important to have and follow a standardized way of working in all functions”. The resulting AIM is visualized in Figure 17 and can also be found in Appendix A.

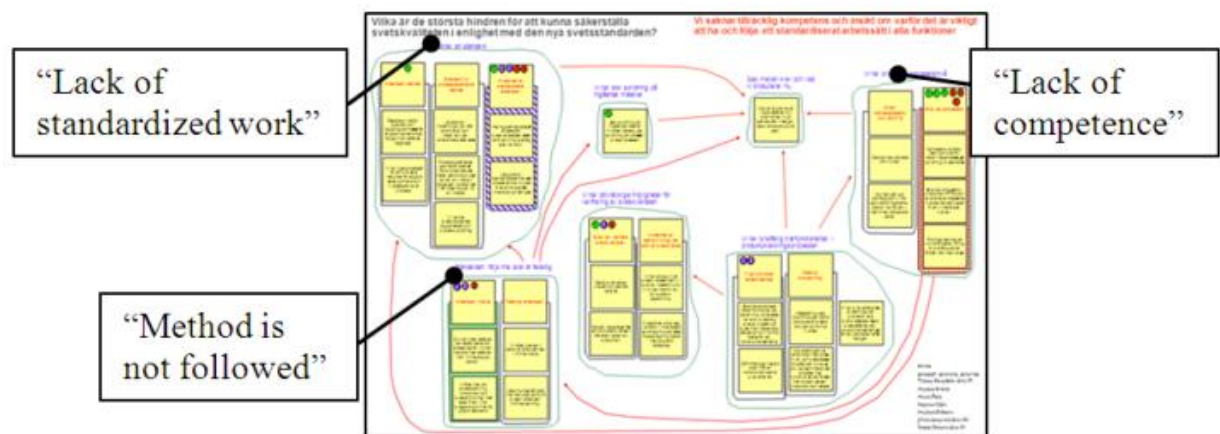


Figure 17: Layout of the resulting AIM.

The causes of the problem were at first identified to be “somewhere else” in the organization and of a technical character. This changed during the workshop and obstacles of a non-technical character were included as well as the belief that the participants’ functions did have an influence on the topic.

4.2.4 Findings

The main findings from the study were the following:

- Obstacles preventing quality assurance of welds can be of both a technical and a non-technical character.
- The causes of the problem were at first identified to be “somewhere else” in the organization but changed during the exercise to include the participants’ own functions.
- To ensure competence about why it is important to have and follow a standardized way of working in all functions was identified as the key factor.

4.3 Currently used evaluation methods

In the following sections the background, questionnaire design, and findings from the study of currently used evaluation methods will be described. The study is also presented in Paper IX and Öberg et al. (2012). The study was carried out during the last quarter of 2011.

4.3.1 Background

The first research question (Evaluation process) requires deeper understanding of the current situation in industries welding structures subjected to fatigue. An investigation of the currently used methods at the different plants at Volvo Construction Equipment was conducted at the end of 2011.

4.3.2 Method

Because of the geographical distance and the type of study, a questionnaire was a suitable method. Representatives from all 12 welding facilities in the company as well as an external company were asked to fill in a template matrix. The choice of participants was based on their knowledge in the field and access to data. The answer rate was 100 % after two reminders had been sent out. The questionnaire was a matrix with the various defect types described in the weld standard (Volvo Group, 2008) on one axis and the detection methods on the other axis. For each of these combinations the participants had to choose any of the following:

- Existing method but not usable
- Usable for our demands
- Limited usability for our demands
- Very limited usability for our demands
- Not usable (not an existing method at the plant)
- Usable for our demands (not an existing method at the plant)

4.3.3 Result

The answers were synthesized in a matrix as shown in Figure 18.

Methods used to identify weld defects		Visual					
Defect	Method						
		1	2	3	4	5	6
		Limitations	Limitations	Limitations	Limitations	Limitations	Limitations
101	Internal and external crack	Limited usability for our demands	only external	only external	only external	ONLY EXTERNAL	External
102	Overlap and cold lap	Limited usability for our demands	only large	only large	only large		Limited usability for our demands
103	external lack of fusion	Limited usability for our demands	only large	only large	only large		Limited usability for our demands
104	internal lack of fusion	Not usable (not existing method at the plant)					Not usable (not existing method at the plant)
105	Not applicable	Not usable (not existing method at the plant)					

Figure 18: Example of the filled-in questionnaire.

4.3.4 Findings

The main findings from the study were the following:

- Visual inspection was the most commonly used evaluation method. All plants used visual inspection and it was also used for most types of defects.
- For some defects, e.g., lack of penetration, there was no existing evaluation method.
- The plants used different methods for detecting the same defect.
- The respondents had different opinions about the ability of the methods to detect defects.

4.4 Precision of visual inspection

In the following sections the background, study design and findings from the study of the precision of visual inspection will be presented. The test and analysis are described in detail in Paper V and in Ericson Öberg and Åstrand (2013).

4.4.1 Background

The synthesis of the currently used evaluation methods showed that visual inspection was the most commonly used evaluation method at the plants. The investigation however indicated that the respondents had different opinions about the efficiency of the method. To better understand the variation occurring in visual inspection this needed to be investigated in connection with research question one (Evaluation process). The study was carried out at the beginning of 2012. The objective of the study was to investigate the repeatability and reproducibility of the visual inspection applied using attribute agreement analysis.

4.4.2 Method

Participants from 12 plants in seven countries met face-to-face for this study. 16 participants (weld auditors, technicians and quality managers) evaluated 16 welds like the one in Figure 19, for 15 defect types, three times each, in a randomized order. For each weld the appraiser should decide whether the weld was defect-free or not, and in the latter case how severe the defect was (four levels). In total 11,520 answers were given and analysed using attribute agreement analysis.

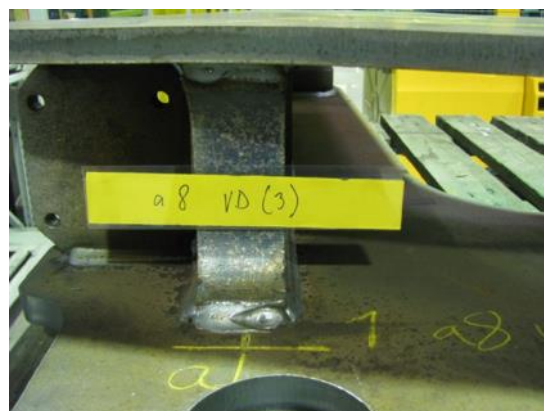


Figure 19: Example of weld evaluated with weld requirements stated on a note.

4.4.3 Result

The results differed depending on the appraisers' experience, and only the operators who regularly performed weld audits were included (11 persons). The result showed a serious mismatch of evaluated demerits between the evaluations. Table 2 shows an example in which the same operator (no. 10) evaluates the same part and gets different results. The data were divided into only ok/not ok and analysed again, to see if the problem was the demerit system itself. The result was slightly better but still very poor. The analysis showed problems concerning repeatability as well as reproducibility.

Table 2: Example of evaluation result

Operator	Weld	Evaluation order	Defect	Demerits	OK/NOK
Operator 10	4109	12	Non-filled weld	5	NOT OK
Operator 10	4109	24	Non-filled weld	0	OK
Operator 10	4109	48	Non-filled weld	25	NOT OK

4.4.4 Findings

The main findings from the study were the following:

- The visual inspection method included unacceptable levels of variation.
- There was an issue with both categorizing into demerits and evaluating ok/not ok.
- The poor result had not been expected by the organization.

4.5 Standardized evaluation methods

The background, method, result and findings from the study about standardized evaluation methods will be presented in the following section. Paper IX describes the study.

4.5.1 Background

The study investigating the currently used evaluation methods indicated a large variation between the sites. Visual inspection was the most commonly used evaluation method. For some defects there was no existing evaluation method, and the plants used different methods for detecting the same defect. The respondents also had different opinions about the ability of the methods to detect defects.

Without standardized procedures it is impossible to exchange one method for a better one; there are rather only new ways added. To keep the quality assurance flexible and agile for new demands, the evaluation methods therefore need to be standardized. As soon as a new requirement occurs, the method can then be changed in a structured way. This also improves the possibility to use the same methods at several sites as well as synergies for training and purchasing of equipment. It was therefore necessary to standardize the situation to reduce the variation and disseminate the knowledge of measurement system analysis (MSA). This supports research question 1 (Evaluation process).

4.5.2 Method

For each defect described in the standard (Volvo Group, 2013), the different methods used were evaluated using measurement system analysis to see which one to prefer. An internal guideline was created including guidance on how to identify the defect, which method to use, the MSA result, and how to judge the severity of the defect.

4.5.3 Result

Differences in preconditions between sites (e.g., different tools used) were identified. Measurement system analysis was not a commonly used tool at all sites. A need for improved training in variation and measurement system analysis was identified. When the more detailed guideline had been created there were discussions of a need for even more precise definitions. When there was no guideline it was not as evident that there were differences in judgement. Visual judgement is the most difficult to standardize.

4.5.4 Findings

The main findings from the study were the following:

- There was a difference in preconditions between sites regarding, e.g., tools.
- MSA was not a commonly used tool to evaluate variation.
- A more detailed guideline created a need for even more definitions.
- It was difficult to standardize visual judgment.

4.6 Assessing weld toe radius

The background, method, result, and findings regarding assessing the weld toe radius will be presented in the following section. The different methods are described in Paper IV. The test and analysis for the radius gauge are also described in Öberg et al. (2012).

4.6.1 Background

In the company-specific weld standard developed in 2008 (Volvo Group, 2008) a new requirement, transition radius between the plate and weld, was included. There was no existing evaluation method available at the company. The objective was therefore to identify an appropriate method for the organization to use. That includes understanding and managing the variation in the measurement system. These studies therefore contribute to research question one (Evaluation process). The first study in this area was carried out in late 2010.

4.6.2 Method

Depending on the information need several methods were investigated. Initially a low-tech method was tested, *radius gauges* in combination with radius master block. The radius gauges consist of several steel blades with different radii on the top. The radius master block has different radii on the four faces that correspond to the weld class requirements 0, 0.3, 1, and 4 mm. First the operator looks at the weld and identifies which of the radii on the block is the closest. The equivalent radius gauge is held against the block to see what the light slit should look like when it matches. Then the radius gauge is placed on the weld. Depending on the appearance of the light slit, the appraiser judges whether the radius is larger or smaller than the radius gauge, see Figure 20.

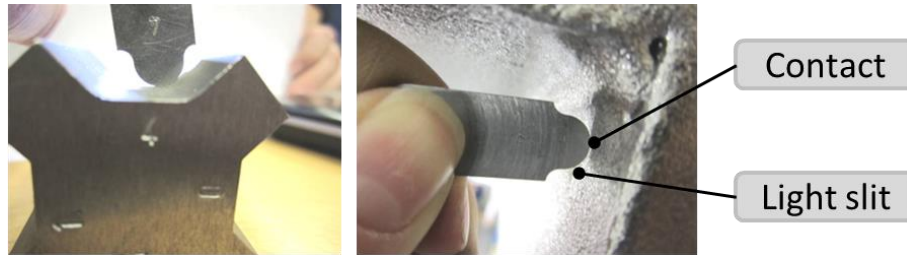


Figure 20: Ocular calibration of light slit appearance when gauge and block match (left) and gauge used on weld to assess whether the weld radius is larger or smaller than the gauge (right).

Several measurement system analyses have been performed of this method since 2010, using both Gauge R&R ANOVA method (continuous data) and Kendall's coefficient of concordance (attribute data).

Another method studied was measuring the radius on *weld impressions* as illustrated in Figure 21. A polymer is applied to the weld surface and after being solidified the impression is cut and measured. Two methods for analysing the impressions were used, WIA (weld impression analysis) and profile projector. The Gauge R&R ANOVA method was used for analysing the measurement system variation.

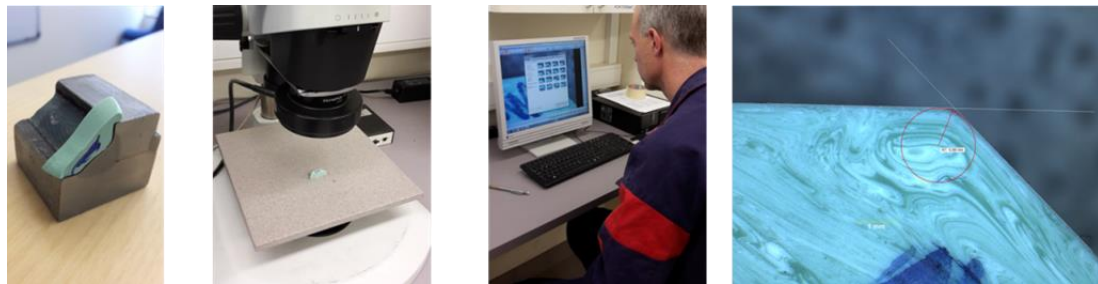


Figure 21: The process steps in WIA (weld impression analysis) consist of making the impression, placing the cut piece under a microscope, drawing support lines, and finally fitting a circle to identify the radius.

The thesis work by Lindgren and Stenberg (Lindgren and Stenberg, 2011) was the start of investigating the possibility to *scan the weld profile* by projecting a laser line onto the weld, see Figure 22. The technique has been developed since (Stenberg et al., 2012), e.g., in the research project Onweld (new ON-line method for quality assurance of WELDeD structures) funded by Vinnova. The measurement system variation was analysed using the Gauge R&R ANOVA method.

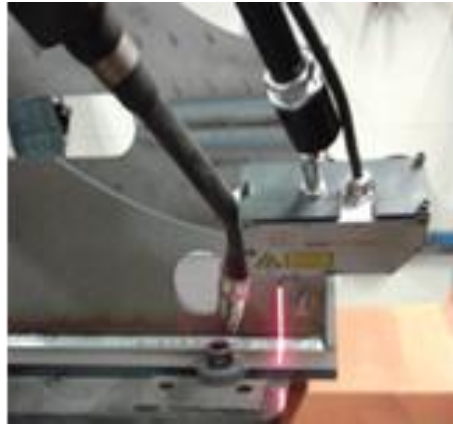


Figure 22: Scanning of the weld profile after welding.

4.6.3 Result

For the *radius gauges* method Kendall's coefficient of concordance showed a very high value both for repeatability and reproducibility (called within appraiser and between appraisers) in the first test. That could be compared with the result from the Gauge R&R ANOVA method when analysed as continuous data where most of the variation, 67.5 %, originated from the measurement system. Later MSAs have, however, shown a better result for the Gauge R&R ANOVA method, probably caused by the appraisers' increased experience of the method.

In the case of weld impressions measured by WIA, the Gauge R&R showed an excellent result, with only 2 % of the variation stemming from the measurement system itself. When using the profile projector for analysing the impression the variation was about 30 %.

When conducting a Gauge R&R analysis on the laser scanning method, the measurement system showed to be very sensitive to vibrations and the distance of the laser. The radius could differ by several millimetres when the laser position was changed and the numerical result of the MSA is therefore of limited value. Additional studies on the causes of these issues need to be conducted before a further measurement system analysis can be done.

4.6.4 Findings

The main findings from the studies conducted were the following:

- Depending on the information need different methods for measuring weld toe radius are suitable. A coarser measurement system can be preferable.
- Variation stemming from the measurement system can be managed by choosing the best suited method for the particular situation.
- The most technically advanced method is not necessarily the best; a simple and inexpensive evaluation option can be sufficient.

4.7 Barriers to monitoring

The research conducted addresses the question why robust in-process monitoring and adaptive control have not been fully implemented in the welding industry. Paper VIII is based on the result from this study. The experiment is also described in detail in Sikström and Ericson Öberg (2016).

4.7.1 Background

The study addresses research question one (Evaluation process). In the research project FaRoMonitA (Fast and robust optical in-process monitoring for welding automation) the

possibilities to monitor penetration depth using arc voltage signals, CMOS vision, and infrared cameras during welding were investigated. An interview study was conducted to understand the perceived barriers to implementation in the industry.

4.7.2 Method

Arc voltage was measured and two types of cameras (vision and IR) monitored the process while cruciform fillet weld samples were welded. The purpose was gap estimation since a relationship between gap size and penetration depth has been established.

The interview study was performed at one plant of each of the companies participating in the research project. The companies are large manufacturing companies in construction equipment (company A), energy (company B), and aerospace (company C), where welding is considered an important process. The interviews were based on semi-structured questions in accordance with Lantz's definition (2007) and were conducted by two persons. Two experienced persons were interviewed at each site. The interviews were recorded.

4.7.3 Result

The experimental study shows that it is possible to monitor penetration during welding using arc voltage measurements, CMOS vision and infrared cameras. The measurement deviation between the three methods is in the same range but the improvement potential is regarded as better for the cameras.

None of the companies interviewed were using in-process monitoring but could see advantages to using it. The interview study indicates that soft issues like competence and financial aspects are as critical as the technical issues, see Figure 23.

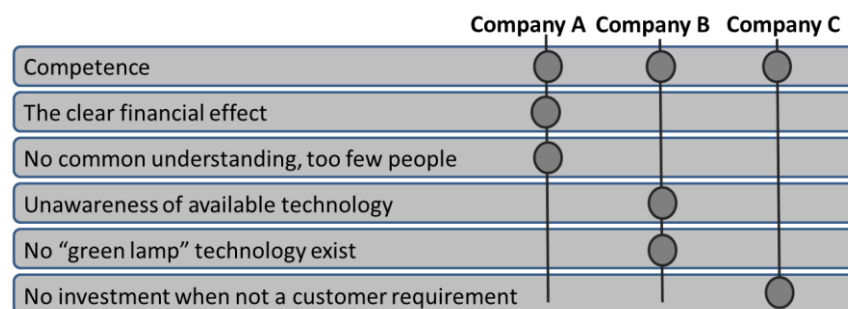


Figure 23: Barriers restricting the use of monitoring according to the interview study.

4.7.4 Findings

The main findings from the study were the following:

- Indirect parameters can be measured, e.g., gap instead of penetration.
- Arc voltage measurements, vision, and infrared cameras can be used for measuring during welding.
- Soft issues such as competence and unclear financial effect are as critical as the technological aspects.

4.8 Weld weight deviation

The study was carried out in several steps, the initial study as a student project and the main part as a Six Sigma project. The initial objective was, in accordance with research question two (Understanding variation), to understand the present situation regarding variation. As the

study developed, the focus shifted towards improvement and benefits. The study is presented in Paper I and Åstrand et al. (2013).

4.8.1 Background

The most common weld type at Volvo CE is fillet weld. The importance of stable and predictable processes with known variation increases when design solutions evolve towards thinner plates to reduce weight. To get an indication of how well the entire production process, from drawing to final product is controlled, any deviation between theoretical and actual weld weight was investigated.

4.8.2 Method

The objective of the initial study was to compare the theoretical weld weight with the actual weld weight for representative welded structures. This was conducted at three different production sites, two at Volvo CE and one at another company. The theoretical weld weight was calculated based on the drawing requirements (weld cross-sectional area multiplied by length and density). Two different methods were used to establish the actual weld weight, depending on the size of the part. For lighter parts the part itself was weighed before and after welding. Because the scale precision was not attainable for heavier parts, the weld wire drum was instead weighed before and after welding. A measurement system analysis was performed to investigate the precision of the scale with a satisfactory result.

The Six Sigma project used methods according to the DMAIC (define, measure, analyse, improve, control) phases. Measurement system analyses were used for investigating the precision of the methods used for analysing the weld size, e.g., throat size (Ericson Öberg et al., 2013). Other methods for acquiring data were interviews, experiments and analysis of archival data. A large part of the data was analysed using the statistical software Minitab version 16. The Six Sigma project was mainly carried out at one of the companies from the initial student project.

4.8.3 Result

The initial student project showed deviations of over 40 % on average with a standard deviation of 0.5 for two of the sites; the third site had a deviation of 26 %.

The main study defined the factors constituting the weld weight deviations as well as the financial consequences. The prevalent method for assessing throat size was not satisfactory for the project's needs. A new method for acquiring the necessary information about weld size and geometry was therefore developed, called weld impression analysis (WIA). A clear connection between gap size and throat size deviation was shown, enabling a financial link between gap variation and cost of excess weld weight. Compensation for gaps in several process steps was also one of the causes identified creating additional weld weight.

4.8.4 Findings

The main findings from the studies were the following:

- There was a large deviation, about 40 %, between theoretical and actual weld weight at two of three plants for the investigated products.
- Compensation for gaps was allowed for in several process steps leading to excess throat size.
- Used measurement methods were not capable of providing the information needed and a new method, WIA, was created.
- The use of weld quality information influenced the deviation

- A clear financial connection between gap variation and weld weight deviation was established.

4.9 Influence of gaps

The background, method, result and findings from the study about the influence of variation in gaps on resource efficiency will be presented in the following section. Papers I, III, and V address the issues included in this study.

4.9.1 Background

Previous studies have shown that gaps have a significant effect on quality defects and excess weld size. No mapping of the current situation was available at Volvo CE nor commonly published and a study to investigate the present situation was therefore initiated. That study and the suggestions for improvement of the varying gap situation contribute to research question two (Understanding variation).

4.9.2 Method

A representative case study (Yin, 2009) was initiated including one Volvo CE plant and several products during five weeks in 2013. The gap size was measured using thickness gauges. The measurement system analysis showed that to be a sufficient tool. Four types of welded products, three units each except for one case with two units, were measured. In total 2,993 welds were evaluated by two persons.

4.9.3 Result

The result showed signs of wide variation both concerning the gap size and presence of an additional weld (root pass). As much as 35 % of the welds had the extra root pass, which came as a surprise to the organization. Resource efficiency is affected by increased presence of quality defects, longer cycle time, and increased consumable usage due to the variation in root pass welding. Three improvement actions were suggested: to continuously measure chosen welds in the production, to perform statistical follow-ups of these welds, and to introduce a standard gauge for assessing whether the gap size requires a root pass or not.

4.9.4 Findings

The main findings from the study were the following:

- There was a wide variation both in size and presence of an extra weld (root pass).
- The existence of a root pass in so many welds was not expected by the organization.
- Gaps affect resource efficiency, e.g., by increased number of defects and consumable usage.
- There was a large potential without heavy investments.

4.10 Workshops control charts of key performance indicators

The study gives input to research question two (Understanding variation). It investigates the current visualization of strategic measures, proposes an improved process of displaying

variation and addresses implementation challenges described in the literature and found in empirical studies. The study is presented in Paper VII.

4.10.1 Background

The control chart, invented by Shewhart (1926), is a tool for visualizing variation. It is commonly used in measurements in industrial production, e.g., machined dimensions. Several sources like Wheeler (2000) and Danielsson and Holgård (2010), show a potential to use it also on high-level key performance indicators (KPIs).

The ideal context to study this is a large company, organized in several functions and showing an interest in using control charts of KPIs. The Volvo CE plant had these characteristics.

4.10.2 Method

The study is divided into two parts, defining clusters of change management theories and holistic multiple case studies in the form of workshops.

Factors identified in change management models were analysed and clustered inspired by the Affinity-interrelationship method (Alänge, 2009). That resulted in 20 themes believed to influence change and implementation.

The case study has a holistic multiple-case design with a single unit of analysis (Yin, 2009). The cases are divided according to which management team they belong to. The workshops were conducted over two years' time, 2011–2012. The workshops were organized with an action approach, meaning that the researcher was not only an observer but intervened by introducing the action (Aagard and Svensson, 2006). The workshop content included both theoretical and practical parts. Content covered included variation, control charts, and the difference between customer demand and the capability of the process.

Four different management teams attended the workshops, plant, assembly, fabrication, and logistics (see Figure 24).

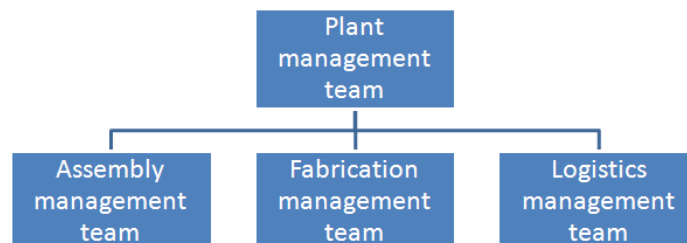


Figure 24: The management teams involved in the study.

The result of the workshops was obtained by using questionnaires, interviews, archival data, and observations. The participants were asked to fill in a questionnaire about their view of the current KPI follow-up before attending the workshop. The questionnaire can be found in Appendix B.

An interview study was conducted by two interviewers in 2012, when 22 persons from different organizational levels were interviewed, ten of which had attended the workshops. The questions used as a basis for the interviews can be found in Appendix C. The interviews were recorded and transcribed by a third person before analysis.

The managers of each management team were also asked to assess to what extent each theme from the literature clustering was fulfilled as well as the believed implementation success.

4.10.3 Result

The initial questionnaire showed a very scattered picture of the current situation among the participants. The presentation of data was often in table format, in some cases supplemented by a bar chart. The observations indicated that the follow-ups mainly focused on short-term and reactive solutions.

When control charts were introduced in the workshops a difference in discussion was noticed. There was a shift from symptom towards cause and a common language around the measurement was created. Figure 25 is an example of a control chart used to understand how the welding affects the plate deformation. It enabled a common understanding of what the process was capable of delivering as well as suggestions for where pre-setting of the fixtures should be used.

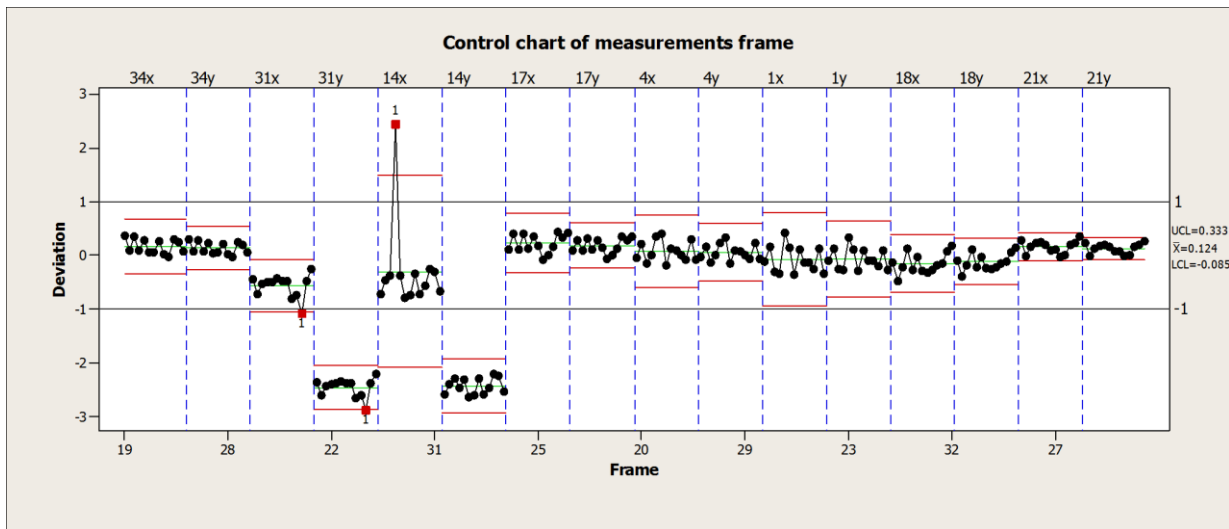


Figure 25: Example of control chart usage used to understand deformations due to welding in the process.

The succeeding interviews revealed that most of those interviewed had some knowledge about control charts, even those that had not participated in any training. Training and knowledge were considered the most important factors for success, indicated by 64 % of the interview answers.

The performance indicator "Material availability at line side" is an example of where a control chart was implemented on high-level KPIs. The performance indicator shows an impressive improvement of the KPI itself over 10 months as shown in Figure 26. During the first 40 days the process is highly unstable. Improvement actions to solve the instability are then taken. The variation decreases, the process mean increases and the process stabilizes after around 150 days. The manager estimated the reduced cost of line stops, balance losses, and additional transports at around 10,000 euro per week.

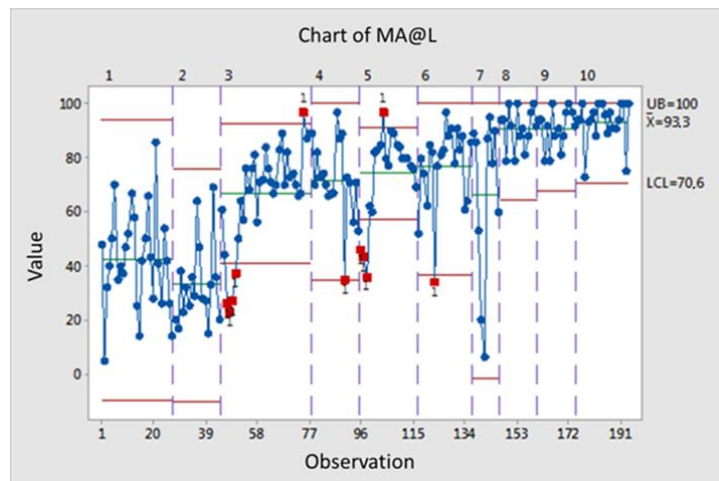


Figure 26: The control chart shows a significant improvement of the performance indicator itself.

The manager comments the result (translated from Swedish):

“For me the control chart has been essential for us to initiate the right activities that give the correct result. In the control chart, we collect the data, but also ensure/validate that our initiated activities take us to our goal.”

The themes from the change management literature synthesis are shown in Figure 27 and are arranged by the number of models in which the theme is present. To have the *goal defined* was the most common theme, followed by *being able to manage in a changing environment* and to have *high-level commitment*. The managers had to state which of the themes they considered as most important for the implementation success, marked with a star in Figure 27. Several themes with a limited presence in the change management literature were, according to the managers, important for the implementation success, e.g., a *clear kick-off* and *dedicated change agents*. The managers were asked to rate to what extent each theme was fulfilled after the workshop as well as the total implementation success in the stages of no fulfilment (0 %), initiative started (25 %), partial fulfilment (50 %), progressing (75 %), and fulfilled (100 %). A mean value was calculated between the managers’ score and the researcher’s assessment. There is a difference in theme fulfilment between the management teams, which agrees with the experienced overall implementation success.

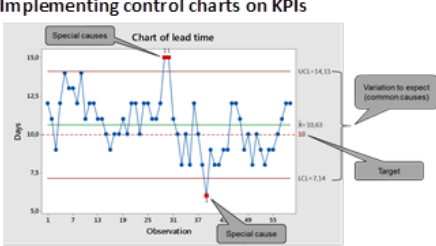
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Figure 27: Experienced theme fulfilment for each management team. The themes considered most important by the managers are marked with a star.

4.10.4 Findings

The main findings from the studies were the following:

- The overall impressions were that control charts of KPIs could be very useful for the management teams.
- Implemented examples show good results and even improvement of the KPI itself.
- The ability to choose the right actions was improved.
- A difference in the discussions was noticed when presenting the data in a control chart instead of a bar chart – there was a shift in language from symptom towards cause.
- Training was essential but not sufficient for success of the implementation.
- Several themes with a limited presence in the change management literature were, according to the managers, important for the implementation success.

4.11 Weld toe radius variation (Six Sigma project)

The background, method, result, and findings from the Six Sigma project analysing the toe radii of the welding process will be presented in the following section. The result from the study is also included in Paper IV.

4.11.1 Background

The purpose of the Six Sigma project was to identify what caused the welding process not to meet the requirement of 0.3 mm in the toe radii on a stable level. Also to identify factors that caused the variation in the observed welding processes was desired. The thesis author did not conduct the study but took part in its initiation and gave support throughout the project. The study addresses research question two (Understanding variation).

4.11.2 Method

The Six Sigma project followed the DMAIC methodology divided into the phases define, measure, analyse, improve, and control (Bergman and Klefsjö, 2010) using suitable tools for each phase.

4.11.3 Result

The project team concluded that to achieve a welding requirement of radius 0.3, knowledge of the welding processes and their cost to the end product for controlling the right materials is necessary. Volvo CE has not previously had continuous data regarding the toe radius. The project collected continuous data by using weld impression analysis (WIA), visualized in Figure 28.

The data show that there is a wide variation in the process. The mean value of the toe radii measured is 0.6 mm, but still about a third of the measurements do not meet the requirement. There is also an asymmetrical quality loss function meaning that the cost of variation increases quickly closer to zero. Smaller variations downwards are much worse than greater variations upwards.

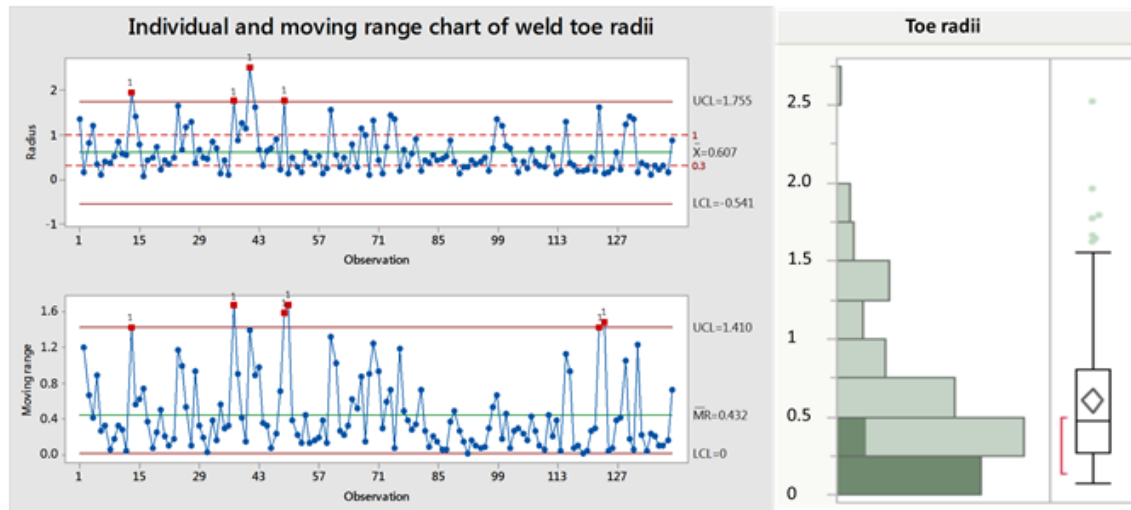


Figure 28: The weld toe radii measured in the project (left) have significant variation even though the mean is 0.6 mm, about one third do not meet the requirement of 0.3 mm (right).

129 factors were identified that might influence the toe radii; the ones believed by experts to have the strongest impact were chosen for further studies, like weld robot, weld wire brand, position of radius, welding speed, number of wires, seam tracking, gas flow, gun angles, current, and voltage. Indications of parameters being more influential than others were observed and a design of experiment (DoE) was suggested to further investigate the effect of gas flow, radius position, welding speed and gun angle.

4.11.4 Findings

The main findings from the study were the following:

- Knowledge about how different parameters affect the weld toe radius is lacking in the company.
- The measurements carried out by the Six Sigma project have created a foundation for future quality improvement work by generating continuous data of the toe radius.
- Increased understanding of differences between factors affecting variation and mean was achieved.
- Initial connections between parameters and weld toe radii were established, both with a variation and a mean perspective.
- Discussions about asymmetrical data were initiated.

4.12 Reactive/proactive evaluation in industry

The background, method, result, and findings from the study about the use of reactive or proactive quality assurance in welding industry will be presented in the following section.

4.12.1 Background

Even though it is commonly believed that it is preferable to have a proactive approach controlling the quality instead of inspecting in a reactive manner, the latter was common at Volvo CE. There are also numerous proofs of the control chart's excellence for managing variation, but the use is not commonly spread. The purpose of the study was therefore to

investigate how proactive the approach to quality assurance was in other companies as well as to study to what extent control charts are used in the welding industry. The study addresses the potential of the research in a wider context outside Volvo CE.

4.12.2 Method

An external interview study was conducted to collect information. Representatives from 22 plants in the welding industry were interviewed. The participating companies were selected based on accessibility, based on previously established contacts. The questions were semi-structured in accordance with Lantz (2007). Due to the geographical distance, most of the interviews were conducted by telephone. The main part of the interviews was made by the same person. One interview was accompanied by another person and two other persons interviewed the remaining two plants. To facilitate the possibility to listen to the interviews several times, they were recorded. The data were compiled and sorted into an Excel file for analysis purposes.

4.12.3 Result

There is a focus on inspecting the product rather than controlling the process. Measurement system analysis is not a widely used tool. Only five out of the 22 companies state that they use control charts. Three of those use them on KPIs. Knowledge about the technique, suitable areas for application and follow-up by higher management were identified by the respondents as important factors for taking variation into account. The data presentation is often not optimized for decision-making and the process for choosing evaluation method differs between plants. The actual cost of poor quality is not clear.

4.12.4 Findings

The main findings from the study were the following:

- There is a focus on inspecting the product rather than controlling the process.
- The process for choosing evaluation method differs between plants.
- The data presentation is often not optimized for decision making.
- Control charts usage is low.
- MSA is not a widely used tool.
- The cost of poor quality is not clear.

4.13 Control charts of KPIs literature study

The background, method, result, and findings from the literature study of control charts of KPIs will be presented in the following section. The research is a part of the work done in the project SuRe BPMS (Sustainable and Resource Efficient Business Performance Measurement Systems). Paper VI presents the study.

4.13.1 Background

To map the attention paid to variation in relation to performance measurement in the literature, a literature review was conducted. The study addresses the potential of the research in a wider context outside Volvo CE.

4.13.2 Method

The literature review consisted of two parts, a systematic and a traditional approach (Jesson et al., 2011). The systematic review consists of six steps: define the research question, design a plan, perform a search, apply exclusion and inclusion criteria, apply quality assessment, and make a synthesis. 10 databases were included in the study and the initial search query was (variation AND KPI AND (performance measure*)).

The traditional literature review instead develops the searches from relevant papers and from there traces other publications, e.g., by investigating papers being referred to.

4.13.3 Result

The most promising database was Emerald, which was therefore chosen for further detailed searches as shown in Table 3.

Table 3: Detailed search result in the Emerald database

Database	Search query	Search field	Time span	Document type	Search date	Search result	Result fit
Emerald	Variation AND KPI AND performance measure*	abstract	All years	All	4 March 2016	4	1 further read (Bai and Sarkis, 2014)
Emerald	Variation AND KPI AND performance measure* AND SPC	all fields	All years	All	4 March 2016	10	3 further reads (Chakraborty and Chuan, 2013; Brown, 2013; Morgan and Dewhurst, 2007)
Emerald	Control chart AND performance measure* AND variation AND implement* AND SPC	all fields	All years	All	14 March 2016	325	5 further reads (MacCarthy and Wasusri, 2002; Caulcutt, 1996; Hamza, 2009; Antony, 2000; Elg et al., 2008)

The traditional literature review added some interesting references (Wilcox and Bourne, 2003; Woodall et al., 2000; Bourne, 2008; Taticchi et al., 2012; Yvonne Coleman, 2013; Maleyeff, 2003; Brimson, 2004; Bergquist and Albing, 2006; Canel et al., 2010; Larsson et al., 2011; Edwards et al., 2007; Sulek, 2005).

4.13.4 Findings

The main findings from the study were the following:

- There are a limited number of examples reported in the literature where variation is considered in performance measurements.
- The examples reported indicate actual opportunities missed when not considering variation in the performance measurement system.

4.14 Empirical distribution of control charts of KPIs

Empirical research from the project SuRe BPMS (Sustainable and Resource Efficient Business Performance Measurement Systems) will be presented in the following section. Paper VI introduces the study.

4.14.1 Background

The objective of the study was to map and categorize the existing range of KPIs used at the seven participating companies. The study contributes to understanding the potential of the research in a wider context outside Volvo CE, in this case Swedish manufacturing companies. The study was conducted at the end of 2015.

4.14.2 Method

The case study had a multiple-case design with embedded units of analysis according to Yin's definition (Yin, 2009). Two of the seven plants belong to the same company. The study had a top-down as well as a bottom-up approach. The top-down study was made by interviewing managers whereas the bottom-up study included interviews, observations, and analysis of archival data. The interviews included questions regarding whether variation is displayed in the measurements. In the observations and analysis of archival data it was noted how the performance measurements were displayed.

4.14.3 Result

The case study showed an almost complete absence of a display of variation in the performance measurements. Only one example out of 3,372 measures included a display of variation in the form of a control chart. Bar charts were commonly used at six of the seven plants. The threshold for changing a bar chart to instead visualize the variation is low, which is promising for future research.

4.14.4 Findings

The main findings from the study were the following:

- The companies have many performance measures.
- Average values are used instead of measures displaying variation.
- Only one out of 3,372 measures showed variation in the form of a control chart.

CHAPTER 5 – Analysis and results

In this chapter the theoretical and empirical findings will be analysed. The findings are synthesized into two areas, “capable evaluation process” and “predictive performance by understanding variation”. A model for designing a quality assurance system for welding based on theory and empirical results presented in this thesis will be proposed.

5.1 Analysis of theory and empirical findings

The objective of the thesis is to “provide insight and tools to enable predictability and thereby facilitate proactive process control in welding towards lighter fatigue loaded products”. This has been investigated through empirical and theoretical studies. The approach to reach the objective can be described as divided into principle, practices, and tools (Hasenkamp et al., 2009; Dean Jr and Bowen, 1994). Based on the research questions the findings can be synthesized into two important areas constituting the prerequisites, “capable evaluation process” and “predictive performance by understanding variation”.

5.1.1 Capable evaluation process

Several of the empirical studies conducted, e.g., “Obstacles to quality assurance”, “Weld weight deviation”, and “Barriers to monitoring” indicate that the obstacles to good quality assurance of welds are not only technical. Soft issues such as competence and unclear financial effect are as critical as the technical aspects. That also means a large potential without heavy investments. The amount of variation occurring at different steps in the manufacturing process came as a surprise to the organization when visualized in the study “Weld weight deviation”.

By understanding the process capability and the factors influencing the final result, a proactive quality approach can be used. The quality can be controlled even before the production process by designing the process and the product in the best way. As an example the findings from the studies “Weld weight deviation” and “Influence of gaps” indicate significant improvement of productivity and quality if the gap size can be proactively controlled, thereby preventing defects and over-welding to occur. Literature references indicate similar results (Hammersberg and Olsson 2010; 2013).

The technological level of NDT equipment is high. A vast amount of research has been performed in the NDT area to develop and improve NDT methods, some examples adjacent to this research being described in Stenberg et al. (2012) and Sikström and Ericson Öberg (2016). However, the variation induced by the measurement methods used for evaluating the process performance also needs to be understood. The frame of reference indicated that evaluation methods used could be incapable of delivering the result needed (Hammersberg and Olsson, 2010). The importance of understanding the variation of the measurement method is addressed in the empirical studies conducted (“Assessing weld toe radius”, “Precision of visual inspection”, “Weld weight deviation”, “Weld toe radius variation”, “Influence of gaps”). To use measurement system analysis to evaluate the amount of variation in the measurement system is not a widely used tool, according to the study “Reactive/proactive evaluation in industry”.

Variation stemming from the measurement system can be managed by choosing the best suited method for the particular situation. The most technically advanced method is not necessarily the best; a simple and inexpensive evaluation method can be sufficient. Visual inspection is the most commonly used evaluation method (“Currently used evaluation methods”), including unacceptable levels of variation (“Precision of visual inspection”).

The study “Currently used evaluation methods” indicated a variation of methods used as well as a lack of evaluation methods for certain defects. The process for choosing evaluation method differs between plants (“Reactive/proactive evaluation in industry”), and there is a focus on inspecting the product rather than controlling the process. Arc voltage measurements, vision cameras, and infrared cameras can be used to measure during welding and it is possible to measure indirect parameters, e.g., gap instead of penetration according to the study “Barriers to monitoring”.

A new method for evaluating weld toe radius, weld impression analysis (WIA), is described in the studies “Assessing weld toe radius” and “Weld toe radius variation”. The study “Obstacles to quality assurance” concluded the importance of ensuring competence regarding why it is important to have and follow a standardized way of working in all functions. The objective of the study “Standardized evaluation methods” was to address these issues and provide a standardized solution with capable methods.

The study “Reactive/proactive evaluation in industry” concludes that reactive quality assurance is still common, meaning inspecting the final product instead of controlling the process. The solution is therefore not costly technical inspection methods but rather increased knowledge of variation and understanding factors influencing the result. A suitable tool to understand how different factors affect the final result is design of experiment (DoE).

The overall objective, the principle, of capable evaluation methods is to be able to base decisions on reliable facts as illustrated in Figure 29. Measurement system analysis has shown to be a useful practice for understanding the variation induced by the measurement system, hence how reliable the measurement data are. Gauge R&R is a suitable tool to achieve this.

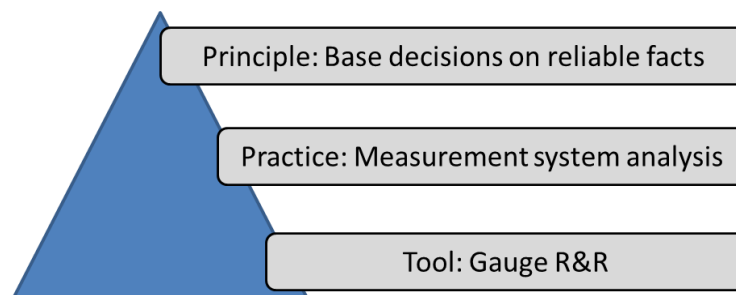


Figure 29: Important principles, practices, and tools to reach a capable evaluation process.

5.1.2 Predictive performance by understanding variation

In the frame of reference several sources point out the importance of getting the right weld quality, no more, no less (Raj et al., 2000; Björk et al., 2008; Stenbacka, 2009; Miller, 2011; Cozens, 2013). The theory however also identifies problems of describing the requirements in a suitable way (Karlsson and Lenander, 2005; Jonsson, 2012; Jonsson et al., 2011). When the process is not fully understood safety margins are created in each step. It is not agreed in the theory whether over-quality affects the cost, but that has been shown, e.g., in the empirical study “Weld weight deviation”.

To be able to predict future performance it is necessary to understand the present situation. The study “Weld weight deviation” indicated a large deviation, about 40 %, between theoretical and actual weld weight at two out of three plants for the products investigated. The study “Influence of gaps” revealed that compensation for gaps was given in several process steps leading to excess throat size. Gaps affect resource efficiency, e.g., by an increased number of defects and consumable usage. The use of weld quality information influenced the

deviation observed. A clear financial connection between gap variation and weld weight deviation was highlighted to be able to get the necessary attention. Great variation both in size and presence of an extra weld (root pass) also influences the observed resource efficiency.

The frame of references suggested tools like control charts to be used for predicting performance (Wheeler, 2000; Shewhart, 1931; Deming, 1994; Danielsson and Holgård, 2010). Actual implemented cases are, however, rare (Wilcox and Bourne, 2003), which was confirmed in the studies “Control charts of KPIs literature study” and “Empirical distribution of control charts of KPIs”. The study “Workshops control charts of KPIs” again demonstrates the power of using control charts of key performance indicators. The ability to choose the right actions was improved and a difference in the discussions was noticed when presenting the data in a control chart instead of a bar chart. A shift in language from symptom towards cause occurred. The implemented example even shows an improvement of the KPI itself.

However, the issue is not the excellence of the methods being questioned but rather the causes of limited diffusion in industry (“Reactive/proactive evaluation in industry”, “Control charts of KPIs literature study” and “Empirical distribution of control charts of KPIs”). Themes important for implementation success addressed in the change management literature were also highlighted in the case study “Workshops control charts of KPIs”, such as having a goal defined and high-level commitment. However, several themes with a limited presence in the change management literature, were according to the managers, important for the implementation success, like a clear kick-off and committed change agents. Figure 30 illustrates that to be able to understand variation (the principle), statistical process control is a useful practice. The control chart is a suitable tool but factors important for the implementation success still need to be considered.

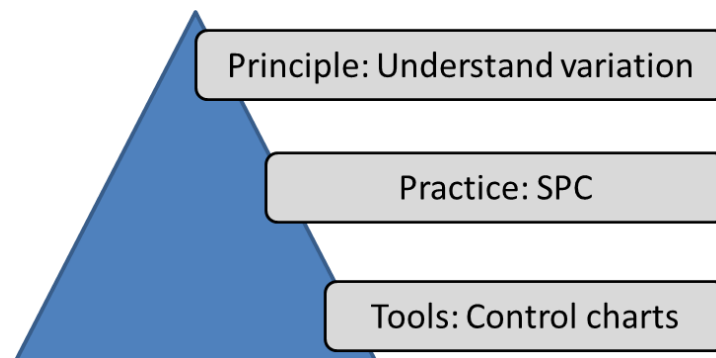


Figure 30: Important principles, practices, and tools to get a predictable performance by understanding variation.

5.2 PULL approach model

The ability to use process information is an important competitive advantage (Cohen and Levinthal, 1990; Kehoe et al., 1992), and the information should be used to manage uncertainty and equivocality (Daft and Lengel, 1986). The way it is presented affects the ability to take correct decisions (Danielsson and Holgård, 2010; Deming, 1994; Wheeler, 2000). Several of the empirical studies conducted indicate that obstacles to predictability and thereby proactive process control are not merely technical, but rather concerned with organizational understanding of performance influenced by variation in a cross-functional context.

Based on the theory and what has been seen in the studies conducted, a suggested model has been developed, called PULL approach for quality assurance. The model is based on traditional lean concepts where the customer need is in focus. The chosen technique or method is based on the information necessary to acquire, rather than existing inspection-methods. The PULL approach has been described in several papers, e.g., Paper II and IV (Öberg et al., 2012; Ericson Öberg et al., 2013; Ericson Öberg and Hammersberg, 2016).

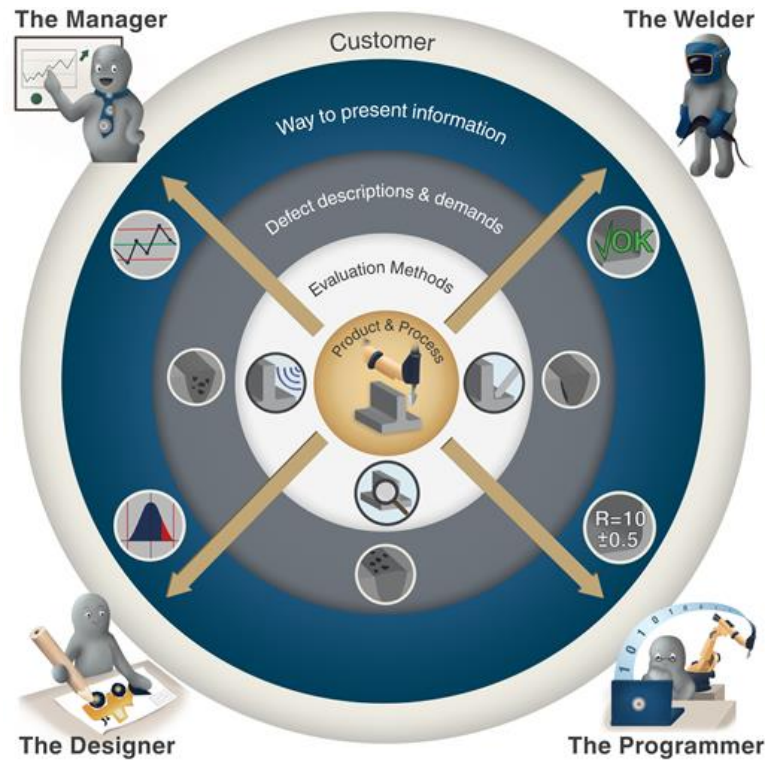


Figure 31: Illustration of components affecting the evaluation system.

Figure 31 illustrates components affecting the evaluation system. People in the manufacturing system need different kinds of information about the product or the process in order to come to the right decision. They are here represented by the manager, the welder, the designer, and the robot programmer.

The following scenario could illustrate the different information needs. The welder is interested in whether the product he or she welded is ok or not to send to the next operation. The weld robot programmer, on the other hand, wants to know if the program he or she made will produce parts within the tolerance limits. The designer is instead interested in the variation of the production process for a certain design alternative, to be able to choose the best suited one. The manager focuses on where the resources for improvement projects should be added.

Not only do they need different kinds of information but it also needs to be presented in different ways. The welder needs an “OK/NOT OK” signal, while the programmer needs to get comparable results between weld and the tolerance limits. The designer wants to see the manufacturing variation for different design alternatives, while the manager needs a visualization of where the most influential problem exists.

It appears that all these different information needs probably require different ways of acquiring the data. A model offering a structured way of taking this into consideration has been developed, see Figure 32.

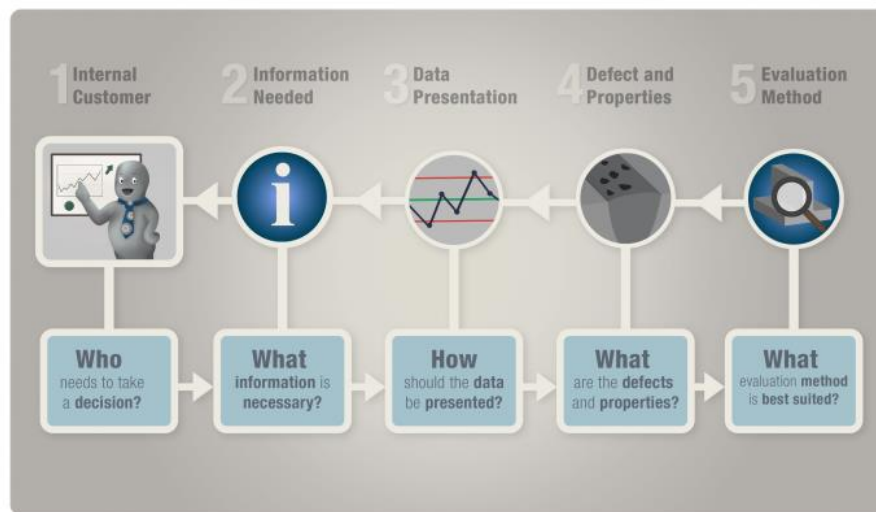


Figure 32: The PULL approach model for evaluation of welds.

5.2.1 Internal customers – who needs to make a decision?

The first step is to identify the “internal customer”, meaning the person or function that needs the information to come to a decision. When starting to investigate, it can be evident that there are many more “internal customers” than first thought of.

5.2.2 Information needs – what information is necessary?

The next step is to identify what information the different internal customers need to come to a decision. It can be anything from an indication of the ongoing process, product within tolerances, or process capability. The information need is not automatically the same thing as the drawing requirements or tolerances.

5.2.3 Data visualisation – how should the data be presented?

Depending on the information need, the data might need to be presented in different ways. A graphical data presentation is often preferred. Control charts have shown to be a good way of presenting information about the stability and variation of a process.

5.2.4 Defects and properties – what are the defects and properties of interest?

This far in the process the actual defects and properties of interest may have changed from what was first believed. The property can be qualitative or quantitative. It can in some cases also be indirect. That means there is a connection between a certain property and the property of interest and the evaluation can therefore be made on the indirect property instead.

The way the requirements are described, e.g., in a standard or on a drawing has great impact on the evaluation method but it is necessary to keep in mind what information the internal customer needs. Depending on the need, it might in some cases be sufficient to only detect the presence of defects while in others these need to be sized and positioned.

5.2.5 Evaluation method – what evaluation method is best suited?

When arriving at this stage the information need has been defined. In the best scenario there is already an evaluation method suitable to deliver this type of information. If not, the steps have led to a definition of what the evaluation method should be able to do. The process may have resulted in the conclusion that it is possible to retrieve the information using an uncomplicated and inexpensive method, in contrast to what was first believed. A critical factor is to assure that the method is good enough for its purpose, e.g., tested for repeatability and reproducibility in a measurement system analysis.

5.2.6 Example of implemented usage

The model was tested at the end of 2012 in a project in which a new manufacturing system for producing engine-carrying structures was to be implemented. Three participants from the ordinary project team together with the author conducted 8 workshops, on average 2 hours long, in which the PULL approach was used. The objective was to identify what information each stakeholder in the project needs as well as how the information should be accessed and presented. Stakeholders and information needs were noted on post-its as Figure 33 shows. Thereafter the identified need on each of the notes was analysed and what and how to assess was identified for each of them. The workshops resulted in 62 identified information needs for which the entire process from customer need to assessment method was described. Half of them were incorporated into the project's action list, the rest were considered to be outside the project scope.



Figure 33: Photo from the workshop identifying stakeholders and information need.

5.2.7 Disadvantages and advantages of the PULL approach model

The model is very straightforward and simple and can be thought of as obvious and common-sense. However, a development of the model is justified since there apparently are examples of the opposite way of working in the industry investigated.

A disadvantage can be that there will probably be a need for several evaluation methods and data presentations for the same problem. This increases the amount of work necessary when planning and executing. It can also be necessary to prioritize among the internal information customers with the consequence that some internal customers will not get customized information. It is, however, then always a conscious decision, which is better than

the opposite. If your business is to develop new evaluation methods, more of a technology push approach can be reasonable. To be able to sell the equipment, it is however necessary to connect the equipment's deliverables to a customer need, requiring a pull approach.

The advantage of the method is the increased chance of getting the right information to the people who need it. The potential influence of the increased decision-making precision is huge. In the short term it can lead to cheaper and less complicated evaluation methods. Long-term it enables the company to grow in the right direction since the decision making is improved. The model also improves the cross-functional work by achieving changes that often fall between the organizational functions. It helps preventing sub-optimization by focusing on the internal customer need.

CHAPTER 6 – Discussion, conclusions, and future research

In this chapter the results and conclusions of the research are discussed. First, there is a general discussion. Thereafter, the quality of the research conducted will be discussed. The fulfilment of the research objective will be argued and the research questions will be briefly answered. The contribution of this thesis to academia as well as industry will be highlighted. Finally, the thesis will end with a presentation of suggested future research.

6.1 General discussion

A consistent theme in this thesis is variation. The ability to understand variation in, e.g., measurement systems (as studied in “Assessing weld toe radius”, “Precision of visual inspection”, and “Standardized evaluation methods”) is revealed by consequences for quality and productivity (as shown in “Weld weight deviation” and “Influence of gaps”). Paper V describes the variation occurring in each step and exemplifies the consequences, illustrated in Figure 34.

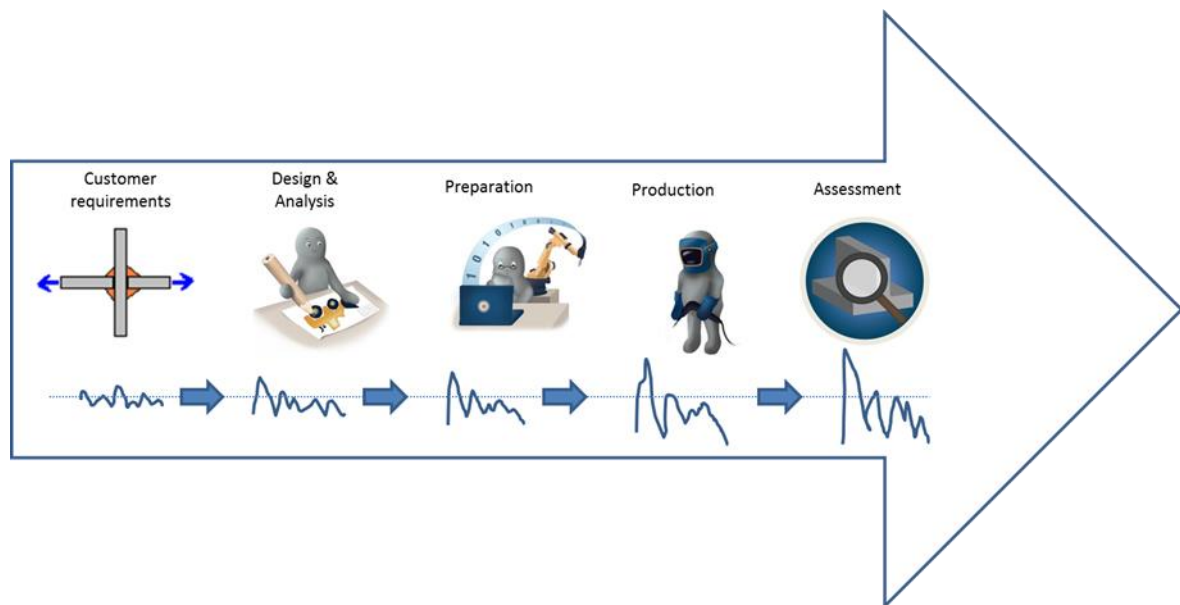


Figure 34: Variation occurring in each production step.

Understanding variation is the necessary starting point for making improvements and managing the variation. The conclusions in the literature are that control charts, measurement system analyses, and design of experiments are suitable tools for understanding the variation in different processes in the organization. That is confirmed by the study “Workshops control charts of KPIs” and described in Paper VII. It is surprising how many good research ideas never make it to the shop floor, an issue investigated in “Reactive/proactive evaluation in industry”, “Control charts of KPIs literature study”, and “Empirical distribution of control charts of KPIs” and described in Papers VI, VII, and VIII. No matter how good the proposed result is, if not implemented, the value is limited. Obstacles are considered in the studies

“Obstacles to quality assurance” and “Barriers for monitoring” and are described in Papers VII and VIII.

One important thing is to have common semantics, to have the same expressions for discussing the process. To have this common language requires a critical mass of people being aware of the phenomenon in question. In many cases there are individuals in the company knowledgeable of improvement directions to follow. That path will probably not be followed until a number of people share the same language to such an extent that they recognize the same path.

To fast-forward this development of common language, workshops have shown to be a useful method as reported in Paper VII. The study “Using control charts of KPIs” exemplifies this. A common language is created to discuss performance and, more importantly, give guidance on how to react. To visualize the performance measurements using control charts triggers analyses of the facts and underlying causes of the problem instead of playing the blame game with finger pointing. The participants mention that it also feels better and relieves the stress of making the wrong decisions to have facts to base decisions on and guidance for suitable actions, hence a more predictable system.

The development can be contradicted by the organizational structure. The way the manufacturer is normally organized can create functional silos. The NDT experts are often organized in a different function than, for example, production, which increases the risk of sub-optimization. This leads to technological push since the experts have their foundation in a certain technology or equipment. It is natural to want to use the technique in which you are a specialist, rather than identify what the internal customer actually needs to know. It is also easy for the rest of the organization to hand over responsibility to another department.

Visualizing variation in all process steps as described in Paper V is one important facilitator. The companies that fully understand how variation affects all processes in the business have a huge competitive advantage. The process will be predictable. No resources will be spent on trying to fix causes of common variation in a stable process. Long-term decisions can be made to restore stable processes that have insufficient capability. If assignable causes occur, they will be visible and suitable countermeasures can be applied to solve those particular issues. In communication between departments in the company it is clear what is required and what the current system can deliver within limits. It is unlikely that managers in the business would not be interested in such a situation.

That leads to the next observation. How come this is not already common practice in the industry? Both industry and academia are divided into certain functions and areas and this topic is in the cross-section of several topics. The term variation has to some degree been hijacked by statisticians. The focus on predictability and industrial applicability has been somewhat lost and shifted towards precise calculations rather than stakeholder need. It is necessary to take back the expression from the area of statistics. Research in the welding industry has also historically been technically focused and more soft issues like change management have not gained a foothold. To enable actual implementation of research results, this area needs to be further addressed.

The research project WIQ can be mentioned as an example. The quality assurance part was at first identified as a technological problem, pointing at finding certain inspection methods. It developed and changed more into finding methods providing appropriate information to the organization. The companies are, however, seldom organized in a way that supports this way of working; it is easier to fit into the normal organizational structure. However, both previous research and the studies conducted show the true potential to be in cross-functional initiatives.

This thinking can be symbolized by a chain (see Figure 35). To improve the overall result it is necessary to have a holistic view and get the links equally strong, connecting to each other. A weak link risks the entire chain to break while strong, incorrectly sub-optimized links will only lead to increased resource usage.

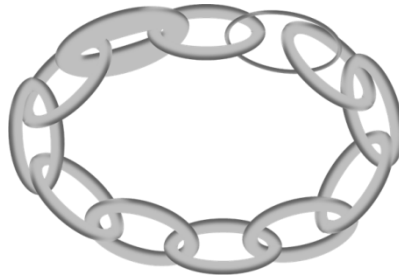


Figure 35: A chain symbolizing the need of getting the links equally strong.

It is interesting to compare this with the German initiative Industrie 4.0. Most of the technical ingredients in the initiative are already available, although used in other applications, e.g., internet-based services in consumer industry. So why is that not implemented fully in the industry? This could be a symptom of the difficulties to get technical solutions implemented when not having considered the soft aspect enough, in a holistic, cross-functional manner.

One definition of quality assurance uses the expression “actions taken by a manufacturing or service organisation to instil confidence in the mind” (Raj et al., 2000: 234). That describes quite well the purpose – to provide information to people to make them feel confident. This was demonstrated in the study “Assessing weld toe radius”. The suggested method for measuring the toe radius was not reliable and the issue almost became a stopper. When the measurement system for weld toe radius instead was made coarser, but stable, it was possible for the organization to move on. The auditors felt confident there was a solution. When the people involved do not feel confident, safety margins are created in each step of the process. That induces waste in the system reducing productivity as shown in, e.g., the study “Weld weight deviation”. It is therefore necessary to create a method for the different functions to speak the same language and start to secure the entire process, not sub-optimizing each part.

Confidence has historically often been created by using technical solutions since it appears easier to trust a complicated device rather than, in our mind, a simple solution. Therefore work needs to be done to increase understanding in this area. A measurement result is often considered “the truth” without reflecting on the measurement error. The organization relies on the existing methods and does not question their reliability. Therefore, the studies introducing and using measurement system analyses (“Precision of visual inspection”, “Currently used evaluation methods”, “Evaluation of weld toe radius”, and “Standardized evaluation methods”), described in, e.g., Papers I and IX, are important in an academic sense to understand present state and existing challenges as well as in an industrial one, to initiate a discussion of a measurement system’s reliability.

It can be easier to buy technical equipment than address organizational issues. Because of the technical history it is no wonder that quality assurance has a reactive technical push approach. It is essential to create opportunities for companies to get out of their silos in order to improve cross-functionality. By using the evaluation information differently, both short-term and long-term savings can be achieved, often without major investments. In the case of fatigue welded structures the long-term development demands cross-functional initiatives. When we do not have full control of our processes, we get increased weight, cost, etc., due to safety margins in each process step.

The PULL approach model, described in Papers II and IV, has been pointed out as a possible way to develop methods to acquire information concerning weld quality in a cross-functional setting. The model is based on several empirical studies as well as literature. The PULL approach model described enables the different functions to gather together around a common issue, leaving functional prestige and roles behind. Many of the parts are “old news” for the individuals. However, the challenge is to gather what everyone knows individually and create a common truth for the team or organization. The PULL approach can adapt to fast

changes and is more difficult for competitors to copy – but it is also more demanding for the company to challenge its way of working instead of buying a solution.

When comparing the research result with the cornerstone model described by Bergman and Klefsjö (2010), similarities can be seen. A central aspect in the cornerstone model is the focus on the *customers*, which is also the case for the PULL approach model. Another important element is to *base decisions on facts*, which requires knowledge about variation and an ability to distinguish between natural variation and variation due to identifiable causes. That has been a central part of the research, often visualized by using control charts. The research has also had a *process* perspective, trying to incorporate individual functions into a whole to avoid sub-optimization. The ability to *continuously improve* is the core essence of the research. There is always a way to get improved quality using fewer resources but there is no “final” solution; there is a continuous process of developing the knowledge. That is why the research has been based on principles, practices, and tools and not only focused on a specific tool. By focusing on the method to achieve a result instead of only focusing on the result, an agile process is created, enabling the currently best known solution to be used. To create conditions for participation and *let everybody be committed* is essential for getting access to the potential of the employees. This has been enabled in the research by introducing methods such as MSA and control charts that help to create confidence in the process and so encourage delegating responsibility. Finally, a *committed leadership* is important to create this quality culture by supporting activities regarding quality financially, morally, and with management resources. The research has supported that by presenting issues in financial terms. Several organizational levels have been involved in the research and have thereby gained increased understanding of, among other things, the influence of variation and suitable countermeasures. Because of the apparent connections with the cornerstone model the research conducted is contributing to a culture of total quality management.

Following the development at Volvo CE over the years it is possible to notice the change in language used among the employees. Suddenly discussions about variation and stability can be heard and examples of implemented measurement system analyses, control charts, designs of experiments, and control plans can be noticed. As an example, an ongoing project with the objective to start up a copied production line at another plant can be mentioned. Common comments from the project team members would be: “To move the technology and the equipment is one thing. To be able to transfer the common understanding of variation is something totally different”. The project team has initiated workshops regarding variation and capable measurement systems and emphasizes the importance of transferring not only the technical solutions but the entire concept.

That is a noticeable change over five years signalling that the company has taken the right course towards predictable processes, improved quality, and increased productivity in the welding industry.

6.2 Method discussion

The research questions 1 (Evaluation process) and 2 (Understanding variation) initially posed in order to fulfil the formulated objective have been answered and will be further presented in the next section. Because of the holistic and cross-functional characteristics of the research area, both qualitative and quantitative research methods were used. The choice of method was based on the characteristic of each study. It is necessary to consider that the research methods chosen affect the conclusions that can be drawn from the research.

Each research method and technique used has been further described in Chapter 3 and Chapter 4. They certainly have their own advantages and disadvantages that need to be considered in the research. Alternative choices of methods could have been made.

Instead of action research, interactive research could have been used. The possible level of participation from the organizations studied were, however, better suited for action research.

Since the factor to analyse needed to be introduced at the company, a common case study without the possibility to influence the organization would not have been an option. In an evaluation of the action research method used, the pre-step and the main steps worked well. However, an improvement of the meta-step, monitoring, could have been achieved by having a better structure of the reflection. Another improvement in the monitoring could be to have more academic resources available when conducting the actual study. In that way one person can focus on introducing the action while another person monitors what is happening in the team.

Part of the interviews could have been done as questionnaires. However, there would have been a risk of losing important data from the interviews that would not have been obtained in a questionnaire.

Interviews could have been used instead of questionnaires. For practical reasons, like travel cost and availability of the interviewed persons at certain times, the choice was, in some cases, made to rather include more people filling in a questionnaire than having a few people interviewed. The later questionnaires followed the structure described by Williamson and Bow (2002). The ones performed early during the research could have been improved with regard to response scales.

To use more quantitative research methods like experiments instead of observations and interviews would probably have increased the internal validity. The holistic and contextual perspective would, however, have suffered and that perspective was prioritized in this research.

The reliability of the research can be considered good. In the quantitative studies the measurement systems have been investigated with respect to repeatability and reproducibility. The data from the qualitative studies have been collected and stored in such a way that other persons could conduct the same analysis.

In the qualitative studies and action research the role of the researcher influences the result. In the action research approach this was even intentional. There is a risk that the behaviour studied was influenced by the fact that the researcher is known at the company. The consequences of this were handled by using triangulation, e.g., by using several sources of data and methods to see any deviation in results. In the interview studies also other interviewers, not previously known at the site, took part to reduce the risk that the respondents tried to give what they believed was “the right” answer. No apparent difference could be seen between the interviewers’ results. The researcher’s position at the company also facilitated access to data and forums that otherwise would not have been possible, and therefore the advantages of being known at the company far exceeded the potential drawbacks.

The internal validity in the quantitative studies was addressed by using statistical tools to establish causal relationships. In the qualitative studies it was more difficult to gain control of the influencing variables, including the investigator’s interference. The purpose of the research was however not necessarily to distinguish all the influencing variables from each other but rather to understand the current situation and improvement possibilities.

The focus of the studies was on issues relevant for Volvo CE. Sampling of participating plants has not been made based on statistical populations but rather on required knowledge of the participants and access to data through contact persons at different companies. That could limit the generalization of the research. However, the studies have been based on literature and previous research and are thereby connected with certain theories. This makes it possible to generalize the result to broader theories and replicate the result to see the external validity or generalization of the research. The studies “Reactive/proactive evaluation in industry” and “Empirical diffusion of control charts of KPIs” also widen the perspective to include other manufacturing companies. “Control charts of KPIs literature study” takes an even broader perspective, including all manufacturing.

When using observation as a method it is critical to keep a structure of observation notes. The note-keeping improved as the researcher’s competence improved.

Multiple sources of evidence have been used in the research, which improves the construct validity. The result of the studies has been reviewed by key informants, especially during research project meetings, research follow-up meetings, and information meetings at the company. In the studies carried out for this thesis the triangulation has mainly consisted of data, methodological, and investigator triangulation. The limited use of theory triangulation has been a trade-off due to limited time, knowledge, and resources. This choice has been considered not to have had any greater influence on the validity of the research result.

6.3 Conclusions

The objective of this thesis was to **“provide insight and tools to enable predictability and thereby facilitate proactive process control in welding towards lighter fatigue loaded products”**. This objective was met by answering the research questions.

RQ 1: *Evaluation process: How should the process for evaluating properties critical to weld quality be designed?*

Theoretical and empirical studies have shown that the current situation is highly affected by variation. There is a gap between what is reflected in definitions and specifications and the actual requirements needed to produce fatigue loaded structures. The evaluation methods used are in some cases not precise enough and there is a lack of evaluation method for certain defects. A common set of definitions is sometimes lacking creating difficulties to express, e.g., the cost of poor quality.

The research has shown the need for using a pull approach when choosing evaluation method, starting with the information need of the internal customer instead of evaluation methods available. The information will be customized with respect to what data to present and how. This will lead to a cost-efficient evaluation method. The accuracy and precision of the evaluation method will be investigated to suit the need. Here measurement system analysis (MSA) is a useful tool. Understanding the connections between the influencing parameters and the intended output properties is necessary to develop from a reactive towards a proactive system. By understanding the connections, it is possible to inspect indirect parameters, e.g., gap instead of penetration, or even control the parameters to get the desired property. Design of experiments (DoE) is a useful tool in this development process.

The research has shown that the evaluation information has a large impact on cost as well as weld quality. In the short term the information affects production cost while in the long term it is crucial to enable process and product development. It is necessary to take variation into account. Control charts have shown to be an effective tool to visualize variation.

RQ 2: *Understanding variation: How should the process variation be described and managed?*

The first step is to be aware of the variation existing in the process. The studies conducted indicate that the current focus is mainly on mean values rather than variation and is a product focus rather than a process focus. The consequences are “firefighting”, by which the system overrides when the organization acts on noise factors, adding variation. The studies have shown the financial consequences leading to high cost, risk of quality issues, and reduced productivity.

Good knowledge of the process is the key to evolve towards predictable, proactive process control. To describe the variation by using control charts has shown to be useful on several organizational levels, both for shop-floor measurements and high-level KPIs. Thereby it is possible to establish whether the process studied is stable or unstable, hence getting guidance on suitable actions. A control chart makes it possible to predict the output and react

accordingly. The studies have shown improved decision making, e.g., in the case with MA@L with strong financial influence.

The barrier to using this way of working is not primarily technical. Results from interview studies indicate that the overlooked soft issues often are as important as technical solutions. To have a critical mass of people talking the same language is necessary. Comparison between change management literature and workshops conducted gives a somewhat diverse picture.

Altogether, the objective of the thesis was fulfilled.

6.4 Contribution of the research

In this section the academic as well as the industrial contribution of the research is summarized.

6.4.1 Academic contribution

This thesis has added new knowledge about how variation affects quality and productivity and how it can be evaluated, presented, and handled systematically in an industrial context of welding. The variation described has been looked at both from a hierarchical perspective and along the value stream. The research shows a development from individual perspective towards team awareness. Obstacles preventing organizations from implementing already existing solutions have been highlighted. A model for choosing evaluation methods based on the internal customer's information need has been suggested. The research has been conducted in the interface between quality, production, and management, thereby adding cross-functional perspectives. The empirical findings increase the awareness of practical implications and provide insights often available only inside the industry.

6.4.2 Industrial contribution

Even though the organizations studied are successful in their business and have significant knowledge in the fields of welding and quality assurance, several improvement areas were identified. The research on control charts of operational measures provided insight and tools that facilitate decision making in a varying environment on all levels. The awareness of variation and its consequences leads to changes in the manufacturing process, e.g., enabling a proactive control approach rather than reactive post-process inspection, hence increased productivity and improved quality.

At one Volvo CE plant, measurement system analysis is now frequently used and there is an increased use of control charts, design of experiments, and control plans. The initial understanding of variation opened up for the use of other Lean Six Sigma principles, practices, and tools. The currently best known evaluation methods are used with the understanding that the results can be trusted. Standardized evaluation methods bridge the gap between the welding standard and the assessment carried out.

The increased understanding of what affects the implementation of already existing solutions is very valuable to the industry. The cost of unimplemented solutions and opportunities lost is enormous.

The research has been a part of several research projects, like WIQ, Lightstruct, FaRoMonitA, and SuReBPMS. The projects have shown successful results, fulfilling the project objectives of enabling weight reduction, robust monitoring, and sustainable performance measurement systems, and indicate significant financial effects. An updated weld standard is also a result of the research included in the projects WIQ and Lightstruct.

6.5 Future research

Future research can take a number of directions. In the short term, knowledge of factors influencing control charts usage on strategic measures will be used in an implementation case study.

The increased understanding of variation serves as a basis for moving into Robust Design Methodology, which means systematic efforts to achieve insensitivity to noise factors. This thesis has also mainly investigated variation and quality assurance in fabrication. However, the translation of customer demands and analysis into requirements needs as well to be mapped and the influence of variation in all steps of the manufacturing needs to be better understood.

The studies have mainly been carried out at companies producing fatigue loaded structures. It would also be of interest to see if similar results would be obtained in other types of manufacturing processes and at other types of organizations, welding industries and others. An area to investigate would be whether there is a connection between production volume and a reactive/proactive focus.

Further research is also required concerning specific evaluation methods. Cold laps are defects possibly influencing fatigue life. Potential evaluation methods to detect cold laps, for process development purposes, have been employed and need to be continued. To better understand the connections between parameters and final result would enable monitoring and later control of the weld result.

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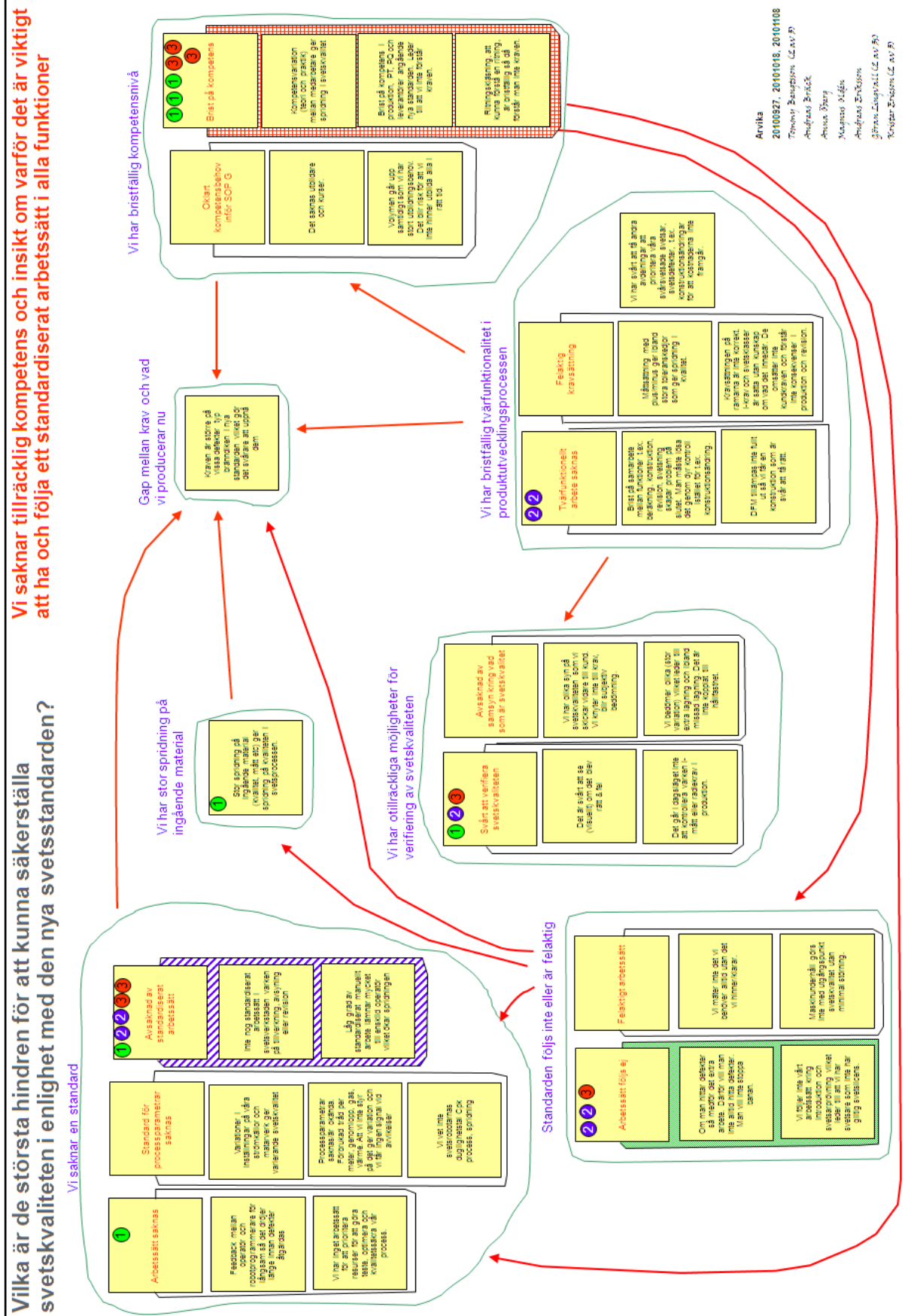
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Appended papers

Appendix A: KJ Shiba [in Swedish]



Appendix B: KPI questionnaire [in Swedish]

KPI/OPI-uppföljning	
1. Om du tänker på ledningsgruppens KPI-genomgång, var tycker du diskussionens fokus ligger? Markera med kryss på linjen	
Dåtid	Framtid
Aktivitet	Passivitet
Reaktiv	Proaktiv
2. Hur mycket tid lägger du per månad (i timmar) på:	
• KPI/OPI-genomgång i ledningsgruppen?	_____
• KPI/OPI-genomgång i andra forum?	_____
• Förberedelser inför KPI/OPI-genomgång?	_____
3. Hur mycket tid lägger din personal totalt per månad (i timmar) på:	
• KPI/OPI-genomgång?	_____
• Förberedelser inför KPI/OPI-genomgång?	_____
4. Hur mycket tid lägger du per dag (i timmar) på daglig uppföljning av KPI/OPI inklusive förberedelser?: _____	
5. Hur mycket tid lägger din personal totalt per dag (i timmar) på daglig uppföljning av KPI/OPI inklusive uppföljning?: _____	
6. Hur mycket påverkar dessa faktorer vid val av målnivå? Markera med kryss	
Externa kundkrav	
Inte alls	Väldigt mycket
Krav från andra delar av den egna organisationen	
Inte alls	Väldigt mycket
Tidigare utfall	
Inte alls	Väldigt mycket
Intern önskad nivå	
Inte alls	Väldigt mycket
7. Vad initierar åtgärder vid KPI/OPI-genomgång?	
Röda siffror	
Inte alls	Väldigt mycket
Magkänsla	
Inte alls	Väldigt mycket
Trender i datan	
Inte alls	Väldigt mycket
Gap mot kundkrav	
Inte alls	Väldigt mycket

Appendix C: Interview questions [in Swedish]

Grundkunskap: Vad vet du om styrdiagram (control chart)?

Känner du till vad ett styrdiagram är?

Vad skiljer ett styrdiagram mot ett vanligt stapeldiagram tex?

Utbildningsnivå: Vad har du för utbildning om styrdiagram?

Har du fått någon genomgång eller utbildning om styrdiagram?

När var det?

Vad innehöll utbildningen?

Var den tillräcklig för dina behov?

Förekomst: För vilka mätetal används styrdiagram?

Kommer du någonstans i kontakt med styrdiagram i ditt arbete och i så fall var?

Kan du ge exempel på typer av mätetal där de används i så fall?

Hur länge har man använt styrdiagram på de här mätetalen?

Har du exempel där man haft styrdiagram men slutat använda det? Vet du i så fall orsaken?

Finns det några mätetal som man inte använder styrdiagram på men som du tror kunde passa? Vilka?

Arbets sätt: Hur ser arbetssättet ut för uppföljning med hjälp av styrdiagram?

Kan du beskriva hur man brukar jobba med styrdiagrammen?

I vilket forum sker detta, tex morgonmöte, ledningsgruppsmöte, enskilt?

Vem tar fram styrdiagrammen?

Hur arbetsintensivt är det att jobba med styrdiagram anser du?

Om och i så fall hur används styrdiagram när man ska fatta beslut?

Vad är enligt din uppfattning avgörande för om man använder styrdiagram eller inte?

Intryck: Vad är fördelarna och nackdelarna med styrdiagram?

Vad är din uppfattning om nyttan med styrdiagram dvs vad är bra med dem?

Ser du några begränsningar med styrdiagram tex att de inte passar så bra i något sammanhang?

Vilka hinder ser du mot att man ska använda styrdiagram?

Vilka faktorer möjliggör ett användande av styrdiagram dvs vad är viktigast för att det ska bli använt.