Department of Built Environment

Why to measure anyway?

On the breakthrough of in-line measurement technology in automotive manufacturing

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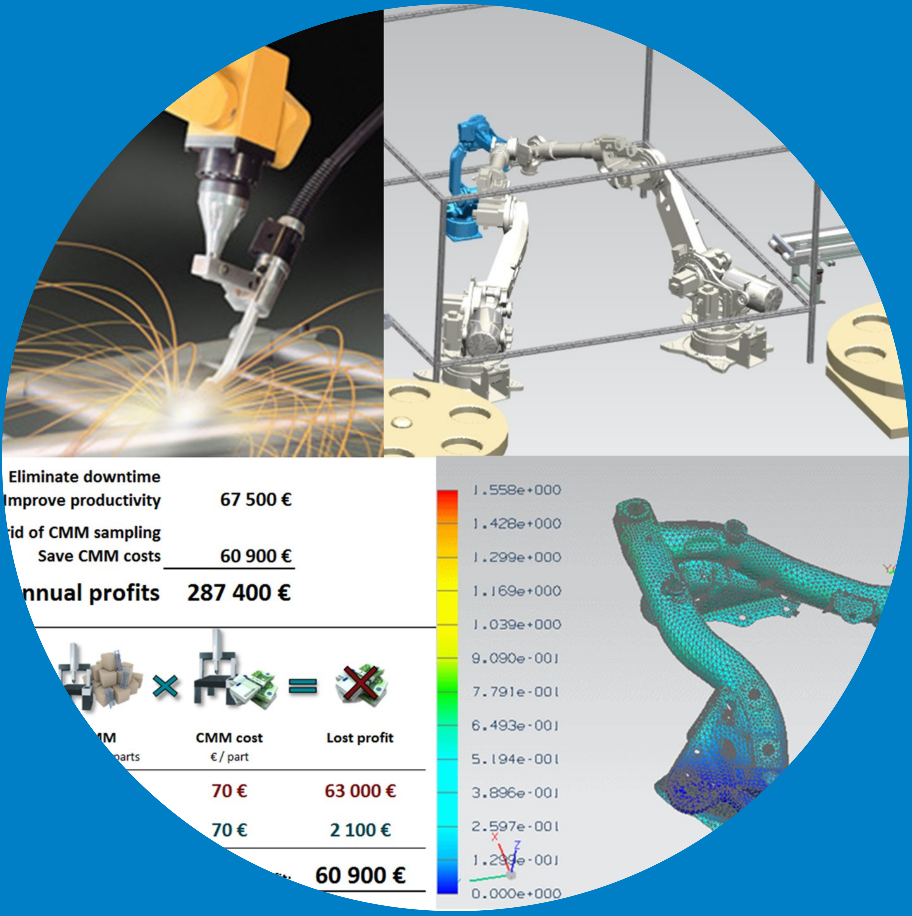
Valtteri Tuominen



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Why to measure anyway?

On the breakthrough of in-line measurement technology in automotive manufacturing

Valtteri Tuominen

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall M1 of the school on 24 November 2017 at 12:00.

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Abstract

This doctoral thesis is about disruptive innovation. It's about understanding the change resistance mechanisms and learning to make a market breakthrough with disruptive technology. This work develops a simple framework for designing the value proposition and market entry strategy for a disruptive innovation.

The metrology markets in automotive industry were facing strong disruption between 2006 and 2016. The traditional measurement and quality control methods had become insufficient for controlling the more complex manufacturing processes. Several new measurement technologies were competing to break through to the markets. This doctoral thesis follows the journey of one in-line measurement technology through all the failures and eventual success.

Based on the theory of disruptive innovation, this thesis presents a hypothesis of three change resistance mechanisms that need to be addressed simultaneously for the disruptive technology to break through to established markets. The development process of these three "change resistance antidotes" are presented in detail.

The first antidote had to counter the tight margins and lack of resources that were preventing mainstream companies from investing to new technology. The first attempts for finding the antidote was about validating accuracy and proving that traditional methods are insufficient for the task. Learning to translate ecological and social impacts of the technology into economic measures was the key for finding the real benefit and solution.

Second antidote was a about finding a way to adapt the new technology without assaulting against existing industry structures. This thesis presents the development of the virtual clamp, which converts a traditional mechanical task into a software task. It is a win-win solution that provides clamped measurement results without the downsides of the heavy weight mechanical clamping device.

Third antidote counters the lack of pull from existing mainstream customers, which makes new emerging technologies to be unattractive. The development of the measurement-aided welding cell places real-time measurement technology into the very core of manufacturing. This highlights the new technology as the enabling factor for future manufacturing.

The hypothesis is further tested in two test cases outside of automotive manufacturing. The positive feedback suggests that the three change resistance antidotes can be used as a practical framework for developing value propositions of disruptive technologies.

Keywords In-line measurement, Disruptive technology, Change resistance, Market entry

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Tiivistelmä

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Tutkimusala Teknologiainnovaation markkinoille pääsy

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Tiivistelmä

Tässä väitöskirjassa luodaan ymmärrys muutosvastarintamekanismeihin, jotka kohdistuvat perinteisiä markkinoita muuttaviin teknologiainnovaatioihin. Tässä työssä luodaan yksinkertainen lähestymistapa, jolla teknologiayritykset voivat suunnitella strategiaa ja arvolupausta uuden markkinan avaamiseen.

Autoteollisuuden mittalaitemarkkinat olivat suuren mullistuksen edessä vuosien 2006 ja 2016 välissä. Perinteiset laadunvalvontamenetelmät eivät enää kyenneet vastamaan yhä monimutkaisempien valmistusprosessien tarpeisiin. Uudistuville mittalaitemarkkinoille pyrki näinä vuosina useita eri yrityksiä ja teknologioita. Tässä väitöskirjassa seurataan yhden mittausteknologian matkaa, vaikeuksien kautta voittoon.

Tässä työssä esitetään innovaatioteoriaan pohjautuva hypoteesi kolmesta muutosvastarinnan mekanismista, joihin tulee vastata, jotta mahdollistetaan teknologiainnovaation läpimurto perinteisille markkinoille. Tässä työssä esitellään kehitysprosessi, jolla uudelle ja innovatiiviselle tuotantomittausteknologialle löydettiin vastalääkkeet kolmelle muutosvastarintamekanismille.

Ensimmäisen muutosvastarinta-vastalääkkeen piti vastata asiakkaiden olemassa olevan liiketoiminnan tiukkoihin marginaaleihin ja resurssipulaan, joka oli yksi syy perinteisille yhtiöille olla investoimatta uusiin teknologioihin. Ensimmäinen yritys vastalääkkeen löytämiseksi liittyi mittalaitteen tarkkuuden verifioimiseen, jolla todistettiin, että perinteiset menetelmät eivät enää riittäneet tehtävään. Vasta ymmärrys kääntää ekologiset ja sosiaalisetkin vaikutukset taloudellisiksi mittareiksi auttoi löytämään todellisen syyn ja hyödyn investoida uuteen mittausteknologiaan.

Toinen muutosvastarinnan vastalääke liittyy tapaan sovittaa ristiriidattomasti uusi teknologia olemassa oleviin teollisuuden rakenteisiin. Tässä työssä esitellään "virtual clamp" -metodin synty ja kehitys. Tällä menetelmällä muutettiin perinteinen mekaaninen tehtävä ohjelmistotehtäväksi. Tästä syntyi "win-win" -ratkaisu, jossa tuotetaan tasoon puristetut mittaustulokset ilman raskasta mekaanista puristinta.

Uusia nousevia teknologioita ei usein nähdä houkuttelevina investointikohteina, koska olemassa olevat asiakkaat eivät vielä sellaista osaa pyytää. Kolmas muutosvastarinnan vastalääke vastaa tähän. Tässä kirjassa esitellään uuden mittausavusteisen hitsaussolun konseptin kehitystarina, jossa tuotantolinjamittauksen rooli valmistuksen ytimessä korostuu.

Esitettyä kolmen muutosvastarintamekanismin hypoteesia testataan vielä kahdessa autoteollisuuden ulkopuolisessa käytännön tapauksessa. Positiivinen palaute antaa olettaa, että esitetystä lähestymistavasta on hyötyä teknologiayrityksille arvolupauksen laatimisessa teknologiainnovaatioille.

Avainsanat Tuotantolinjamittaus, Teknologiainnovaatio, Muutosvastarinta, Pääsy markkinoille

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Preface

"You can only connect
the dots afterwards"

-Steve Jobs

In a sense, this doctoral thesis is high level of science. Higher than flight level 270 or 27 000 feet above sea level, to be precise. Working in global automotive industry made airplanes and airport lounges familiar. With the help of noise cancelling earphones and hot coffee, I learned to utilize these thousands of travel hours efficiently.

How did I end up in writing articles and a doctoral thesis in an airplane? In his famous speech to Stanford's 2005 graduating class, Steve Jobs said two things that stuck in my mind: "follow your heart and trust that it knows where it's going" and "you can only connect the dots afterwards". My path to becoming a PhD follows these themes.

When studying for my master's degree, I chose my courses based on interest, not based on the study plan. Following my heart led me to exceed the amount of required studies by a third. I struggled to explain myself a rational reason for not graduating easier and faster.

Couple of months before graduation I was in Tallinn, Estonia together with my friend Iikka. He said over a pint of beer: "Man, you've almost completed the amount of studies needed for a doctoral degree!" Before the pint was empty, I had decided to become a PhD.

I wanted a job from a technology company right after graduating. One day a certain class was cancelled, and without anything else to do, I found myself from a company visit to Mapvision Ltd. Fairly soon I realized that the company had nothing to do with maps. I decided to apply for a position to write my master's thesis. Luckily, I got the job.

As a young engineer in the first full time job, I would have never pursued the PhD if the courses weren't already completed. But since they were, I started to see opportunities for research all around. In my research plan to professor Henrik Haggrén, I tried to explain how photogrammetry, industrial management, organizational psychology and environmental strategies would fit together as a doctoral study plan. Against all my expectations, the plan was accepted and even praised to be a fresh interdisciplinary approach. Now, suddenly, studying all these extra courses started to make sense.

During the ten years at Mapvision I travelled around the world doing all possible jobs with great people in many different roles. Working with new technology in the conventional automotive industry threw interesting research questions in front of us. Since I now had the plan to become a PhD, I ended up publish scientific papers on the work we did.

So, I did what Steve Jobs told. I followed my heart. Now after ten years, the research topics start to come together. The articles start to form a very interesting big. "You can only connect the dots afterwards". This doctoral thesis is my way of connecting them.

Letter of thanks

"As we express our gratitude, we must never forget that the
highest appreciation is not to utter words, but to live by them."

- John F. Kennedy

I am truly grateful that I was given this opportunity of being the one telling this story. But it should not be forgotten that there were many people who made all this possible.

Antti Knuuttila hired me. He let me grow and gather experience from a wide array of roles during the ten years. Professor Henrik Haggrén supported me on my slightly unconventional path of becoming a PhD. The interdisciplinary approach of combining a variety of viewpoints would have not been possible without Antti and Henrik. Thank you.

There are salesmen who can sell ice to Eskimos. Terho Valtonen is one of those. I got my learning to sell a technical solution from Terho. Without the tireless work of Mario Lopez-Jorkama writing down all customer comments and making travel fun, we would have never opened the US market. This eventually led to the development of the cost model and value proposition described in chapter 2, so thank you Terho and Super-Mario.

During the micrometre test in Spain (chapter 2.1), I couldn't calibrate the measurement system. I called Esa Leikas, who was always there to help: "There has never been a system that wouldn't calibrate. This will not be the first". Ilkka Niini and Petteri Pöntinen could find a mathematical solution for any problem. Kosti Kannas did a fantastic job in managing the test projects with BMW and VTT in chapter 4. Thanks Esa, Ilkka, Petteri and Kosti.

We spent half a lifetime in automotive factories with Janne Juslin. He never gave up when we worked through nights and weekends. Janne built the test device for virtual clamp (chapter 3) and was brainstorming the MAWC (chapter 4). Thanks Janne, it was a blast!

Teemu Mehtiö turned the idea of virtual clamp (chapter 3) into a production-capable software in a blink of an eye. Teemu and Tommi Wulff helped me to understand the role of organization culture in a growing technology company. These guys also took the time to read and comment my writings. Thank you Teemu and Tommi for the inspiration!

My old buddy, Johannes Kankare, always took time to comment my work. His highly intelligent and insightful feedback improved the work throughout the years. My godmother and Finland's first sustainability science professor, Helena Kahiluoto, brought invaluable insight in linking this work to disruptive innovation. Thanks Jokke and Helena!

My mom, Marketta Tuominen, taught me to think deeper and have passion for work. My dad, Ilkka Tuominen, taught me to work hard and get things done. He ignited the spark for global business and traveling. This thesis would have never seen daylight without the combination given by them. My girlfriend, Soila Nykänen, pulled me out of the treadmill by reminding that there are other things in life than work. Thanks mom, dad and Muumi!

Contents

List of abbreviations

AIAG	Automotive industry action group
ANOVA	Analysis of variance
ARM	Average and range method
BMW	Bayerische Motoren Werke
CAD	Computer-aided design
CMM	Co-ordinate measuring machine
FEM	Finite element method
FFT	Fast Fourier transformation
IFT	Inverse Fourier Transformation
MAWC	Measurement-aided welding cell
MSA	Measurement system analysis
OEM	Original equipment manufacturer
R&R	Repeatability and reproducibility
SPC	Statistical process control
UK	United Kingdom
USD	United States dollar
VDI	Verein Deutscher Ingenieure - the association of German engineers
VP	Vice president
VTT	Technical Research Centre of Finland - teknillinen tutkimuskeskus

List of publications

I. Tuominen, V., 2012. Cost Modeling of Inspection Strategies in Automotive Quality Control. Engineering Management Research; Vol. 1, No. 2; 2012. ISSN 1927-7318 E-ISSN 1927-7326

II. Patala, S., Jalkala, A., Keränen, J., Väisänen, S., Tuominen, V., Soukka, R., 2016. Sustainable value propositions: Framework and implications for technology suppliers. Industrial Marketing Management; Vol. 59, November 2016. http://dx.doi.org/10.1016/j.indmarman.2016.03.001

III. Tuominen, V., 2011. Virtual clamping in automotive production line measurement. Expert Systems with Applications Vol. 38, Issue 12, November/December 2011. ISSN 0957-4174.

IV. Tuominen, V., 2017. Validating the virtual clamp with CMM correlation on automotive production lines. The International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-017-0579-4

V. Tuominen, V., 2015. The measurement-aided welding cell—giving sight to the blind. The International Journal of Advanced Manufacturing Technology, 86(1), 371-386. ISSN 1433-3015. DOI 10.1007/s00170-015-8193-9.

Authors contribution

I. The author of this thesis was the sole author of the paper.

II. The author of this thesis developed the idea of comparing traditional mechanical measurement systems and the new optical measurement system from environmental point of view. The author initiated this work as co-operation with Sanni Väisänen and Risto Soukka. Later this work was integrated to a broader research done by Samuli Patala, Anne Jalkala and Joona Keränen from Lappeenranta University of Technology.

III. The author of this thesis was the sole author of the paper.

IV. The author of this thesis was the sole author of the paper.

V. The author of this thesis was the sole author of the paper.

1 Introduction

*“Inflection point is a time in the life of business
when its fundamentals are about to change”*

- Andy Grove

This doctoral thesis is about disruptive innovation. It’s about learning to understand the change resistance mechanism that new technology faces on market entry. We explain how we learned to work ourselves through them in our ten-year market entry. Finally, we conclude these learnings into a simple framework of “three change resistance antidotes”. This framework is aimed for helping technology providers to design the market entry strategy into conventional industries.

In a way, this book tells a story of our ten-year adventure in global automotive industry. It shows how we failed to convince the manufacturing companies, again and again. There is a saying that winners don’t fail, they learn. This book tells how we picked ourselves up after every failure, learned something new and kept going. Finally, we made the break through.

This book can be read in many ways. One might start viewing measurement in a new way or get inspired by the vision of future manufacturing. Others might be able use our calculation tools for selling measurement systems. Some might even draw insights around innovation research. However, to truly understand what this doctoral thesis is really all about, a short story needs to be told. It’s a story about monkeys, bananas and a scientist.

Some decades ago this scientist designed a sociological experiment. He had a small society of monkeys in an empty warehouse. In the middle of the warehouse there were ladders. At the top of the ladders there was a platform with a banana tree. Every time a monkey went for the ladders, the scientist turned on sprinklers of ice cold water. It didn’t take long for the monkeys to prohibit climbing the ladders. The culture grew strong. Whenever a monkey started to climb the ladders, others pulled him down and gave a punishment.

Years passed, the scientist retired and eventually died. There was nobody to turn on the sprinklers. But still today, whenever a monkey goes for the ladders, others pull him down. Nobody remembers the reason, but everybody knows that you don’t climb the ladders.

The automotive manufacturing was experiencing something similar. There is the fourth industrial revolution (chapter 1.1) that sets new demands for the industry (chapter 1.2). This has brought new complicated manufacturing methods (chapter 1.3) that require new ways to measure and demand new measurement technologies (chapter 1.4).

But just as the monkeys are afraid to climb the ladders, the manufacturing companies are reluctant to change. In chapters 1.5 and 1.6 we turn to literature and theories to understand better why the change resistance exists and why we eventually succeeded. Chapter 1.7 finally binds the five publications together and builds the structure of this doctoral thesis.

1.1 Industry 4.0 – next industrial revolution

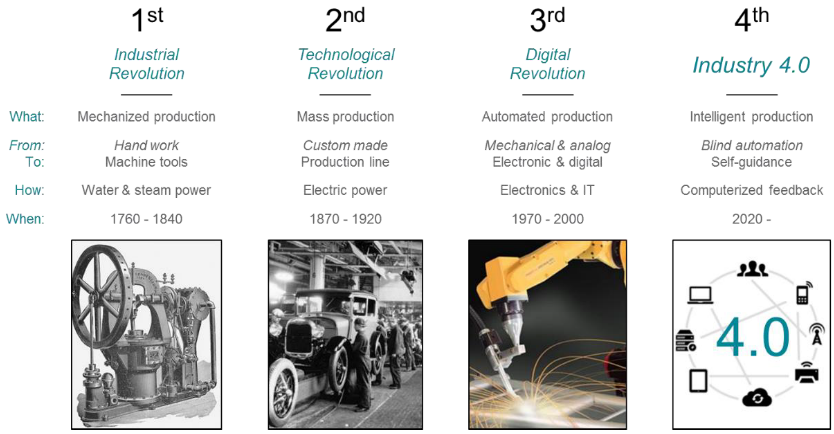
We have seen already three industrial revolutions in the past two and half centuries of the industrial era. The first industrial revolution happened between 1760 and 1840 when we moved from hand work to machine tools by using water and steam power. The second, “technological revolution”, happened between 1870 and 1920 when we moved from custom-made to mass production, enabled by electric power and production lines. From the early 1970’s we witnessed the emergence of electronics, information technology and robotics. We called it the “digital revolution”.

It is said that the complexity and productivity of the industry increased because of these revolutions. It is the other way around. The demand for increased complexity and productivity were the drivers for the revolutions. Today the manufacturing industry faces demand for shortening product life-cycles, increased product variation better cost-quality ratio. We are witnessing the drivers for the next industrial revolution.

The "fourth industrial revolution" refers to the next generation of manufacturing, where automation technology is improved by self-optimization and intelligent feedback. This is needed to support the workers in an increasingly complex manufacturing environment.

Industry 4.0 is a term that was first introduced in 2011, when a set of recommendations were presented to the German government. It is a long-term vision in which the deindustrialization of the European manufacturing sector is being reversed. It is an initiative to fight against the cheap labour of the third countries with intelligent automation. Similar long-term goals are being pursued by the Smart Manufacturing Leadership Coalition and the Industrial Internet initiative in the United States.

Despite its different names, the fourth industrial revolution is all about intelligent feedback within the manufacturing process. It’s about bringing the humans, machines and information together. It’s about increasing the productivity by smarter manufacturing.



	1st *Industrial Revolution*	2nd *Technological Revolution*	3rd *Digital Revolution*	4th *Industry 4.0*
What:	Mechanized production	Mass production	Automated production	Intelligent production
From: To:	*Hand work* Machine tools	*Custom made* Production line	*Mechanical & analog* Electronic & digital	*Blind automation* Self-guidance
How:	Water & steam power	Electric power	Electronics & IT	Computerized feedback
When:	1760 - 1840	1870 - 1920	1970 - 2000	2020 -

Figure 1. Four industrial revolutions.

1.2 Trends in automotive industry

What does this fourth industrial revolution mean for the automotive industry and especially body and chassis manufacturing?

Product variety in the automotive industry has more than doubled in the last decade, while the average product life cycle has decreased from 8 to 4 years. One example of this kind of change is the Volkswagen Golf, which first rolled off the production line in 1974; in 2016, it has reached its seventh generation. Since its launch, the product life cycle has shortened from 10 years to 3 years. Also, the development period for a new Golf has shrunk from 48 months to 25 months, and is expected to drop to 20 months by 2018. (Berger, 2012)

At the same time the tightening emission regulations have resulted in the demand for lighter materials, such as aluminium and magnesium. The demand for higher structural strength with lower weight have brought new manufacturing processes that are much more complicated than the traditional processes.

The automotive industry is getting more globalized all the time. At the same time, there is a need to respond to local consumer behaviours, such as produce big SUVs for Americans. Regional characteristics, such as natural resources or labour cost puts pressures to move manufacturing to different locations. In practice this means that BMW needs to maintain high quality with uneducated Mexican workers.

The cost of defects and failures increases significantly. Previously it was common to have rework areas next to assembly lines. This allowed most defects to be corrected by replacing the bad part with a good one. Today, most cars are uniquely built to customer order, making them individuals. Taking a replacement part from the rack is not possible since that part goes specifically to the next car. It is not uncommon that a missing weld nut in a part causes the almost finished car to be disassembled or scrapped.

Figure 2. Volkswagen Golf from 1974 to 2016.(Image: Motortrend web-site, 2016)

1.3 Manufacturing of body and chassis parts

The contextual focus in this doctoral thesis is in automotive body and chassis manufacturing. Therefore, we will explain briefly the manufacturing methods used in the industry with the focus on the new processes where in-line measurement plays a big role.

Most modern cars have very similar design from the structural point of view. The body of the car is assembled in stages. First the underbody is assembled together from the front module, middle floor and rear floor. This assembly is then given the side structures, such as the A-pillar and B-pillar as well as the roof. This assembly is called body-in-white.

The chassis of the car builds in a similar way from several parts. Front subframe goes eventually under the engine, trailing arms are used to attach the wheels and cross car beam will hold all the instruments, steering wheel and the glove box.

Depending on the car design, there are 20-30 body and chassis parts, which typically are manufactured in different locations than the assembly line of the car. Some examples of these parts are shown in Figure 3. Today, most of these parts are manufactured by different companies, called tier-1 suppliers. Some of the parts are even designed by the suppliers.

One of the most common processes to manufacture body and chassis parts is arc welding. In a typical welded part, a cross car beam, there are a couple of dozen small sub-components that are placed to a welding fixture. Then, an arc welding robot welds these components together. All the components cannot be welded together in the same operation, so there are typically several consecutive operations where the part in cumulatively built. Figure 4 shows an example of how a cross car beam is constructed from sub-components. Figure 5 shows an example of a welding fixture for such part.

The dimensional variation in an arc welding process come from several sources. Sub-components can have dimensional variation, they might not fit the fixture or operators might place them badly. The biggest source of variation, however, comes from the heat distortion caused by the welding itself. The cumulative effect between several operations makes it difficult to get the variation under control.

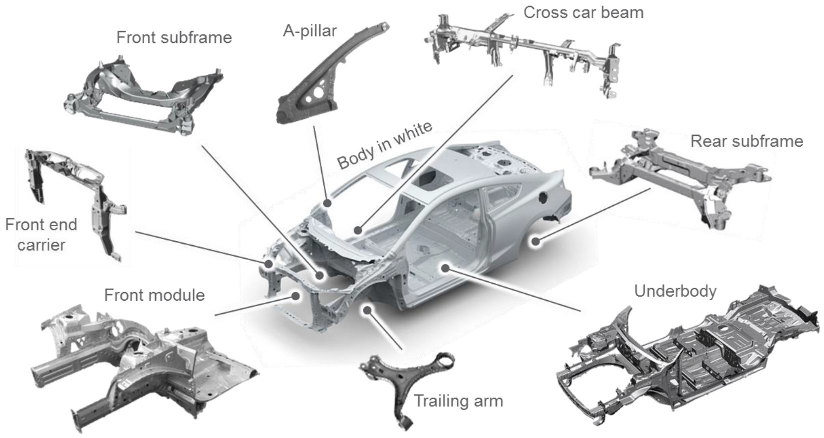


Figure 3. Examples of typical body and chassis parts.

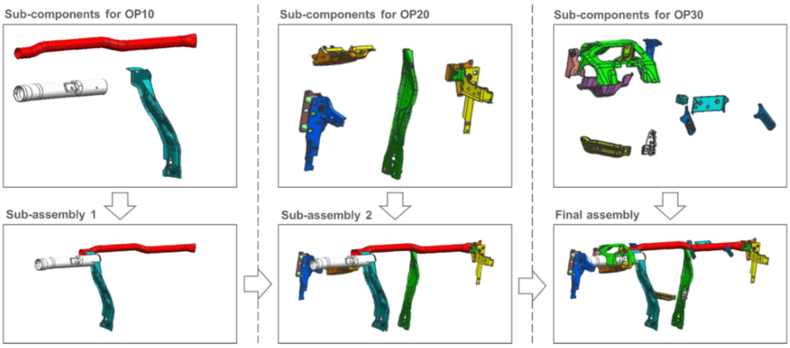


Figure 4. Example of a three-operation welding process of a cross car beam.

Figure 5. Two-operation welding fixture for a cross car beam. (Nash web-site, 2016)

In addition to getting the variation under control, adjusting the process is also very complicated. There can be several sub-components welded on top of each other. Adjusting the position of one will have an effect to the others, but how much? Is the gap between the sub-components still small enough for the weld seam? How much more will the wider gap cause heat distortion and to which direction? The introduction of aluminium has complicated the already challenging process even more.

The demand for light weight parts has introduced two new processes to the mainstream manufacturing. Hot stamping process achieves significantly higher strength, which reduces the amount of metal in structural parts, such as an A-pillar. Figure 6 shows a hot stamping process, where a cold metal blank (1) is heated to 950 °C (2). The red-hot blank is pressed (3) to its form. The very rapid cooling (4) hardens the steel to become extremely strong. (APT web-site, 2016)

The accuracy of a hot stamping process is not sufficient, so the final dimensions to the part are made by a laser cutter, which is a completely isolated process (Figure 7. Even though the laser itself is extremely accurate, the high variation of the stamp part combined with manual positioning even enhance the complete dimensional variation.

Magnesium parts are phenomenally light weight. Manufacturing for example a front end carrier out of magnesium has the same difficulties as the hot stamping process and then some. Instead of having two isolated process steps, there can be five. Some of these steps can have parallel operations to match the cycle time requirements. Figure 8 shows a typical process layout which results in having 48 possible process streams, each having individual behaviour and characteristics.

The manufacturing processes of body and chassis parts, no matter if they are arc welding, hot stamping of magnesium casting, are getting more and more complicated and more difficult to control.

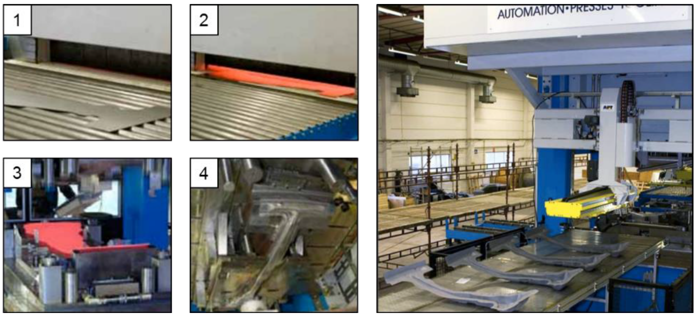


Figure 6. Hot stamping process of a B-pillar. (APT web-site, 2016)

Figure 7. Laser cutter working on a hot stamped B-pillar. (Trumpf web-site, 2016)

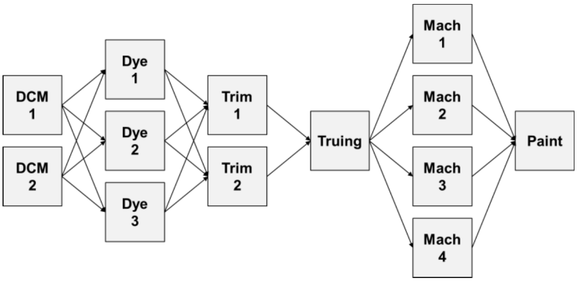


Figure 8. Process chart of a typical manufacturing process of a magnesium liftgate

1.4 Disruption of metrology markets

Since the 1990's, in-line measurement technologies had been used for measuring complete car bodies or other valuable parts directly on the production line. However, the clear majority of car parts were not seen as valuable enough to be measured with expensive hi-tech systems. The manufacturing of these body and chassis parts was controlled by sample measurements and simple mechanical gauges. These methods, however, started to become powerless when the complexity of manufacturing processes increased.

Between 2006 and 2016, the automotive metrology market was completely disrupted. By the end of this ten-year period, in-line measurement became the fastest growing metrology market in the automotive industry (Frost & Sullivan, 2014; Frost & Sullivan, 2015). This trend was caught by the established measurement companies. They acquired smaller tech companies and launched new products. The market started to see also new players.

The highly-increased competition was not on which technology was better. It was more about who will formulate what the future manufacturing needs from the measurement system. Depending on the needs, different technology would fit better. There were four main technologies competing to become the next industry "de facto standard" (Figure 9).

Traditional CMM vendors offered new features, such as surface scanning. For the manufacturing companies, upgrading familiar technology without having to change the ways of operating was the easy road. This solution offered less new benefits for controlling increased the complexity, but caused less change resistance.

White light scanners were one of the "new mainstream" technologies and was offered by several large measurement companies. It could create a 3D surface model of the measured part. It wasn't quite fast enough for measuring every single part produced, but the amount of information provided was comprehensive. It was perfect for reverse engineering and analysing single parts, but had limitations in controlling the process in real-time.

Laser sensor systems were the other of the "new mainstream" technologies, focusing in real-time process control. Same base technology was used to measure complete car bodies since the 1990's. It had some technical limitations, but the technology and the ways of operating were familiar to the industry.

Multi-camera technology was a completely new and unique technology, intended for real-time process control. It had limitations in single part analysis and being offered only by one small tech company raised a lot of uncertainty. However, the technology outperformed all competitors if the evaluation criteria was tied to real-time process control.

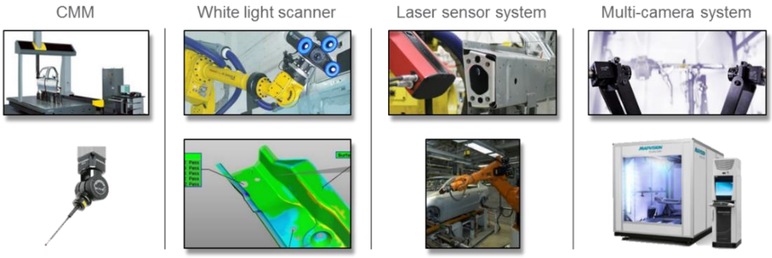


Figure 9. Four competing measurement technologies in 2006 – 2016.

1.5 The failures and the breakthrough

During the disruption of metrology markets from 2006 and 2016, we were working in the small Finnish tech company, Mapvision Ltd. The multi-camera technology the company had developed was unique. Compared to competing solutions, it allowed significantly more points to be measured. It was more robust in real operating conditions, since it didn't rely on mechanics as other solutions did. There were some limitations related to the complexity of programming and implementing the system.

The technology gained a lot of interest. In the very beginning of the ten-year journey we already had installations among the most respected car makers, Daimler and BMW, as well as other technology enthusiasts. In the technology adoption lifecycle (Bohlen & Beal, 1957), we saw ourselves having success with the innovators and early adopters. We were aware that the disruptive nature of the technology would make it even more challenging to push through to the mainstream customers (Moore, 1991). To conquer the markets, we had to find a way to cross the chasm to the early majority (Figure 10).

To make the transition, we did everything by the book (Moore, 1991); we chose the target market and positioned the product as the best solution for 100% in-line measurement of body and chassis components. We developed the whole product concept, including services and built the marketing strategy based on this. We tested several distribution channels and had flexible pricing. We were confident about the success.

Having all this in place, we started our market entry to North America in 2010. Luckily even, we had two systems delivered to North America, even though the decision was made in Europe. We established local presence through a partner and supported the sales actively by our best people. We gained a lot of momentum and interest among several customers. However, by the end of 2013, after three years, we had zero sales.

Then everything changed. In 2014, we had been actively selling to eight mainstream customers. Between mid-2014 and mid-2015, six of these eight placed a purchase order. Sales went from 0 to 3 million USD in one year of time. Suddenly, we had opened the challenging US market after several years of failing.

How did we suddenly jump across the chasm and make the breakthrough? We had all the elements Moore (1991) proposed already in 2010. What made the mainstream customers buy at the same time? We started to seek answers from the theory of disruptive innovation.

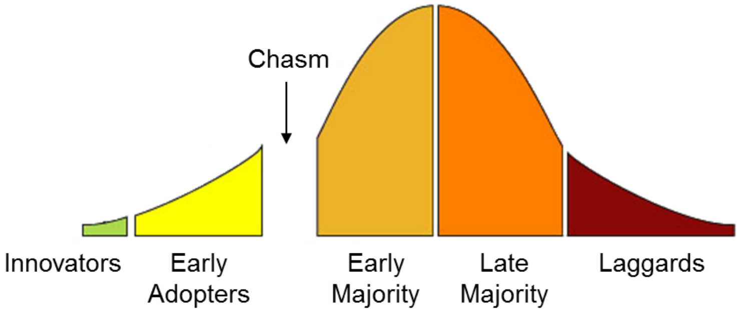


Figure 10. Technology adaptation cycle: "crossing the chasm". (Moore, 1991)

1.6 Theory of disruptive innovation

Andy Grove, the long-time CEO and master mind at Intel Corporation, is remembered by shaping the way how we see technology and business. He used the term of strategic inflection point to describe a moment in the life of business when new technology enables a change that is so powerful that it fundamentally alters the way business is done.

One example of such an inflection point happened in the music industry a decade ago. The music distribution business was fundamentally altered by internet based music distribution. With iTunes, Apple became the biggest music vendor in the world in 2010, without selling a single disk.

Theory of disruptive innovation explains this phenomenon in more detail. To be regarded as disruptive, the innovation must create new markets and new value networks, eventually displacing established products and companies from the market. This means that all new technologies or innovation are not disruptive by nature. For example, the first automobiles were not regarded as disruptive innovation since they were luxury items, available for few, and thus did not displace horse carriages as the means of transportation. Later, Ford's Model T became a disruptive innovation since it's low manufacturing cost made it available for the masses and thus fundamentally changed the transportation business. (Bower & Christensen, 1995; Assink, 2006; Christensen, 2003)

The theory of disruptive innovation provides insight to three key mechanisms of change resistance that are in significance regarding our experiences during the ten years.

First, the established market-leading companies must operate by the tight margins and other restraints of the existing business models. The pursue of disruptive innovation would take scarce development resources that are needed to compete in the existing business environment. Incremental development on sustaining innovations carries less risk, achieves higher penetration and has higher impact on established markets. Since disruptive innovations can hurt the market-leading companies, they naturally try to keep the status-quo. (Christensen, 1997; Assink, 2006)

Second, disruptive technology does not equal disruptive innovation. It is rather the new business model or new way of operating that the new technology enables that eventually creates the disruption on the markets (Christensen, 2003). Implementing new technology typically faces a lot of change resistance since it is often seen as an assault against the existing structures (Zeleny, 2009). As an example, the horse whip makers where resisting the automobiles since they were afraid of losing their jobs.

Third, the new emerging technologies are seen typically unattractive by established companies, even if they would have the potential of revolutionizing the industry. It is not what their current mainstream customers are requesting, since their requirements come from the past. The technology is easily seen as a threat to surrounding companies across the business network and thus generate resistance. For example, the electric car will be resisted by gas station operators. Because of the resistance and the lack of pull from existing customers, new technology tends to get ignored. (Bower, 2002; Zeleny, 2009)

These aspects are countered by the perspective of "constructive disruptive technology". If the decision-makers understood the technology change as a whole, the companies could receive significant economic benefits without disrupting the current way too much.

1.7 This thesis: publications, structure and hypothesis

For ten years, we fought against change resistance and tried to convince the manufacturing companies to invest into a high-tech measurement system. We looked around every corner and went through a lot of research and development to overcome the change resistance. We ended up introducing completely new methods to a very traditional industry and challenged old conventions. Along the way, we published some of our significant findings in various academic journals. These five publications form the core of this doctoral thesis.

Publication **I** started from the assumption that the traditional measurement methods were not sufficient to control the manufacturing processes. This was proven by assigning a monetary cost for process problems. Based on this, we built a framework for modelling the cost impact of different measurement methods.

Publication **II** extends the previous work from purely monetary value to include also environmental and social impacts. It presents a framework for developing a more comprehensive value proposition, including indirect savings and increased profits, as well.

Publication **III** was a result of trying to find an answer to a paradox; the industry norms required that parts were clamped during measurement, but traditional way of clamping killed the benefits of the new measurement technology. This work presents the research and development of the "virtual clamp", a solution where the part is measured without physical clamping, but the clamped results are provided mathematically.

Publication **IV** continues with the virtual clamp by developing a method to validate that it works in real-life installations. This work also brings the development to a closure as several high-profile manufacturing companies approve it after comprehensive validation.

Publication **V** started from a visionary discussion of how the future of welding process could benefit from the new measurement technology. We ended up re-designing the whole concept of welding. This work introduces the technical concept of the "measurement-aided welding cell" and presents further development projects with BMW among others.

The main driver for our research was not academic methodology, but rather the practical need to overcome real-life change resistance. Therefore, the five publications spread across several fields of science. Publication **I** was about economics and statistics, where **II** discussed environmental impact. Publication **III** covered mechanical engineering and **IV** was about metrology. Publication **V** falls under advanced manufacturing technologies.

Second outcome of letting real-life challenges set the study plan was the problem to explain how the five different publications would form one solid entity. Steve Jobs said: "you can only connect the dots afterwards". This was also the case with our research. Only after finishing the last publications, they started to form a clear picture together.

The last dots to connect was to understand that this work was never about measurement, manufacturing or automotive industry. This work was about disruptive innovation and how to break through the change resistance. Reflecting the five publications against the theory of disruptive innovation brought the insight of three mechanism of change resistance that we tried to overcome with our research. Only after overcoming all three mechanisms, we finally made a successful break through to traditional markets.

The hypothesis of this doctoral thesis finally fell in place. For a disruptive technology to break through, there needs to be three “change resistance antidotes”:

1. **Economic driver.** The comprehension that the tight margins and lack of development resources need to be countered. When the decision makers of established companies discuss about investing to the disruptive technology, they need to talk about maximizing profit margins, not minimizing technology risks. They need to see the disruptive technology as the answer to their tight margins. In order to make the return on investment clear and visible, pragmatic calculation tool with simple logic is needed.

2. **Win-win adaptation.** New technology allows things to be done differently. It is typically seen as an assault against existing structures. This fear needs to be eliminated. The decision makers need to see that the new technology only enhances the existing structures, but doesn’t require changing of them. Since the power of fear is more powerful than the power of benefits, there cannot be change resistors among the decision makers. Thus, the adaptation of the new technology needs to be a win-win for every stakeholder.

3. **Bold vision.** New emerging technologies are seen unattractive because there is no pull from existing traditional customers. To counter the lack of pull from the existing customers and past requirements, a bold vision will help the decision makers to spend time in investigating the new technology. During a market disruption, several competing technologies try to establish themselves as the future solution. To stand out, there needs to be a bold vision that both highlights the need to change and describes this technology as the enabling factor.

Chapter 2 explains the development of the first change resistance antidote: the economic driver. It goes through our learning journey from accuracy to economic benefits. This chapter is based on publications **I** and **II** as well as some additional research.

Chapter 3 describes how the second change resistance antidote was created: the win-win adaptation. It goes through the learning journey of pushing the virtual clamp into automotive manufacturing. This chapter is based on publications **III** and **IV**.

Chapter 4 presents our third change resistance antidote: the bold vision. It goes through the development of “measurement-aided welding cell”. This chapter is based on publication **V** as well as some supplemental findings from further development.

Chapter 5 takes the three change resistance antidotes and tests the hypothesis outside the automotive industry. In addition to general discussion, this chapter presents two real-life case studies were the three change resistance antidotes have been used in practice.

Chapter 6 finally concludes the work and findings and provokes some discussion on how such an interdisciplinary approach could be used to help tech companies in larger scale.

2 Economic driver: from accuracy to money

"Money is not the only answer,
but it makes a difference"

- Barack Obama

Publications
I & II

"Looks like a fantastic piece of technology, but why would I invest half-a-million bucks?" We had faced the same change resistance mechanism so many times before. Without a clear reason to buy, we couldn't overcome the tight margins and restricted budgets. You don't need to be very experienced in sales to know that you need to sell benefits. We knew this. The tricky part, as it turned out, was to understand and articulate this reason.

Our search of that reason first took us to the core of measurement, to verifying the accuracy of the new technology. After learning that accuracy wasn't actually a benefit, we started to study the traditional method of statistical process control (SPC) to prove that it is incapable for controlling the new complex processes. Even though not being a real benefit, this learning process took us closer to the game-changing discovery.

Learning to translate ecological and social impacts of the technology into economic measures was the key for finding the real benefit. Not only could we calculate the return on investment, we could show the comprehensive set of positive impacts the new technology enabled. The new technology had become the answer to their tight margins.

2.1 Measurement starts from accuracy

What is the first thing that comes to your mind about measurement? That's right. Accuracy. The first natural question was how to convince the manufacturing companies that the new 100% in-line measurement technology was accurate. The research for understanding the accuracy of the 100% in-line measurement system started in 2006. We studied how well a Mapvision 4D optical measurement system could measure a precisely machined steel part. We used a micrometre device to create accurately known movements. We used VDI 2634 guideline to evaluate results, since it was the only standard for optical measurement systems at the time. (Tuominen, 2007; VDI, 2002)

Year later in 2007 we presented this to German manufacturing companies and learned that they used another method for verifying the accuracy. The AIAG MSA (Dietrich et al., 1999; MSA, 2002) standards were designed for the traditional measurement technologies and the conventional paradigm where measurement was a post-process check, not an integral part of the process.

We believed that a new method was needed for the in-line measurement task. We continued the previous work and developed a method where we attached sub-components from the actual production part to a micrometre device (Figure 11). We followed the two well-known standards, VDI 2634 and AIAG MSA, to ensure that it gets accepted by the industry. We modified the calculation of the C_{gk} –index from the AIAG MSA to include the accurately known micrometre movements instead of accurately know dimension of a calibration artefact. Table 1 shows the comparison between the original and new calculation of test results. Equation 1 shows the detailed calculation of the C'_{gk} –index.

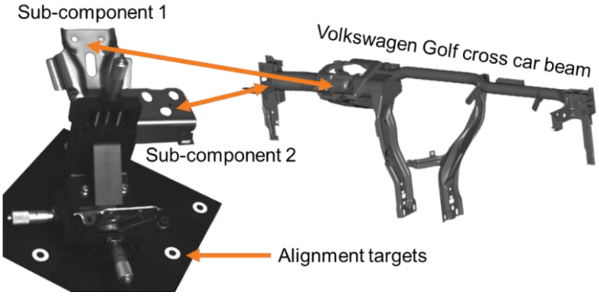


Figure 11. Micrometre device with attached sub-components. (Tuominen & Niini, 2008)

AIAG MSA type-1 study		Micrometre method	
$C_{gk} = \frac{0.1 \cdot T\left\|\bar{x}_g - x_m\right\|}{2 \cdot s_g}$		$C'_{gk} = \frac{0.1 \cdot T\left\|\bar{x}_{g-m}\right\|}{2 \cdot s'_g}$	
T	Tolerance range for measured feature	T	Tolerance range for measured feature
$\left\|\bar{x}_g - x_m\right\|$	Average difference between measured and nominal position (from calibrated standard)	$\left\|\bar{x}_{g-m}\right\|$	Average difference between measured and nominal position (from calibrated micrometer)
s_g	Standard deviation of measurement values around known fixed position	s'_g	Standard deviation of measurement values around known moved positions

Table 1. Result evaluation of original AIAG MSA and micrometre test. (Tuominen & Niini, 2008)

$$C'_{gk} = \frac{0.1 \cdot T\left|\bar{x}_{g-m}\right|}{2 \cdot s'_g} = \frac{0.1 \cdot T\left|\frac{1}{n}\sum_{i=1}^{n}\left(x_{gi} - x_{mi}\right)\right|}{2 \cdot \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{gi} - x_{mi}\right)^2 - \frac{1}{n^2}\left[\sum_{i=1}^{n}\left(x_{gi} - x_{mi}\right)\right]^2}}$$

Equation 1. Calculation of C'_{gk} -index. (Tuominen & Niini, 2008)

, where:

T	Tolerance range for measured feature	x_{gi}	Measured value at position *i*
n	Number of measured positions	x_{mi}	known value at position *i*

In the summer of 2007 we managed to convince one major manufacturing company to use the micrometre method for verifying the accuracy of their in-line measurement system in Barcelona, Spain. This was a system for Volkswagen Golf cross car beam (Figure 11). Even though we had now a real use case as a reference and one published article (Tuominen & Niini, 2008), we were not able to get this method accepted by the industry.

However, we found use for the micrometre method in several R&D projects were new measurement algorithms and methods were tested. More importantly, it became an extremely powerful way of demonstrating the capabilities of the system at fairs and exhibitions. Figure 12 shows such an arrangement in Control 2011, world's leading measurement exhibition in Stuttgart, Germany. The visitors could move one corner of a subframe, and compare both results, the micrometre and the in-line measurement system.

We had to face it. The micrometre method was not the answer for why to invest to in-line measurement. It never became spear head for pushing new measurement technology to the industry. But it is fair to say, to some extent at least, that it contributed in it.

Figure 12. Micrometre method used at Control 2011 exhibition.

2.2 Sampling doesn't work. And we can prove it.

We started to ask ourselves new questions. If accuracy requirement was not the driver, what other drivers there are for the manufacturing companies to measure? The answer was found from literature. On May 16, 1924 Dr. Walter A. Shewhart introduced a method for controlling the quality of a process, the "control chart". It's known today as the "Shewhart chart". This was the birth of statistical process control (SPC). (Wikipedia, 2016)

SPC is traditionally based on sampling, which means that typically one sample part is measured out of thousand parts. Statistical tools are then used to estimate the process based on these few samples. Traditionally, the reliability of SPC was ensured by validating high accuracy for the few sample measurements.

First, we started to figure out how we could use the micrometre test to show that the new technology would be better for the SPC. However, it didn't take long to figure out the game changing question. It was not how *accurate* the sampling measurements were. It was how *frequent* the sampling measurements were.

If we could show that more frequent samples were significantly better for SPC, we had an advantage over the traditional measurement systems which were very slow. We turned to literature. What was the relation between sampling frequency and SPC reliability? What was a proper sampling rate?

This turned out to be significantly more complex question than we thought. First of all, the literature widely agrees that reliable statistical estimate requires from 20 to 50 measurements. This means that reliable information of the process is available after a month of production. Dozens of thousands of parts would be produced and shipped. (Student, 1908; Kane, 1986; Franklin, 1999; Dietrich et al., 1999; MSA, 2002)

We knew that the processes used in body and chassis part manufacturing had a lot of variation, on daily or even hourly basis (chapter 1.3). This started to articulate our thinking. How frequent would the sampling need to be for detecting the variation of modern processes?

We started to simulate how well the SPC tools would detect process trends with different sampling rates. With ten times more frequent sampling rate problems would be detected at the end of the day when only 90 were made (see Figure 13). To gain better understanding, we turned to the theories of signal processing for help. We assumed the manufacturing process to be a “signal”, out of which we could identify significant frequencies by conducting a Fourier analysis. Knowing the significant frequencies would allow us to determine the needed sampling rate for detecting them.

We conducted a Fast Fourier Transformation (FFT) to break down the process to individual frequencies. Then we used Inverse Fourier Transformation (IFT) to test how much of the frequencies we would need to reconstruct a reasonably similar process. We tested three different sample rates, one out of 400, 100 and 10. Figure 14 shows that even with the 1/10 sampling rate, the extremes of the process would remain undetected.

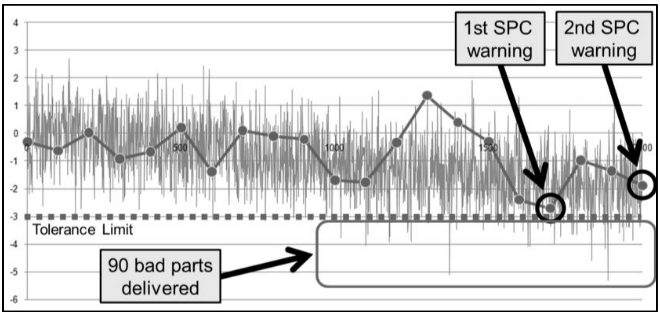


Figure 13. Simulation how sampling detects a falling trend in the manufacturing process.

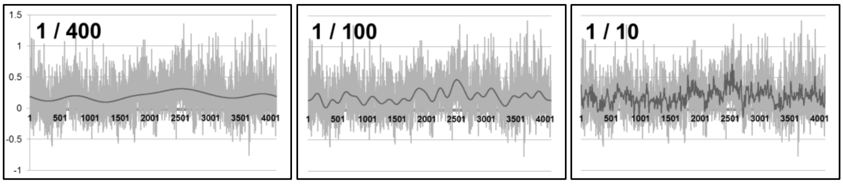


Figure 14. Inverse Fourier Transformation (dark) for a manufacturing process (light).

Literature review showed that we were not the firsts discussing the trade-off in sampling. Increasing sampling rate increases inspection costs. Reducing sampling rate reduces the amount of information. Since 1940's the discussion has circled over the essential questions of quality control (Vardeman & Jobe, 1999; Deming, 1982; Barnard, 1954; Mood, 1943):

- How disastrous is an undetected defective part?
- How often and how quickly can there come a failure to the process?
- What is the cost for receiving a data sample?

In the eighties and nineties these questions were built into a mathematical model for calculating the average inspection and consequence cost (Vander Wiel & Wardeman, 1994; Deming, 1982; Deming, 1986; Lorenzen, 1985):

$$\pi\,[k_I + (1-p)w_G\,k_{GF} + p(1-w_D)k_{DF} + pw_D k_{DP}] + (1-\pi)pk_{DU}$$

, where:

π	Sampling rate	w_D	Probability for bad part to pass inspection
k_I	Cost to inspect one part	k_{DF}	Cost when a bad part fails inspection
p	Probability for a bad part	k_{DP}	Cost when a bad part passes inspection
w_G	Probability for a good part to fail inspection	k_{DU}	Cost when a bad part is shipped without inspection
k_{GF}	Cost when a good part fails inspection		

Equation 2. Inspection and consequence cost of a part, depending on sampling rate.

To simplify the equation, we create a donation of A:

$$A = (1-w_D)(k_{DU} - k_{DF}) + w_D(k_{DU} - k_{DP}) + w_G k_{GF}$$

Equation 3. Donation for A for simplifying the equation.

This way the equation simplifies to:

$$pk_{DU} + \pi(k_I + w_G k_{GF} - pA)$$

Equation 4. Simplified equation for inspection and consequence cost of a part.

Since all costs are non-negative and all probabilities are between 0 and 1, minimizing the equation happens by changing the value of π (sampling rate). Depending on the value of A, there are only two possibilities for the optimal solution for minimizing the equation. If $(k_I + w_G k_{GF} - pA) > 0$, the equation is minimized by having $\pi = 0$. If $(k_I + w_G k_{GF} - pA) < 0$, the equation is minimized by $\pi = 1$.

In other words, the minimum cost of a part is reached either by not measuring anything or by measuring everything, regardless of any other parameters. This was in line with the understanding we gained from our earlier research. If the process is stable, the measurements do not provide additional value. If the process is unstable, sampling doesn't provide enough information for controlling it. As discussed in chapter 1.3, the manufacturing processes of body and chassis parts are far from stable.

We had suddenly developed bullet proof evidence to convince that the only rational way was to measure 100% of the parts. Traditional measurement technologies were not fast enough, so investing to in-line technology was the only logical outcome.

After the micrometre epistle, we learned that automotive companies had strong change resistance by nature. We understood that there is a great amount of people who have built their career on using the SPC. Presenting a technology that would make this group of people obsolete would even strengthen the change resistance.

We tried to tackle this by presenting 100% in-line measurement just as a more powerful data source for the existing SPC tools. Instead of replacing the SPC, we would make it better. We researched how χ^2 -test, student's t-test and running average method would enhance the traditional discrete calculation methods of the SPC. The results showed a significant improvement in detecting problems in the process. (Wulff, 2011)

We were sure we had the answer. We had the mathematical evidence. We had tackled the change resistance. A Finnish engineer couldn't think of any logical counter-argument. We were right. The manufacturing people followed the mathematical equations. They loved the idea of using 100% data for SPC. They agreed with everything. "This all makes perfect sense, but we can't invest to 100% in-line measurement, it's just too expensive".

We had hit the same roadblock all over again. But this time we didn't understand why.

2.3 Why would I invest half-a-million bucks?

We had come a long way from accuracy to process control. We had begun opening the US market. There was a great interest towards the new technology. We had the bullet proof evidence that 100% in-line measurement was the only logical solution. But still, we hadn't been able to sell a single system between 2010 and 2013.

In every game, there is a pivot point. Ours was one afternoon meeting with a large manufacturing company in Michigan, USA. The Vice President said after our presentation: "Looks like a fantastic piece of technology, but why would I invest half-a-million bucks?" We stuttered a long list of faster, better and more accurate. We went through our bullet proof mathematical equations. The VP rhetorically repeated his question while he was walking out the room. We didn't get the deal.

We had a long discussion on our drive back to the hotel. This was it. This was the question we needed to answer. But how? Hadn't we just proven that the cost optimal inspection strategy is to measure 100%?

Then it hit us. The VP wasn't really interested in minimizing cost of *inspection* processes. He was interested in minimizing cost in *his manufacturing* process. Instead of having a mathematical model of the inspection process, we would need to have a mathematical model of the manufacturing process. Now the target became clear. We sat down with several of our customers and asked about their most typical manufacturing and bad quality costs. What was the root cause, what the cost was and what was the probability?

We listed several typical defect types, each having very different probabilities and very different consequence costs. For example, if an installation hole of a non-critical component is 3 mm out of tolerance, which can happen daily, it will cause some 30 dollars' worth of manual re-work. In the other hand, if a safety critical component is bad, this could cause a recall of thousands or millions of vehicles from consumers. This might happen once a decade, but has a cost of millions or billions. Toyota Motor Corporation made a good case example in 2009 and 2010 with a recall campaign of 9 million vehicles having a cost of 2 billion US dollars. (Toyota pressroom online, 2010) (BBC News online, 2010).

We went back to the drawing board with our inspection cost mathematics. We modified the model to consider different types of defects, as shown in Equation 5. Using this new model, we could present the most typical defects and their average cost per part (see Table 2). Depending on the case, we could show dozens or hundreds of thousands in savings per year if 100% in-line measurement would eliminate these costs. (Publ. I)

At the same time, we were working in co-operation with Lappeenranta University of Technology to show the economic and environmental benefits of using new optical in-line measurement technology. This topic fit well a research project for developing a framework for sustainable value proposition. The targeted triple bottom line meant that product life cycle value would include not only economical, but also environmental and social benefits. In our case the framework considered maintenance downtime, sampling inspection costs and traceability of produced parts. (Publ. II)

$$\pi k_I + \sum_{i=1}^{n} \{\pi[(1-p_i)w_{G\,i}\,k_{GF\,i} + p_i(1-w_{D\,i})k_{DF\,i} + p_i w_{D\,i} k_{DP\,i}] + (1-\pi)p_i k_{DU\,i}\}$$

, where:

i	Type of defect	$k_{GF\,i}$	Cost when type *i* good part fails inspection
π	Sampling rate	$w_{D\,i}$	Probability for type *i* bad part to pass inspection
k_I	Cost to inspect one part	$k_{DF\,i}$	Cost when type *i* bad part fails inspection
p	Probability for type *i* bad part	$k_{DP\,i}$	Cost when type *i* bad part passes inspection
$w_{G\,i}$	Probability for type *i* good part to fail inspection	$k_{DU\,i}$	Cost when type *i* bad part is shipped without inspection

Equation 5. Cost model of different types of manufacturing defects. (Publ. I)

i	Description of defect	Defect causes	Cost of delivered bad part	Probability of defect		Cost of found bad part	Probability of measurement error
			$k_{DP\,i}$ $k_{DU\,i}$	p_i	Occurs	$k_{GF\,i}$ $k_{DF\,i}$	$w_{G\,i}$ $w_{D\,i}$
1	Installation hole 3 mm out of tolerance	Re-work on assembly line	30 €	1 %	10 per day	10 €	0.5 %
2	Installation hole 10 mm out of tolerance	Assembly line stops	200 €	0.2 %	2 per day	10 €	0.2 %
3	Missing sub-component	Disassemble or scrap car	12 k €	0.003 %	0.8 per month	10 €	0.01 %
4	Defected component detected after assembly	Re-work on completed cars	300 k €	1 ppm	0.3 per year	10 €	0.005 %
5	Defected component detected after delivery	Public re-call of delivered cars	1.8 M €	0.3 ppm	0.09 per year	10 €	0.005 %

Table 2. Typical defects the manufacturing companies had in their processes. (Publ. I)

As seen from Figure 15, these value creation mechanisms resulted in higher production volumes, reduced inspection costs and saved energy costs. The framework proposed an increase in annual profit of 300,000 € for a typical production line. (Publ. II)

We combined the sustainable value proposition framework (Publ. II) with the cost model of inspection strategies (Publ. I). After simplification, this resulted in a practical Excel-sheet that calculated the annual increase in profit based on the actual numbers given by the manufacturing company (see Figure 16).

We never met the Vice President again and never got the chance to answer his question "why would I invest half-a-million bucks". But we answered this question to many other manufacturing companies. We believe our answer was correct and in the following year we got a lot of evidence to support this. 3 million pieces of evidence, to be exact.

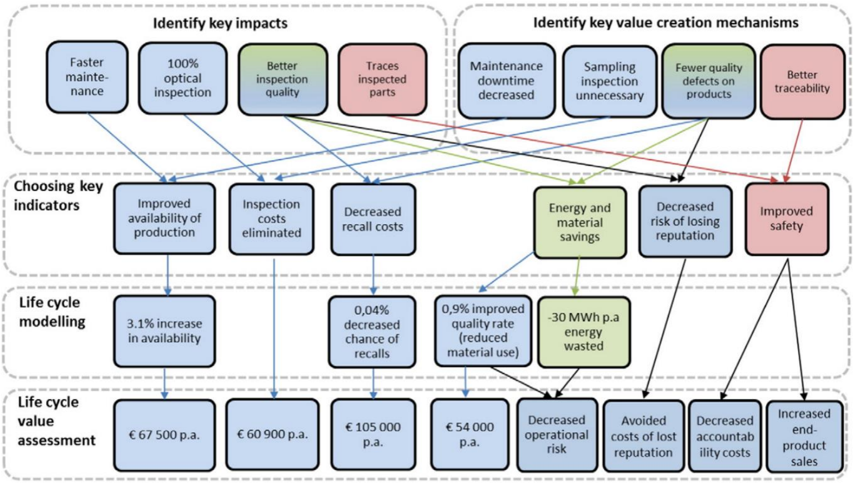
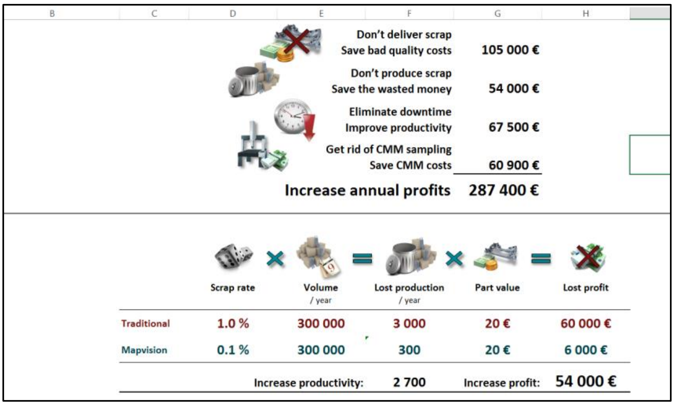


Figure 15. Sustainable value proposition for 100% in-line measurement. (Publ. II)



Don't deliver scrap
Save bad quality costs 105 000 €

Don't produce scrap
Save the wasted money 54 000 €

Eliminate downtime
Improve productivity 67 500 €

Get rid of CMM sampling
Save CMM costs 60 900 €

Increase annual profits 287 400 €

	Scrap rate	×	Volume / year	=	Lost production / year	×	Part value	=	Lost profit
Traditional	1.0 %		300 000		3 000		20 €		60 000 €
Mapvision	0.1 %		300 000		300		20 €		6 000 €
			Increase productivity:		2 700		Increase profit:		54 000 €

Figure 16. Excel tool for calculating increased annual profits.

3 Win-win adaptation: virtual clamp

“The less there is to justify a traditional custom,
the harder it is to get rid of it”

- Mark Twain

Publications
III & IV

Déjà vu. We were having the same discussion again. Different year, different people, different country, but the same discussion. Everybody was impressed by our unique ability to measure parts without a mechanical clamp. Our technology was the only one not needing a heavy mechanical structure, which enabled significant benefits compared to any other technology. Even though everybody understood this, we always hit the same wall.

“We must measure the part clamped. If you want to sell a system, you must clamp the part.” Building a heavy mechanical structure into our system would make the new technology obsolete, just like keeping your mobile phone plugged into the wall all the time.

This was the second change resistance mechanism we faced. We spent several years in finding a way to bring the benefits of the new technology without assaulting against the existing structures of the industry. Eventually, we found a win-win solution.

3.1 Mechanical clamping

For several decades when a body or chassis part has been measured, it has been placed into a mechanical clamping device that mechanically presses the twist away from the part. Figure 17 shows a typical mechanical clamping device for a front subframe.

We found different reasons for doing this. First, some operations, such as tooling, are done while part is clamped. To control these, the clamped measurement results are needed. Second argumentation says that clamped measurements simulate how the part will fit the final assembly. Third reason was that traditional measurement technologies couldn’t measure a twisted part. Finally, the strongest argument was that the specification said so.

When these strong reasons are combined with one of the most conventional and risk-avoiding industries in the world, it is obvious why nobody had ever challenged the concept of mechanical clamping. But that’s exactly what we needed to do. Why? Because a mechanical clamp prevents the in-line measurement to be utilized to its full potential.

First, when the mechanical clamp *squeezes* the twist away from the parts, it prevents measurement data to be used for *adjusting* the twist away from the process. Second, the heavy weight steel structure of the clamp prevents the otherwise programmable in-line measurement system to flexibly change products or adapt to engineering changes. Third, the precision-mechanics are expensive investment and require costly maintenance.

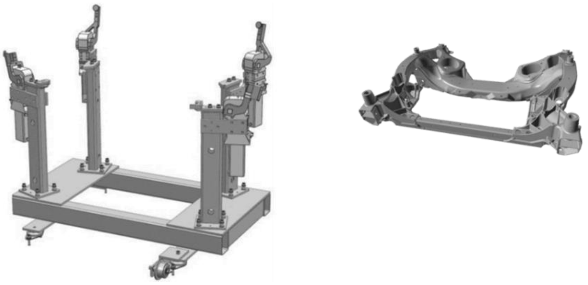


Figure 17. Mechanical clamp and BMW front subframe. (Publ. IV)

During the first years, we had to modify, re-engineer or even remove mechanical structures from the clamping devices inside the in-line measurement system because they were causing so much mechanical problems in the production, see Figure 18. Obviously, doing metal work on heavy weight structures using power tools within a calibrated optical measurement system is not the easiest operation. Even worse, the manufacturing companies saw these operations as the fault of unreliable new measurement technology.

The mechanical clamp was preventing the benefits of the new in-line measurement technology from realizing, from many different perspectives. For several years, we tried to convince the manufacturing companies to discard the mechanical clamp. No matter what tricks we played, the above discussed reasons for having the clamp were too strong and the requirement for clamping always remained.

But then we realized that clamping as a concept is not a problem and there actually are some true benefits of having the clamped results. The problem was that the clamping was done with a *mechanical* device. Would it be possible to do the clamping *virtually* by software and thus eliminate the downsides of the mechanical clamping device? If this would be possible, not only could we argument our case against the mechanical clamp, but we would be able to provide a win-win solution to the manufacturing companies. Getting best of both worlds would make our value proposition even stronger!

Figure 18. Janne cutting off a part of the clamping device in May 2008.

3.2 Developing the virtual clamp method

During the summer of 2007 we entertained ourselves with the idea of virtually clamping the parts. The we started to entertain people from Daimler and BMW with the idea. Finally, in December 2007, we built a test arrangement where we had a special mechanical clamping device within a Mapvision Quality Gate 4200 Series in-line measurement system. In this clamping device, it was possible to create controlled and accurately known deformations to the part (Figure 19). Daimler supported the research by providing us with five front subframes of the upcoming E-class Mercedes.

After having the test arrangements set up we started to formulate the hypothesis to be validated with the empirical testing. The first assumption was that the clamping would not cause deformations that would exceed the elastic limit, allowing us to use a linear model. Literature on material science supported this assumption. Second question was whether different individual parts of the same product behaved in a similar way.

We tested these two hypotheses empirically by first measuring the parts without causing any deformation. This defined the 0-position. Then we turned the micrometre device in the clamp to bend the corner 0.1 mm and re-measured. We repeated these 0.1 mm steps until we reached 1.5 mm deformation and then we started to go down until -1.5 mm.

For every measurement point and every co-ordinate, we fitted a linear model (Equation 6). Then we calculated the difference between the measurement data to the linear model. The data showed a clear linear behaviour. The difference between the model and measured data was around 0.02 mm within one part and less than 0.04 when all five parts were included. This level of difference falls within the general measurement uncertainty of in-line measurement systems. The data analysis included almost 40,000 data points, which increased our confidence that both hypotheses were valid.

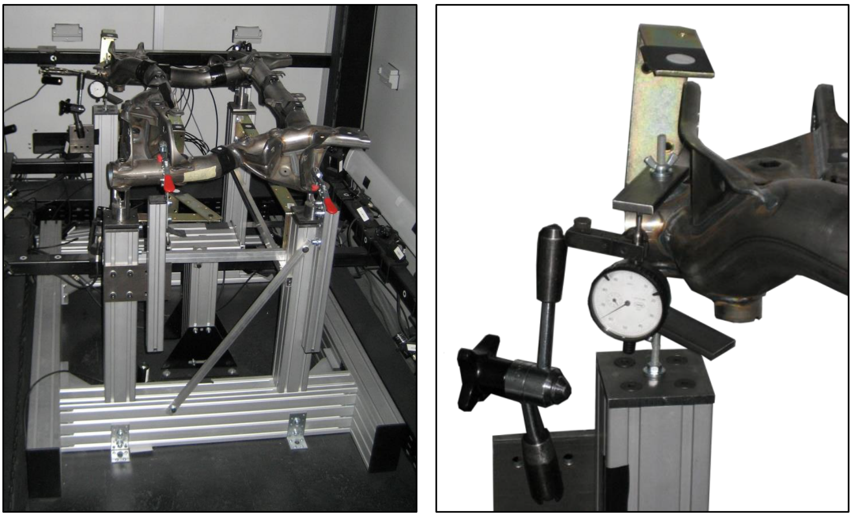


Figure 19. Special clamping device and the mechanism to control deformation. (Publ. III)

$$Y_i = m_i X + b_i$$

, where:

X	Known displacement of the corner	m_i	Point-specific *i* coefficient for linear model
Y_i	Value for measuring point *i*	$w_{D\ i}$	point-specific *i* constant for linear model

Equation 6. Point-specific linear model used in the virtual clamp. (Publ. III)

We had shown that we could accurately model the clamping deformations with a point-specific linear model. But where would we get the parameters to the model? One school of thought in our discussions was to have a "virtual clamping studio" where we would test a few pre-production parts and empirically determine the parameters, just as we did in the research. The problem was that this way we would still need to have the mechanical clamp.

The other school of thought was to get the parameters from a FEM (finite element method) simulation. The debate was whether the method was accurate enough since the real parts had variation in weld seams and material thickness that could cause unpredictable behaviour. Well, there was only one way to find out.

First, we built a mesh model out of the solid CAD model of the same subframe we used in the empirical research. Then we built similar constraints to the software model as in the mechanical clamp. Three corner points were fixed in Z-direction and one corner point was given the freedom to move in Z-direction (Figure 20 left). Finally, we created similar 0.1 mm step displacements to the free corner as in the mechanical clamp. On each step, we recorder the movement of every measurement point across the part (Figure 20 right).

There was a lot of learning on how to set the constraints correctly, but finally we had comparable data between the empirical measurements and the FEM measurements. The results showed that the difference between these data sets was in average 0.042 mm. The results were saying that the FEM-approach did not bring practically any uncertainty.

From December 2007 to December 2008 we made thousands of measurements, gathered gigabytes of data and spent hundreds of hours analysing. For the first time in the world we had undisputable results: virtual clamp works!

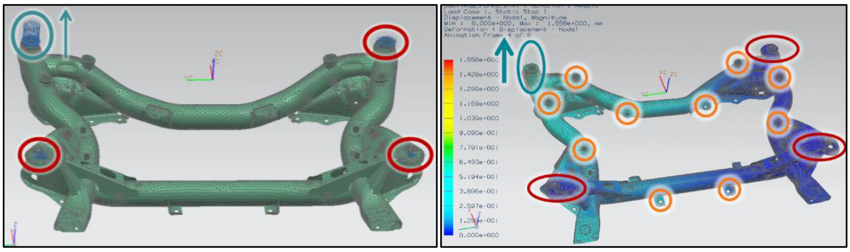


Figure 20. Simulation of the clamp (left) and recorded movements (right). (Publ. III & IV)

3.3 First virtual clamp on a production line

As typical Finnish engineers, we thought that we had solved the problem. We had better technology, now everybody would just start using it. It didn't go like that.

In 2009, we introduce the new solution and the results to automotive manufacturers and leading OEM's, such as Audi, BMW and Daimler. We faced a new obstacle. People who had worked with mechanics all their career were afraid of the new solution. "Interesting idea. Results look very good. But we don't believe it's reliable in real production use". Reliable? It was simple linear algebra. Clamping couldn't get any more reliable.

It was not only the manufacturing companies who were afraid for the new solution. Before presenting the virtual clamp to a major manufacturing company, our own German sales manager said: "There will never be a virtual clamp in Germany. Especially in Brackwede".

For the next three years, we hit our head against this change resistance, repeatedly. We started to lose our hope until one meeting in February 2012. We were invited to our major customer in UK. They had several in-line measurement systems, oddly, without mechanical clamps. They had faced a critical issue with the end customer and topic of the meeting was to develop a plan to install mechanical clamps to the existing systems.

This time we took a different approach. Instead of presenting our finalized virtual clamp solution, we asked the quality people how they had coped with the situation before. They had been using a "mathematical clamp", where they manipulated the alignment parameters to compensate for the twist in the part. We presented our research as something that might complement their method. "The mathematics seem a bit more sophisticated, but this is what I've been doing in the measurement lab!" We asked if he would like to take his method to the next level. We proposed that together we would implement the "slightly more sophisticated" solution directly on the production line.

It was a typical day in UK. It was cold, it was raining and the sky was grey. But for virtual clamp, the sun just started to shine. Supported by the senior quality manager, we implemented the world's first virtual clamp. It solved their problem with the end customer and soon they had several production lines running with virtual clamps.

Figure 21. Happy engineers after the world's first virtual clamp implementation.

3.4 Correlation test as the validation method

Having a few virtual clamps in real production use allowed us to change our message. Instead of introducing an idea, we introduced a “standard solution that is already used by leading manufacturers.” This raised a lot of interest and we faced the next question: how do we validate that it works? There were naturally no industry guidelines how to validate a virtual clamp since we had just invented the whole thing. So, we had to develop one.

We had learned not to assault against existing structures and decided to follow a commonly used “correlation test”. Here the same part is measured first with a certified CMM and then with the system under validation. Results are compared and if the differences are less than 0.2 mm, the test is passed. We would just compare the virtually clamped results of the in-line measurement system to the mechanically clamped results of the CMM. This logic was easily understood and accepted by the manufacturing companies.

However, during the first validations, we run into a new obstacle. Traditional correlation test is for mechanical gages which can measure roughly a dozen physical features, each with maximum 3 coordinates. In a typical 10-part correlation test, this results in 300 measurement comparisons. Modern in-line measurement systems are capable of measuring hundreds of physical features on a part. With all the derivative calculated features, this can sum up to roughly 10,000 measurement comparisons.

When the CMM and the in-line measurement system perform well, the measurement uncertainty for welded assemblies is 0.06 mm (1σ) and the errors are normally distributed. Thus, if both systems would perform perfectly, there is a 0.05 % statistical probability that a point exceeds the 0.2 mm acceptance limit. With the traditional 300-point comparison test, there is an 86 % ($0.9995^{300} = 0.8607$) probability for passing the correlation test. With 10,000-point comparisons, the probability is 0.7 % ($0.9995^{10\,000} = 0.0067$). In other words, with the large amount of data from modern systems it is impossible to pass the test, even if both systems perform perfectly.

AIAG MSA standards were renewed a decade ago when simple arithmetic calculations of the ARM (average range method) where replaced with statistical ANOVA-method (analysis of variance) (MSA, 2002; Dietrich et al., 1999; Tuominen & Niini, 2008; Publ. IV). Similarly, we kept the actual correlation test the same, but introduced four statistical indicators for the evaluation: random error, bias, net correlation and correlation range. In addition to addressing the original issue, this gave more understanding and thus enabled corrective actions. Middle case in Figure 22 can be improved by adjusting a simple offset, while the right case in Figure 22 is caused by a more fundamental problem or error.

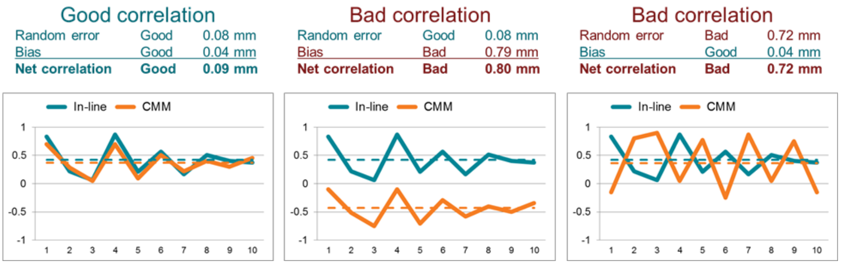


Figure 22. Illustration of three different correlations on ten parts. (Pub. IV)

3.5 Four validation projects

We had developed a completely new way for clamping the parts during measurement and it was already used by couple of mainstream manufacturing companies. We had now introduced a scientific method for validating the functionality of the virtual clamp, which was in line with automotive standards. Final step was to get major manufacturing companies to approve the virtual clamp. Having acceptance of the virtual clamp by strong names, we had a chance of making this method a standard in the automotive industry.

Between March 2012 and November 2015, we carried out virtual clamp validation projects with four leading automotive manufacturing companies, one being BMW Dingolfing. In three of the validation projects the produced part was a front subframe where the clamping was applied traditionally to the four corners (left in Figure 23). In the BMW project the produced part was the drivemodule of the i3 electric car. This part was chosen since it was believed to be the most complicated part for virtual clamp. The clamping was applied to the front forks (right in Figure 23). Test setup is explained in detail in Publ. IV. As a summary, the validation projects answered three research questions:

1. **Does a virtual clamp give the same results as a mechanical clamp?** This was studied in two research projects. The net correlation in direct comparison was 0.04 mm, so they are very close. Similar results were found in laboratory testing (Publ. IV). The answer was: Yes, within the general uncertainty budget.
2. **Does a virtual clamp affect the correlation with a CMM?** This was studied in three research projects. The outcome was that the virtual clamp improved the correlation to the CMM by an average of 0.009, compared to free-state measurement. The answer was: Yes, but in a positive way.
3. **Does the twist in the part affect the accuracy of a virtual clamp?** This was studied in one research project. The conclusion was that the amount of twist does not decrease the accuracy of a virtual clamp. The answer was: No, the amount of twist does not have a significant effect.

The accuracy of the virtual clamp was validated to be in the range of 0.01 mm to 0.04 mm, which is less than the diameter of human hair. Temperature variations in stable operating conditions cause several times greater dimensional variation. The validation results showed that the virtual clamp reduced the overall measurement uncertainty budget. (Ley B., 1999; Kaye & Laby, 2010; Publ. IV)

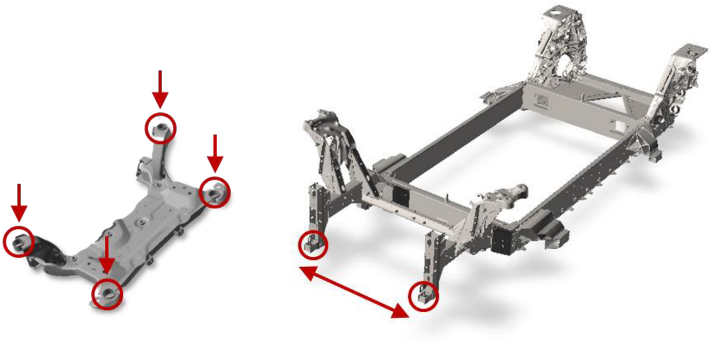


Figure 23. Front subframe (left) and the BMW drivemodule (right). (Publ. IV)

3.6 Virtual clamp became reality

We started our virtual clamp journey in 2007 when no one else openly challenged the concept of mechanical clamping. For a long time, we were trying to assault against existing industry structures by proposing that there would be no clamping at all. Having a mechanical clamp was not an option either. Without knowing it at the time, we were against the second of the three change resistance mechanisms.

With the virtual clamp, we converted a traditional mechanical task into a software task. As with many other innovations, the pivot point was when we realized that the new solution shouldn't *change* the existing industry structures, but to *adapt* into them. By transforming our thinking towards adaptation, we started to make even a greater change.

Not only did the virtual clamp provide a win-win solution for adapting the new technology to the existing structures, but it became a selling point for customers: it enhanced the superior image of the new technology and highlighted the importance of real-time process control. As it turned out, none of the systems sold to the North American market had a mechanical clamp. The decision makers saw virtual clamp as an improvement to the existing structures, not as an assault against them.

The first paper about the virtual clamp in 2011 (Publ. III) ends with a conclusion: *"By the feedback from the automotive industry it seems like virtual clamp might be reality on some production lines, even in the near future. When this happens, the fourth and the most daring hypothesis is proven to be valid: the automotive industry can be changed."*

By the end of 2016, over a dozen automotive companies around the world had approved the virtual clamp for current and future projects. Over 40 production lines were running with a virtual clamp. Several million virtually-clamped parts had been assembled into cars that were driving on the roads. When we started in 2007, there were none.

Maybe changing the automotive industry is too bold of a statement. Or maybe it's not. But one thing is for sure: today there are virtual clamps in Germany. Especially in Brackwede.

4 Bold vision: the future of welding cells

"The best way to predict
your future is to create it"

\- Abraham Lincoln

Publication
V

We were having lunch in a factory cafeteria in northern Germany when this automation engineer told me his vision. In a future car factory, there would be only two employees: one man and one dog. The man's job was to feed the dog. The dog's job was to prevent the man from touching the automatically running machines. I laughed and ate my schnitzel.

A few months later in the fall of 2008 we were working over a weekend with my colleague Janne when I told this joke over a few beers. We realized that even though we had spent a lot of time in the innovation centre of the leading welding robot manufacturer, we hadn't heard any technical visions about future welding. We had a few more beers and envisioned how such a system would look like. The evening ended up with a text on an empty cigarette box: "Sight to the blind".

Developing our concept measurement-aided welding cell (MAWC) provided us with a completely new viewpoint. It made us see measurement as an integral part of the manufacturing process, instead of the traditional post-process operation. We learned to position real-time measurement as the enabling technology of future manufacturing, rather than the competing measurement technologies.

Without knowing it, we were addressing the last of the three change resistance mechanisms. New emerging technologies are seen unattractive because there is no pull from existing customer requirements. We were building a bold vision to articulate the importance of the new technology so that decision makers spend time in investigating it. A project that started as a discussion over a beer turned out to play a significant role in the market breakthrough of the in-line measurement technology.

4.1 The concept of the MAWC

The traditional way to produce a welded assembly is to have a heavy weight welding fixture where sub-components are placed. The mechanical fixture holds the components in position while welding robots weld the components together (chapter 1.3). The heavy weight welding fixture allows only one part type to be manufactured on one production line. In our thinking, the increasing demand for flexibility was addressed by replacing the welding fixture with two programmable robots holding the sub-components while the third welds them together. The robots were programmable thus flexible.

We understood that this wouldn't work blindly since the positioning of the sub-components in a hand of a robot wasn't nearly as accurate as needed. To make this work, the robots would need to be guided by continuous measurement. Figure 24 shows the concept of a "measurement-aided welding cell" (MAWC) where an integrated measurement system surrounds the complete welding volume. There are two handling robots that hold the components and one welding robot. The components of the part are fed to the cell by two conveyors. Different types of components require that the grippers are adjustable (Figure 25). More significant differences in the components require that the robots change the whole gripper from the gripper holster.

We did a technical review that showed that the design is technically feasible. All the needed technical components are widely used in the industry. But the glue that held everything in place, the in-line measurement, was never used to automatically guide welding operations. The biggest question mark was in the very heart of welding: heat distortion. It was not enough that the robots held the components in the correct positions prior to welding. The heat distortion would change the dimensions during and after the welding.

We ended up to the conclusion that there were three levels of measurement feedback needed. First measurement (level 1) is done prior to welding. It is used to guide the robots to correct starting position. The second measurement (level 2) is done right after the welding to check what happened during the welding. This brings also the first element of automatic learning. The starting positions of the next part are compensated based on the measured heat distortion (Figure 26). There are ten to twenty welding operations where each can change the dimensions of the previous steps. This is compensated by level 3 feedback. Figure 27 shows the overall feedback process in a MAWC.

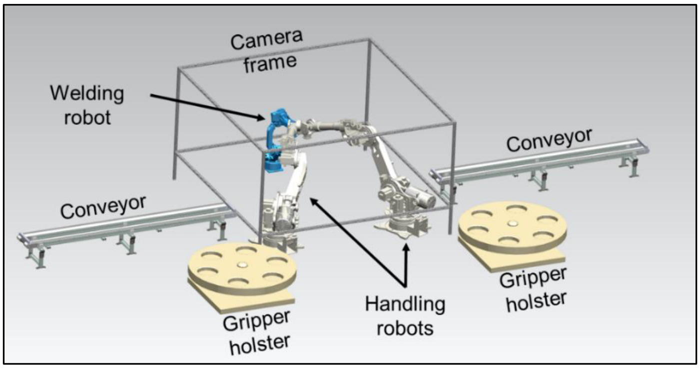


Figure 24. Concept design of a measurement-aided welding cell. (Publ. V)

Figure 25. Adaptive gripper holding different components. (Motoman web-site, 2012)

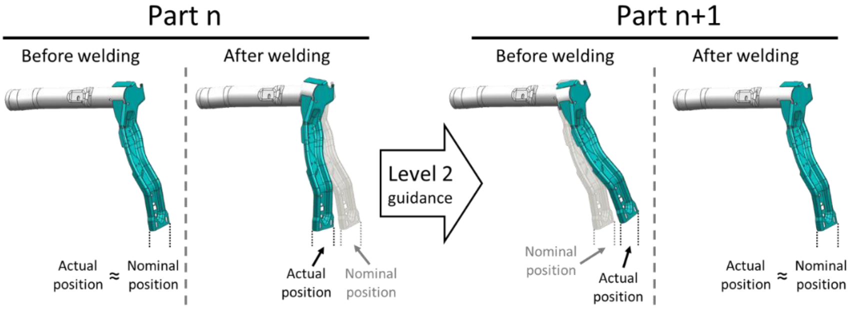


Figure 26. Level 2 guidance compensates the heat distortion. (Publ. V)

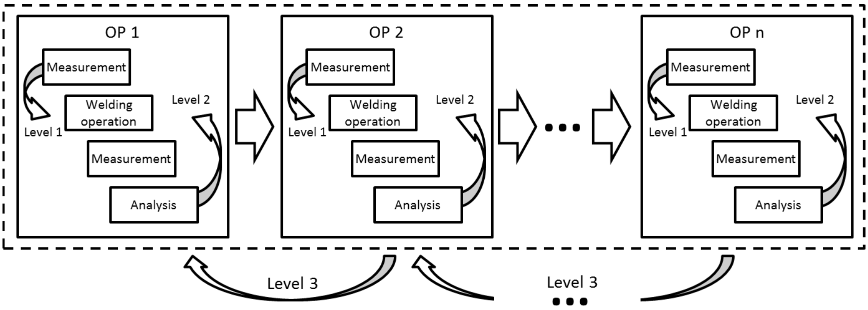


Figure 27. Three levels of feedback in MAWC process. (Publ. V)

4.2 From theory to practice

We knew that presenting this concept to the auto makers would not make them to build the next car model using a MAWC. But we hoped that by sharing a practical concept, they would open their minds and share their thoughts on the same topic. Our wish came true. It turned out that BMW had also been thinking about the next generation of welding. They had identified two critical capabilities for future welding. First, the cell would need to measure the positions of the sub-components prior to welding to be able to adjust the welding robots. Second, the future welding cell would need to check the position and quality of the weld seams to ensure high quality output.

It was not a long shot to see that these corresponded perfectly with the level 1 and 2 feedbacks in the MAWC concept. After recognizing the mutual benefit, the natural next step was to discuss about a joint development project. We started with the weld seam position and quality check in the fall of 2011 at BMW Dingolfing facilities in Germany. We ended up doing the development on the welding line of the front subframe of the Rolls-Royce Ghost due to its low volumes.

After successful results, it was time to proceed with the adjustment of welding robots based on pre-measurement. We made a test set-up where we had two overlapping metal plates on a platform. The one above could be moved in 2D. The intersection of the two plates simulated the place where the weld seam was needed. The plate was moved, after which a handling robot took the platform inside the measurement system. The measurement system calculated the needed compensation and gave it to the robot with simple 2D offsets. After this the welding robot drove the new adjusted path. We used a black marker instead of a real welding torch.

The results of this were encouraging and the natural next step was to develop similar capabilities for 3D robot guidance. We started discussions with different companies and institutions to join the development project. During 2014 and 2015 the development work was done in cooperation with VTT.

The functionality was demonstrated by having a test plate randomly (+/- 10 mm) positioned at the pickup station. The robot gripped the plate and put it into the measurement system. The robot adjusted the plate position and the welding path based on the measurement. The welding robot drove along the adjusted welding path with the black marker. This routine was repeated several times and the path was drawn accurately to the same place on the plate, whatever its location (Figure 28). Figure 29 shows the operations during the process.

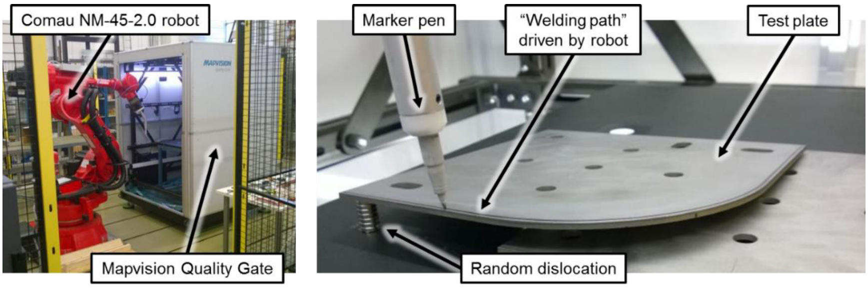


Figure 28. The welding path was adjusted based on measurement feedback. (Publ. V)

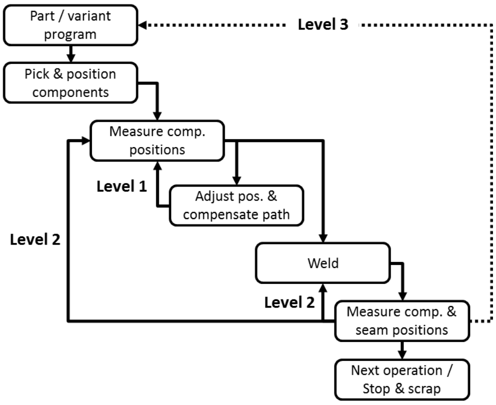


Figure 29. Three levels of guidance actions during one MAWC operation step. (Publ. V)

4.3 MAWC – technical dream or future reality?

During the several years that we researched the concept of MAWC, we had dozens and dozens of discussions with several people from leading manufacturers in the automotive industry. There was a unanimous opinion that the traditional fixed welding cannot answer the future needs.

In a MAWC, changing between products is mainly a software task, making manufacture of low volume products efficient, since capacity can be distributed to across multiple products. Adapting to engineering changes and introducing new parts is fast due to the automatic learning, which addresses the shortening product life cycles. The investments to production capacity can be made significantly later and the capacity can be matched accurately against actual demand (Figure 30).

The benefits of MAWC manufacturing are significant and the trends in the automotive industry are generating demand of new manufacturing technologies. On the other hand, the welded assemblies are the skeleton of a car and car makers will certainly not risk the backbone of their business. As in many futuristic visions, it is possible that the MAWC will not realize exactly as envisioned. Most probably we will see hybrid solutions where some elements of the MAWC are introduced to a traditional welding cell.

The high-flying idea that was born over a few pints of beer has turned into successful co-operation with BMW and a completed research project with VTT and other partners. One German manufacturer was planning to develop a test system for welding actual parts.

For the first time in the world, we created a concept were the welding wouldn't be based on hardware fixtures. We even took the first steps in developing it in practice. Only the future will tell how accurate our vision was. But coming back to Abraham Lincoln's quote, it's fair to say that we did our deed in predicting and maybe even creating the future.

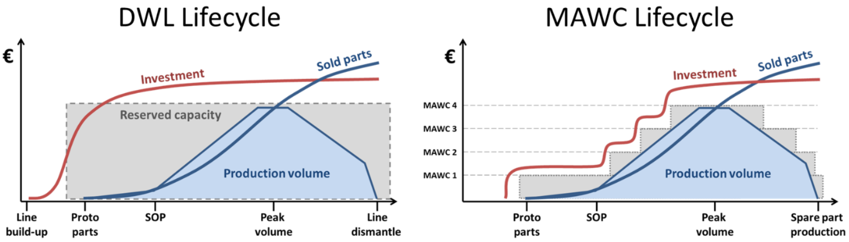


Figure 30. Production lifecycle with investment cost. Comparison of a traditional welding line (DWL) and MAWC. (Publ. V)

5 Testing the hypothesis

“You can't prove any hypothesis,
you can only improve or disprove it”

- Christopher Monckton

From the theories of technology adaptation lifecycle and disruptive innovation, we identified three change resistance mechanism that new technology faces during market entry. Previous chapters present the work we did to overcome this change resistance during our ten-year journey in the automotive industry. The sudden market breakthrough to the challenging US market was a result of addressing all the three mechanisms at the same time, which lead us to develop the idea of “three change resistance antidotes”. Our hypothesis was that all the three needed to be addressed simultaneously to ensure a successful market breakthrough.

Probably this kind of a hypothesis can never be proven. There are so many other aspects and circumstances that can explain success or failure. However, we can test the hypothesis by using it in practice and observing whether it provides the desired influence or not. Following the words of British aristocrat and respected scientist, Christopher Monckton: "You can't prove any hypothesis, you can only improve or disprove it."

To test the hypothesis, we will first discuss two well-known cases of disruptive innovation, iTunes and Über. We will point out how the three change resistance antidotes can help to capture the essence of the successful or unsuccessful breakthrough of the new technology.

Then, we will present two real-life cases from industries far away from automotive manufacturing. We will explain how we have used the three antidotes for designing the market entry strategy for a high-tech product for monitoring the temperature of sensitive goods during transportation. Even though both cases are still ongoing, we will disclose the experiences and feedback from using this hypothesis as a tool.

5.1 General discussion: iTunes and Über

Let’s test our hypothesis with Apple and iTunes. In the beginning of this millennia the music industry was disrupted and Apple became the largest music vendor without selling a single disk. Cheaper music and the ability to buy one song at a time was the economic driver. The convention of buying music on disks was reformed with a win-win adaptation. The artists and consumers didn’t need to change their conception of having music on albums, the delivery was just made easier. Their bold vision of having music on every device anywhere is already an every-day reality. Apple had all the three change resistance antidotes which lead to success.

Let’s then take Über under review. The economic driver was cheaper taxi rides and taxi-ordering process as well as simple and compelling business model for the drivers. Their bold vision of re-inventing the taxi rides went as far as visioning self-driving taxis, which is already being piloted in practice together with Volvo. This means that they had two out of the three change resistance antidotes. In some countries, they got the third one as well, the win-win adaptation. In these countries, the taxi drivers just enhanced their existing work with the easy mobile app based system. But in some countries, for instance Finland, the win-win adaptation failed. The taxi driver union and some regulators felt that the new technology was an assault against the existing structures. Über was not able to adapt into the existing structures and never got the third antidotes in place. One of the three antidotes was missing, the change resistance won and Über didn’t break through in Finland.

Explaining the breakthrough success of iTunes and Über by the three change resistance antidotes is over-simplifying the reality. Clearly, there’s a lot more to it. But we are building an argumentation here. We propose that these three antidotes should be taken as a framework for design the key message and value proposition. Based on our hypothesis, addressing these three mechanisms will give a better chance for successful breakthrough.

5.2 Test case: market entry strategy for IoT -technology

After successfully opening the US market, it was time to move on to new challenges. It was time to move away from automotive industry. We got the opportunity to start working with another small Finnish technology company that had 10 years of experience of cloud-based IoT-solutions for measuring temperature. However, they had not been able to penetrate international markets even though they had very strong domestic customers in pharmaceutical and laboratory industries.

As with any small Finnish engineering company, there are plenty of improvement areas in several business areas, from sales to leadership, from R&D to organization culture. However, the first natural starting point for international market entry is to get a clear and focused strategy. In the past years, the company had been very technology oriented, which had driven the company to develop new technology and products repeatedly. Every time they faced one of the change resistance mechanisms, they developed a new product. This is very natural for us engineers.

Since 2015 the owners of the company started systematically to drive the company towards international growth and to work on strategy. This was a perfect scenario for testing the hypothesis of three change resistance antidotes for an IoT measurement solution. The high-level vision and strategic thinking was linked to the emerging market disruption of “cold chain monitoring” market, which had was very similar characteristics to the metrology market disruption in the automotive manufacturing (chapter 1.4).

During 2017 we started to design market entry strategy for two customer groups. First was the transportation of blood, second was the cold chain of pharmaceuticals. Our core message for both industries was about utilizing the measurement data to steer and manage the logistic operations, not only to report temperature failures. The short vision statement was: “from temperature maintenance to intelligent cold chain”.

It is too early to report financial success, but at the time of writing this chapter, we have brought two of the world's largest logistics companies, an airline, a gigantic pharma company and global official authorities around the table to design the future of intelligent cold chain. It's fair to say that this is well done for a small technology company during the first year of international market entry.

5.3 Antidotes for blood transportation

In the first case, we are introducing a new temperature monitoring technology to one of the world's largest human medicine laboratory service providers. In their central laboratory, they analyse blood samples sent by their customer clinics and hospitals. A common problem is that if the temperature gets outside limits during the transportation, it spoils the sample. Still, the current world view is that it is economically impossible to have real-time temperature monitoring in every transportation box.

From the very beginning, we put the three change resistance antidotes on the table. We started to formulate the economic driver by turning the discussion around from the cost of technology towards how much more profit is made by reducing bad quality costs. The logic was the same as presented in chapter 2 and we even used the same cost model.

The second antidote, the win-win adaptation, is about not introducing additional operations for the workers in either end of the transportation chain. This is addressed by having fast enough data transfer and fully automatic processing of the data.

The third antidote, the bold vision, challenges the convention of thinking the samples as batches. Instead, we start to see them as individual samples that have specific temperature limits. Linking the temperature information to each individual sample allows identification of individual corrupted samples, instead of wasting the whole box. This vision was further developed by tying each sample to the moment when the blood is taken by the nurse. This would give full traceability to their complete pre-analytics process that currently counts for 65 % of all operational problems. This was perfectly in line with the high-level vision: "from temperature maintenance to intelligent cold chain".

One of the top executives said that "you are the first ones to take the discussion to this level. Others just talk about algorithms and sensors." The lab company has invested into first pilot project that continued with a second stage with a target of global implementation of the new technology.

5.4 Antidotes for pharmaceutical logistics

Our second case focuses in solving a critical problem within the pharma industry. Every year, 2 – 12 Billion Euros worth of pharmaceuticals are thrown away because the temperature has exceeded the allowed limits during the logistics chain.

Today pharma companies are placing manual temperature loggers in the transportation boxes. The loggers are manually read at the end of the logistics chain and the logger will tell if there was a temperature excursion. However, the harm is already done and the shipment goes to waste. The only way to address the problem is to have automatic temperature sensors providing real-time data to the cloud. The battery technology of today gives only one feasible option: low-power sensors in the transportation box and an internet gateway at every point of the chain that uploads the sensor data to the cloud. Figure 31 shows the pharma logistics chain and the proposed real-time solution.

The challenge of this solution is that every player would need to invest into a gateway for the ecosystem to work. Several points of strong change resistance make this a perfect test case for the three antidotes. In this test case, we started contacting several different players along the logistics chain and adjusted the three antidotes to match to each player.

First change resistance antidote, the economic driver, comes eventually from the huge amount of wasted medicine. In addition to that, the current way of manually sending reports and claims creates a lot of costs for each player along the chain. Even though these costs need to be identified separately for each of the companies along the chain, this is straight forward work and follows similar approach as presented in chapter 2.

The second antidote, the win-win adaptation, was the tricky part. According to our hypothesis, if there is even one change resistor, the breakthrough will not happen. Thus, we needed to develop a proposal where gateway would both enhance their current work and wouldn't require changes to their current structures. And this needed to apply to each of the different players along the chain. We proposed that the trucking companies would use the gateway and couple of sensors to monitor their trucks in real-time. We proposed that the terminals would use the gateway and a couple of sensors to warn if their facility automation has a failure. We proposed that the hospitals and pharmacies would monitor their refrigerators. Pharma company was the simple one: no need for manual data handling anymore.

The third antidote, the bold vision, was again linked to the intelligent cold chain. Having the visibility and manage the logistics chain with real-time temperature data enabled the operators to move from reporting the problems to preventing the problems. This vision gained high level of interest among all players.

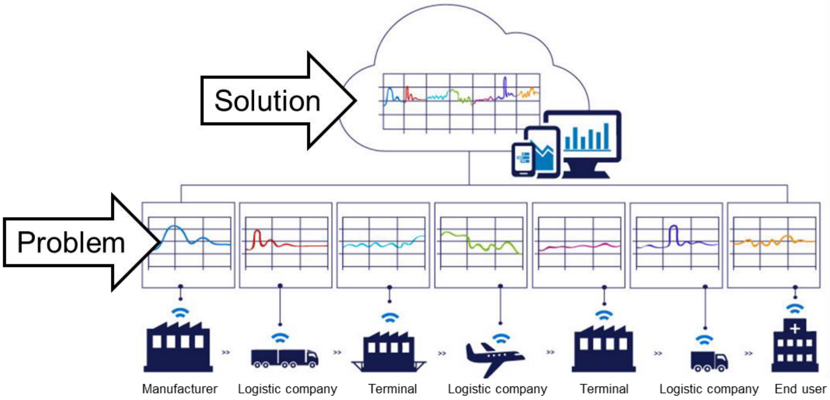


Figure 31. From temperature maintenance to intelligent cold chain

6 Conclusions and discussion

“You must be the change you
want to see in the world”

-Mahatma Gandhi

“You can only connect the dots afterwards”. We started our ten-year journey without a clear understanding where we were or where we would be heading. But we had a clear task in mind: we wanted to make a breakthrough with our unique in-line measurement technology to the automotive markets. One by one we addressed the obstacles we faced and fought the change resistance. This lead us to develop a bunch of new methods and solutions for the automotive manufacturing.

Only after the sudden successful breakthrough to North American markets we started to connect the dots. The theories of technology adaptation lifecycle and disruptive innovation led us to formulate our hypothesis of three change resistance antidotes. Our hypothesis stated that for a disruptive technology to break through, all three antidotes needed to be in place. We tested this hypothesis in two other industries. The objective was not to prove or disprove the hypothesis, but to find out whether the framework brings practical value for technology companies. The financial outcome will validate the success somewhere in 2018 or 2019. But the positive feedback from customers already indicates that the this is an extremely powerful framework for developing the market entry strategy for the technology company.

Even though we believe that it’s time to stamp this doctoral thesis as completed, our journey in the field of disruptive innovation is only just about to begin. This said, we must ask ourselves whether we created something worthwhile? Were our findings and insights significant enough to be published as a doctoral thesis? Did we make a change?

Well, we turned several years of zero-sales into a multi-million-dollar business. We reformed the way leading automotive manufacturers see in-line measurement and witnessed millions of virtually-clamped parts roll on to the roads. We helped the world’s leading car maker to develop next generation welding, based on our technical vision. We reflected this success against academic frameworks and developed a hypothesis. We saw strong indication that following our framework of the three antidotes, we could replicate the success in other industries. It is fair to say that we made a small dent in the universe.

But most importantly, we learned a lot. Most of this we have already discussed in this thesis. However, there is one thing that has not been given attention even though it is by far the most significant learning of our ten-year journey. In human mind, the emotional elements have superior power over rational elements. Human fear creates stronger change resistance than any rational argumentation can win. Addressing fear with rational argumentation will provoke cognitive distortion, a phenomenon where counter-arguments sound rational but are untrue. We witnessed this a lot, and most of it within our own team. We argue that even in a highly technologically oriented company, good leaders and organizational culture are more important than great engineers and superior products. At the end of this doctoral thesis, we would like to provoke some thoughts and discussion raising from this important learning.

Bus drivers need to be qualified as well as doctors. But we have no qualification for leading organisations and managing companies. If we agree that we need better leaders to grow our tech companies, where do we educate and qualify them? Ironically, the only commonly known qualification for management and leadership, the MBA, is not recognized as an official educational degree in the education system of Finland.

How about the much-praised role of R&D in creating economic growth in Finland? We already had a superior product for ten years. To make our breakthrough, we needed to get closer to the customer and learn their business. We needed the ability to understand the economic benefits and formulate a simple value proposition. These are more of sales, marketing and strategic leadership skills than R&D skills. We have institutions such as TEKES that fund R&D projects and help small companies to grow. Using these funds for business development, sales and marketing is often restricted, even if these would be the most important areas of development.

We can find a lot of similarities between these examples, our journey in the automotive industry and the story about the monkeys who were afraid to climb the ladders. For some reason, change is always accompanied with fear. But understanding that the strongest counter force for change is fear, can be liberating. Why? Because it means that the only thing you need for initiating change, is courage. Courage to ask questions. Courage to fail. Courage to step on the ladders, climb and just see what happens. And don’t worry if you are afraid. Without fear, there is no courage. As Gandhi puts it so well:

“You must be the change you want to see in the world.”

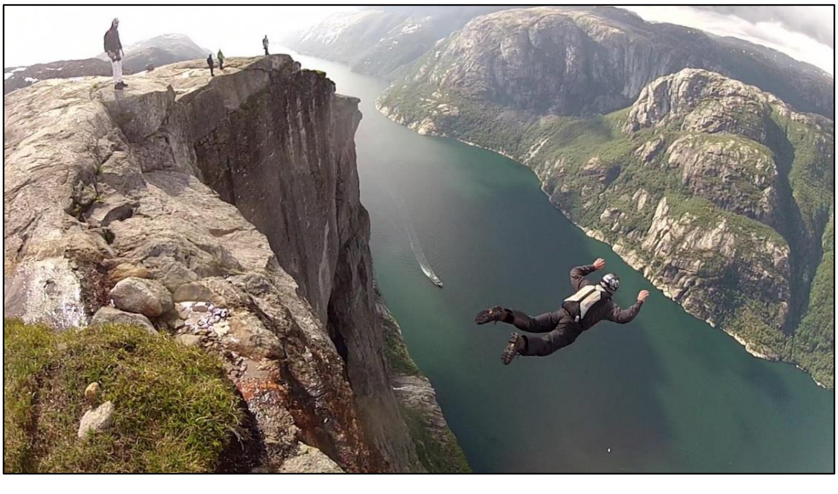


Figure 32. Without fear, there is no courage. Kjerag, Norway 2015.

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Monkeys, bananas and a scientist.

Some decades ago this scientist designed a sociological experiment. He had a small society of monkeys in an empty warehouse. In the middle of the warehouse there were ladders. At the top of the ladders there was a platform with a banana tree. Every time a monkey went for the ladders, the scientist turned on sprinklers of ice cold water. It didn't take long for the monkeys to prohibit climbing the ladders. The culture grew strong. Whenever a monkey started to climb the ladders, others pulled him down and gave a punishment.

Years passed, the scientist retired and eventually died. There was nobody to turn on the sprinklers. But still today, whenever a monkey goes for the ladders, others pull him down. Nobody remembers the reason, but everybody knows that you don't climb the ladders.

This doctoral thesis tells the story of the monkey who climbed the ladders.

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