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POKA-YOKE METHODS IN MAKE-TO-ORDER PRODUCTION

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ABSTRACT

Johannes Huuskonen: Poka-Yoke Methods in Make-to-Order Production
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Poka-yoke applications are tools aimed at creating defect-free production environment by removing the possibility of mistake or recognizing the mistake at as early a stage as possible. Thus, the poka-yoke applications ensure that customers do not receive defected products. In made-to-order production it is possible to fulfill the customer needs by providing customizable products which leads to the manufacturing company having to be able to function in a complex manufacturing environment. There is little existing research of poka-yoke methods in make-to-order production.

The goal of this master's thesis is to define what kind of mistakes operators make in make-to-order production and how those mistakes could be prevented using poka-yoke methods. The research is completed as a quantitative action research in cooperation with a case company that manufactures weather and industrial measurement devices. The product catalogue of the case company is diverse and production volumes are small.

The primary data used in the research is a collection of customer complaints from the year 2019. A secondary set of data is gathered from work instructions, order forms and standard work sheets. Based on the data it is identified which types of defects cause customer complaints and in which production phase they occur. After the production phase is identified poka-yoke methods are applied to eliminate the mistakes that lead to the defects form the production phase.

The research shows that a large portion of customer complaints result from a part missing from the order or the wrong part being in the order. Most of the missing or wrong parts are accessories that are collected at the end of the production line. Based on the root cause analysis, the mistakes are a result of the production phase not guiding the operator enough, instead the production phase requires the operator to make multiple production related choices.

To eliminate the mistakes in the packing phase four poka-yoke applications are evaluated. Based on the evaluation a method with opening lids to indicate what to pack is deemed best, but the method did not fit into the existing manufacturing environment. A light-guided system guides the operators to pick the right products based on the product configuration and was evaluated to be the second-best option. A scale system that checks whether the products that have been packed weigh the correct amount but does not guide the operator in making the choices during the picking process. A barcode reading method could help the operator by checking every product as it is being packed, but scanning every product while packing is too slow.

The light-guided system and scale system were piloted in two different production cells. The results were promising, because no mistakes that would lead to defects were made during the pilot. However, the pilot was rather short, and more research is required to prove that the poka-yoke methods applied lead to mistake-free production. What can be said on the results is that poka-yoke methods can be used for decreasing mistakes and mistake-proofing packing mistakes in the case company. Based on the results, the challenge with poka-yoke applications in MTO production is that there are so many different errors that multiple poka-yoke applications are needed to prevent them. This being the case, it could be possible that the defining factor for mistakes is the 'decision-making density', which would mean that the tasks where decision making by the operator is required the most are the most potential tasks for mistakes. More research in different types of production environments are needed to generalize the findings.

Keywords: poka-yoke, make-to-order production, manufacturing mistakes

TIIVISTELMÄ

Johannes Huuskonen: Poka-yoke-menetelmät tilauksesta valmistavassa tuotannossa
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Poka-yoke-menetelmät ovat virhevarmoihin tuotantomenetelmiin tähtääviä työkaluja, joilla varmistetaan, että valmistuksessa ei voida tehdä virhettä tai virhe tunnistetaan mahdollisimman nopeasti sen esiinnyttyä. Poka-yoke-menetelmillä varmistetaan, että asiakkaat eivät vastaanota viallisia tuotteita. Tilauksesta valmistavassa tuotantoympäristössä asiakkaiden vaatimukset voidaan täyttää kustomoitavilla tuoteratkaisuilla, mikä vaatii valmistavalta yritykseltä kykyä toimia monimutkaisissa tuotantoympäristöissä. Poka-yoke-menetelmien sopivuudesta tilauksesta valmistavaan tuotantoon on tehty vain vähän tutkimusta.

Tämän diplomityön tavoitteena on selvittää, minkälaisia virheitä tuotannon työntekijät tekevät tilauksesta valmistavassa tuotantoympäristössä ja miten näitä virheitä voidaan ehkäistä käyttämällä poka-yoke-menetelmiä. Tutkimus toteutetaan kvantitatiivisena toimintatutkimuksena yhteistyössä kohdeyrityksen kanssa, joka valmistaa säälaitteita ja teollisia mittalaitteita. Kohdeyrityksen tuotevalikoima on laaja ja tuotteiden volyymit ovat pieniä.

Tutkimuksen ensisijainen aineisto koostuu kohdeyrityksen asiakasvalituksista vuonna 2019. Toissijaisena aineistona käytetään valmistuksessa käytettäviä työohjeita, tuotteiden tilauslomakkeita ja tuotannon työstandardidokumentteja. Aineiston pohjalta tunnistetaan, mitkä virhetyypit aiheuttavat asiakasvalituksia ja missä valmistuksen vaiheessa virheet esiintyvät. Virheen alkuperän perusteella suunnitellaan, millä poka-yoke-menetelmillä valmistusvirheet voidaan eliminoida kyseisestä vaiheesta kokonaan.

Tutkimuksen tulokset osoittavat, että suurin osa asiakasvalituksista johtuu siitä, että tuotepakkauksesta puuttuu osia tai pakkaus sisältää vääriä osia. Valtaosa puuttuvista ja vääristä osista ovat lisäosia, jotka keräillään valmistuksen viimeisessä vaiheessa. Juurisyyanalyysin perusteella virheet johtuvat siitä, että valmistusprosessi ei ohjaa työntekijöitä tarpeeksi, vaan valmistusprosessi vaatii työntekijöiltä lukuisia valmistukseen liittyviä päätöksiä.

Keräilyvaiheessa syntyvien virheiden eliminoimiseksi arvioidaan neljää erilaista poka-yoke-sovellusta. Arvioinnin perusteella keräilylaatikoiden yhteyteen asennettavat automaattiset luukut olisivat paras ratkaisu keräilyvirheiden eliminoimiseksi, mutta järjestelmä ei sovi kohdeyrityksen tuotantoympäristöön. Valo-ohjausratkaisu ohjaa työntekijöitä keräämään tuotekonfiguraation mukaiset osat valojen avulla ja arvioitiin toiseksi parhaaksi poke-yoke-sovellukseksi. Vaakasovelluksella tarkistetaan jälkikäteen, että oikeat osat on pakattu vertaamalla valmistettua tuotetta standardin mukaiseen massaan. Vaakasovellus auttaa tarkistamaan oikean massan, mutta ei ohjaa työntekijöitä keräämään oikeita osia. Viivakoodinlukijan avulla kerättävät tuotteet voidaan tarkistaa keräilyn yhteydessä lukemalla osien viivakoodit. Sovellus ohjaa työntekijää keräämään oikeat tuotteet, mutta jokaisen osan viivakoodin lukeminen hidastaa tuotteen valmistusprosessia.

Tutkimuksessa testattiin valo-ohjausjärjestelmää ja vaakasovellusta kahdessa eri tuotantosolussa. Tulokset ovat lupaavia, sillä yhtäkään valmistusvirhettä ei esiintynyt kymmenen viikon testijakson aikana. Testijakso oli lyhyt, joten lisätutkimusta tarvitaan varmistamaan, että sovelletut poka-yoke-sovellukset saivat aikaiseksi virheiden eliminoimisen. Tulosten perusteella voidaan kuitenkin osoittaa, että keräilyvirheitä voidaan vähentää poka-yoke-menetelmien avulla kohdeyrityksessä. Tutkimus osoittaa, että poka-yoke menetelmien käyttö tilauksesta valmistavassa tuotannossa on haastavaa, sillä valmistusvirheet ovat moninaisia ja useita ratkaisuja tarvitaan kaikkien virheiden eliminoimiseksi. Vaikuttaa siltä, että työvaiheet, joissa tuotantoon liittyviä päätöksiä tehdään paljon ovat virhealtteimpia, jonka vuoksi näissä työvaiheissa tarvitaan poka-yoke-menetelmiä virheiden estämiseksi. Jatkotutkimusta erilaisissa tuotantoympäristöissä tarvitaan tulosten yleistämiseksi.

Avainsanat: poka-yoke, tilauksesta valmistava tuotanto, valmistusvirheet

PREFACE

This thesis concludes my studies in Tampere University. May it be the last project work that is uploaded to Moodle at midnight.

I want to thank the case company for the possibility to participate in a meaningful project as an active team member. Many people in the company have offered valuable knowledge in different phases of the project. Thank you to Reetta for the guidance during the entire thesis project. Thank you to Miia for the valuable feedback from the academic perspective during the writing process.

I am grateful for Miisa for all the help, support, and company during the months and months of social distancing. Thank you.

Helsinki, 24 November 2020

Johannes Huuskonen

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LIST OF SYMBOLS AND ABBREVIATIONS

ASQ	American Society for Quality
ATO	Assemble-to-order
ETO	Engineer-to-order
MTO	Make-to-order
MTS	Make-to-stock
OCC	Operator Choice Complexity
OQC	Outbound Quality Control
SPC	Statistical Process Control
ZQC	Zero Quality Control

1. INTRODUCTION

1.1 The Background of the Study

It is researched in this thesis how manufacturing processes can be improved so that the number of defected products is decreased. Continuous improvement originates from Japanese word kaizen and its purpose is to involve all employees of the organization in improving functions (Ortiz 2009). Especially improving the quality of products has been important for companies because it can give them a competitive advantage in the markets (Singh 2013). In this context, quality has a customer-oriented focus: the goal of exceeding customer expectations (Sower 2011, p. 6-7). In industrial manufacturing, none of the quality tools have been as ambitious as Zero Quality Control (ZQC) created by Shigeo Shingo in the 1980s. Its foundations lay in the idea that in most manufacturing processes a certain number of defected products are allowed, and zero defects could not be achieved by using the existing quality control tools. According to Shingo, zero defects is possible only if the two key elements of ZQC are used: source inspection and poka-yoke methods. (Shingo 1986)

Poka-yoke is Japanese and means mistake-proofing. Poka-yoke methods are used so that they immediately make mistakes obvious to see or prevent them from occurring at all. In source inspection, the conditions of the process are improved in advance so that defected products cannot be manufactured. (Shingo 1986)

Typical poka-yoke devices are jigs, counters, sensors, and warning devices that ensure that parts are assembled correctly, the right amount of parts are used, and parts move correctly in the process (Shingo 1986). Devices are preferably simple and inexpensive but implementing poka-yoke systems can still be challenging (Pötters et al. 2018). Successful implementation requires that root causes of possible or realized defects are known. In addition, even if a poka-yoke system is able to remove the possibility of defect in one part of the process, it might add a new possibility in other part of the process. (Lee-Mortimer 1991)

Many presented poka-yoke applications in literature seem to be used in an environment where products are manufactured in serial production. In many case studies, a poka-yoke application is used to fix a repetitive task in a processing phase where defects tend to occur (Lazarevich et al. 2019; Shimbun 1987; Shingo 1986). If production environments are divided into four types based on the order penetration point (OPP) (Olhager 2003), it can be noticed that research has focused on make-to-stock (MTS) production environment. The characteristics of make-to-order (MTO) production include products that can be customized according to the customer's needs, which requires flexibility in the manufacturing process (Olhager 2003). This might make it difficult to implement poka-yoke devices in MTO production because manufacturing is likely to include more variation compared to MTS production. So far, research about the suitability of poka-yoke methods in MTO production is very limited. Shingo (1986, p. 137) claimed that poka-yoke methods can be used in high-diversity, low-volume production but the claim lacks evidence for it. In addition, Stewart & Grout (2001) argued that the characteristics of manufacturing mistakes in MTO production environment are optimal for poka-yoke methods since mistakes occur when there are no routine tasks in production. Fast-Berglund et al. (2013) proved that there is a positive correlation between manufacturing complexity and assembly errors. The need for poka-yoke methods in MTO production is evident but the problem is to find the methods that support the production where products are customized.

Garvin (1987) stated that there are eight dimensions in product quality, which are performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. In this thesis, it is researched how poka-yoke methods could be applied in MTO production environment. It includes researching the types of mistakes that are made in production, possibilities of implementing poka-yoke methods in MTO production and the effect of poka-yoke applications on the number of defected products. Therefore, it can be recognized that the dimension of product quality that is tried to be improved in this thesis, is reliability. The thesis is done in cooperation with a case company that manufactures customized products and aims to reduce the number of defected products.

1.2 Case Company

The case company is a manufacturer of environment and industrial measurement devices and it operates around the globe. This thesis is made in cooperation with the function of the company that manufactures instruments. The products are very customizable, and volumes of the products are low.

Currently, the company has a separate quality control team that makes inspections based on sampling. One way the company measures its realized quality is the number of customer complaints that occur when a customer receives a delivery where one or more product is defected. The share of customer complaints in relation to all deliveries was 0.51 % in 2019 and the goal is to reduce it to 0.4 %. To match the target, the company has launched several activities that aim to reduce the number of complaints.

The factory consists of multiple production cells. Each cell has its own selection of products that can only be manufactured there. The manufacturing process is mostly done manually, and the operator begins manufacturing when they receive an order. They need to pay attention to the configuration code that tells which parts are installed in the product. Manufacturing materials are located inside boxes in each production cells and operators pick the materials they need themselves.

1.3 Research Objectives, Questions, and Scope

Customer complaints can be reduced by either detecting defects before they are delivered to the customer or by preventing defects from occurring. The objective is to find effective poka-yoke applications that could reduce the number of customer complaints immediately either by using poka-yoke methods after every manufacturing phase to get immediate feedback or by using source inspection in which case poka-yoke applications are preventive tools that prevents defects from occurring at all. The objective also includes a commercial basis for the case company. Their values include meeting the expectations of their customers, so the quality of their products needs to be constantly improved.

To be able to implement poka-yoke applications, it is necessary to understand the types of mistakes that occur in manufacturing and lead into defects. As it turns out, there is no specific research made about mistakes in MTO production. Therefore, it must be researched what kind of defects occur and what kind of mistakes make them possible. These objectives lead to the following research questions:

1. What kind of mistakes operators make in MTO production?
2. Which poka-yoke methods could prevent operators from making mistakes in MTO production at the case company?

The questions are answered based on literature review, data analysis of the customer complaint data, and poka-yoke pilots. The literature review presents the core idea of poka-yoke and its link to quality control and gives some examples how poka-yoke methods have been used in production. The customer complaint data of selected production cells is analyzed to understand the root causes of the complaints so that different types of mistakes and their occurrence can be found. Pilots are conducted based on the literature and customer complaint data. Based on the indicative results it can be answered how effective poka-yoke applications are in MTO production.

Poka-yoke methods were closely linked to ZQC in Shingo's original work of poka-yoke methods. Shingo argued that ZQC should replace statistical process control (SPC) because ZQC was enough to achieve zero defects. Even though poka-yoke is a generally accepted method in academic research, the role of ZQC as a substitute for SPC has been questioned. Some researchers have showed that ZQC works better as a complementary approach for SPC. (Grout & Downs 1998; Stewart & Grout 2001) In this thesis, the focus is on poka-yoke methods. Even though the elements of ZQC are researched in the thesis, the approach itself is excluded from the thesis. This delimitation means that the role of SPC is not questioned and preventive tools like poka-yoke methods are assumed to be used together with SPC.

1.4 Structure of the Thesis

The thesis consists of six chapters. The second chapter presents the theoretical background for the research. Firstly, the review of quality management in overall is presented. The essential parts of quality management in the thesis include quality assurance and control, defects and errors in manufacturing, and root cause analysis. The chapter includes a review of different types of mistakes and psychology of mistakes. The actual usage of poka-yoke methods, how they are divided, and what kind of defects different methods aim to prevent are presented lastly in the first part. Three inspection methods are generally used in poka-yoke literature so characteristics of those three methods are presented. The second part of the literature chapter presents different production environments based on the customer order decoupling point. The chapter presents the characteristics of MTO production. In the third part the connection between poka-yoke methods and production environment is presented.

Methodology is presented in the third chapter. The philosophy in the thesis is pragmatic. The goal of the thesis is to find practices that improve the manufacturing process. Therefore, to find working solutions is desired. The thesis is an action research that consists of historic data and participating in the process development. It is tested how existing theory about poka-yoke methods works in MTO production environment. The theory is put into practice to test how it works. The research requires quantitative actions since the overall picture is formed from previous data and this data is compared to the data after improvements. Successful implementation requires understanding the needs of different stakeholders, such as operators. In practice, the research consists of three phases: analyzing previous customer complaint, finding root causes for the defects, and finding poka-yoke applications that prevent those defects. In addition, two poka-yoke application pilots are presented. The current situation is represented through statistical analysis. Event data analysis tells where and at which points of the process the customer complaints occur. Root causes are sought by evaluating the customer complaint data and researching the production cells. Process improvements are piloted after the root causes have been identified and they are evaluated based on the possibility of new defects.

Chapter 4 includes the results and is divided into three parts. First, the current situation is presented by evaluating the customer complaint data. The types of defects that occur in different production cells is analyzed. The results of the data analysis lead to believe that there were three major error types and those were selected for further analysis. In the second part, a root cause analysis is completed for the selected errors to understand why and where these defects occurred. The errors were produced mainly in packing operations: in situations where operators are required to make active decisions. in the third subchapter solutions are created to eliminate the packing errors. They are evaluated through a Framework for Assessing Poka-yoke Devices by Saurin et al. (2012). Though the framework proved useful, the researcher is forced to use his own deliberation in selecting the final solutions for piloting. The fourth subchapter is the improvement part where the faulty processes are piloted by using poka-yoke methods. The pilots proved successful, though the observation period was short.

Discussion part is presented in the fifth chapter and it collects the literature and findings from the results together. It is discussed whether the pilot or pilots are suitable for the case company. Based on the pilots the suitability of poka-yoke methods in MTO production is evaluated to be usable, though there is no one solution for each situation. Poka-yoke solutions are most efficient with mistakes that are repeated often. By eliminating a common error type, the quality of the process is elevated. This also frees resources in quality control to focus on errors that are less commonplace. This may create long term improvements in reaching customers' expectations. Recommendations for future improvements in the case company are presented based on this perspective.

Chapter 6 concludes the thesis by evaluating to what extent the objectives of the thesis were achieved. The research concludes that poka-yoke applications are usable in MTO production in the case company and in other similar production environments. As the literature presented, it was found that mistakes are most common where humans have most impact. Solutions for minimizing the impact were discovered. The solutions implemented in the specific production environment are a much-needed addition to poka-yoke related research, as the field is yet very narrow. A process for implementing in a MTO environment is presented. However, as the research is based around one production facility, major findings cannot be validated without further research. Some ideas for further research topics are presented to conclude the study.

2. THEORETICAL BACKGROUND

2.1 Quality Management

Quality can be defined in many ways depending on the context. Feigenbaum (1951) linked quality together with customer satisfaction (see Sower 2011, p. 6). Sower (2011, p. 6) reminded that internal customers need to be acknowledged, too. Garvin (1987) presented the eight dimensions of product quality that included dimensions such as performance, reliability, and aesthetics. Different dimensions are used to define service quality and hospital service quality (Sower 2011, p. 7-8). American Society for Quality (ASQ) defines quality by using two technical dimensions: the ability of the product characteristics to satisfy needs and the ability to be free of deficiencies (Quality Glossary). The second dimension has similar contents as Garvin's dimension of reliability, which both are related to the capability to manufacture products that work properly. This definition is the most relevant in this research.

Quality management can be defined as the totality of functions that are involved in the determination and achievement of quality (ASQ Statistics division 1983, see Sower 2011, p. 20). This chapter presents the concepts of quality management that are relevant in manufacturing environment and in this study.

2.1.1 Quality Assurance and Quality Control

According to ISO-9000 standard, quality assurance is a part of quality management system that aims to provide confidence so that quality requirements will be fulfilled. In comparison, quality control aims to fulfil those quality requirements. (Quality Management Systems 2015) Stevenson (2018) divided approaches of quality assurance into inspections, process control, and continuous improvement, where inspection alone is the least progressive approach and continuous improvement is the most progressive approach. In continuous improvement approach the idea is that it is possible to build quality into the process, which improves the conditions of the process before the actual manufacturing is started. (Stevenson 2018, p. 417-418) The approaches of quality assurance are presented in Figure 1.

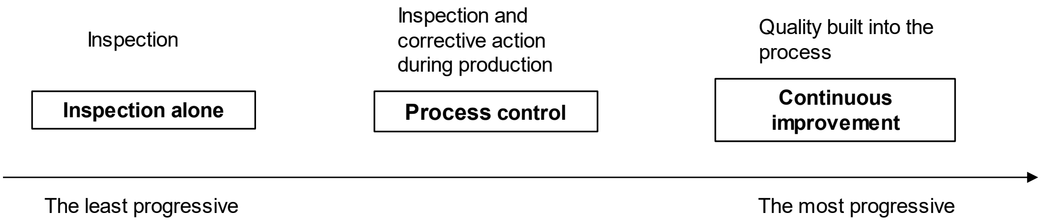

Figure 1. Approaches of Quality Assurance (adapted from Stevenson 2018, p. 418).

The main tasks for quality assurance include:

1. setting up quality goals and monitoring them, and providing information
2. managing quality of products and processes
3. managing quality control of products and processes. (van de Water & de Vries 1992)

Quality assurance is a comprehensive concept of the entire quality system that includes all activities that aim to produce the products with appropriate quality. Traditionally quality assurance has been seen as a costly, product-driven operation that is needed to detect errors. Recently, customers have become the driver of quality assurance and preventing errors entirely has been the target instead of detecting them. (Sower 2011, p. 26)

Quality control is sometimes confused with quality assurance, but quality control has a narrower focus than quality assurance. Quality control aims to eliminate the problems in the actual process. (Sower 2011, p. 20) According to Russell (2005, p. 3), quality control is more like a part of inspections and operational techniques so that the requirements of quality are fulfilled. Stevenson (2018, p. 417) highlights the role of quality control as a process that measures output to a standard and takes corrective actions when needed.

2.1.2 Inspection Methods

Inspection is an important aspect of quality control that ensures that goods match with a standard. In production, inspections can be done before, during, or after production. Inspection that is done in advance ensures that conditions for production are acceptable before the manufacturing process is started. (Stevenson 2018, p. 418) Shingo (1986) divided inspections into three approaches, which fit well to Stevenson’s quality assurance approaches. Shingo (1986) used the terms judgment inspection, informative inspection, and source inspection. Here judgment inspection is the least progressive and source inspection is the most progressive approach.

In judgment inspection, products are inspected in the end of the manufacturing process to check whether they are defected or not. Judgment inspection lacks the feedback loop back to the manufacturing process so improvements cannot be made. Therefore, judgment inspection merely discovers defects, and no actions are made to find any causes for them. Even though judgment inspection has a little value for process improvements, it is much better than no inspection at all. If products were not inspected, defected products would end up to the customer. (Shingo 1986, p. 41)

Informative inspection improves quality control operation by creating the feedback loop between the inspection and the source of the defect (Shingo 1986, p. 66). The loop for informative inspection cycle is illustrated in Figure 2.

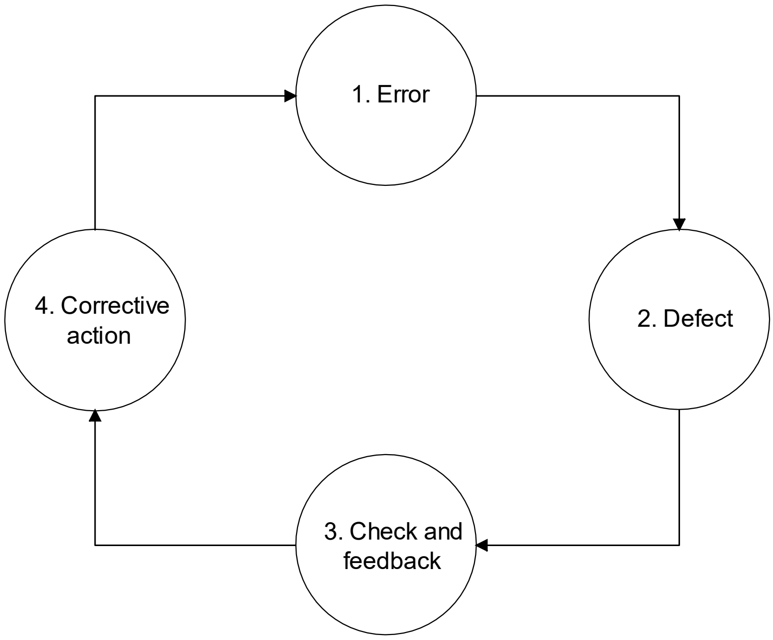

Figure 2. Informative Inspection Loop (adapted from Shingo 1986, p. 53).

The core of the informative inspection method is that once a defected product is detected, feedback is sent to the source of the defect so that corrective actions can be made. This creates an opportunity to improve the process so that defects can be reduced in the future. The arrow between corrective action and error phases illustrates that there is always a new error that needs to be corrected. Shingo (1986) argued that the time from the error to the corrective action should be as short as possible, which led him to improve inspection methods according to this principle. (Shingo 1986, p. 65--81)

Statistical process control (SPC) is an often-used example of informative inspection (Fisher 1999; Shingo 1986; Stewart & Grout 2001; Lazarevic et al. 2019). SPC uses statistically based control charts to reduce future defects, which means that it uses the information gained from occurred defects. SPC systems also use statistics to set control limits to identify abnormal situations from normal situations. When abnormalities occur, the information is sent to the source of abnormalities so that corrective actions can be taken. Usually inspections are made in samples. (Shingo 1986) Shingo tended to use statistical quality control as a synonymous to SPC even though the latter one can also be included to be a part of statistical quality control (Grout & Downs 1998). In this study, SPC is used when discussing of statistics in quality control.

According to Stevenson (2018), SPC is needed because every process includes a certain amount of variation and it needs to be known that the process is in control. Random variation is created by several small factors that alone do not have a significant impact on the process output. It is nonrandom variation that makes the process unstable. Nonrandom variation is usually an effect of an identifiable source like human accuracy or an unreliable machine. Therefore, nonrandom variation needs to be eliminated to achieve a stable process. (Stevenson 2016, p. 423-424)

Shingo (1986) criticizes SPC methods for that charts represent the current state and do not offer any guarantee for future improvements in quality. Another issue is that abnormalities show up randomly, so they might not be found in statistical sampling. Thirdly, it takes time to make corrective actions so new defects are likely to occur. However, Shingo also gives SPC credit for being able to reduce defect rates significantly. (Shingo 1986, p. 66-67)

These arguments were the reasons for Shingo to propose shortening the feedback loop, aiming to inspect 100 percent of the products, and preventing defected products from leaving the manufacturing process. This required new types of checks in manufacturing process: successive checks and self-checks. (Fisher 1999; Shingo 1986)

In successive checks and self-checks, the check is made before the next operating phase is started. Successive check system was developed to inspect 100 percent of the products and shorten the feedback loop. In successive check process the item is checked right after it is received from the previous work phase. If a defect is identified, the item is returned before it is processed further, which makes it possible to make immediate corrective actions to the item. (Shingo 1986, p. 67-81)

To get even faster feedback when defects occur, self-check systems are used. A self-check operation of three phases is presented in Figure 3.

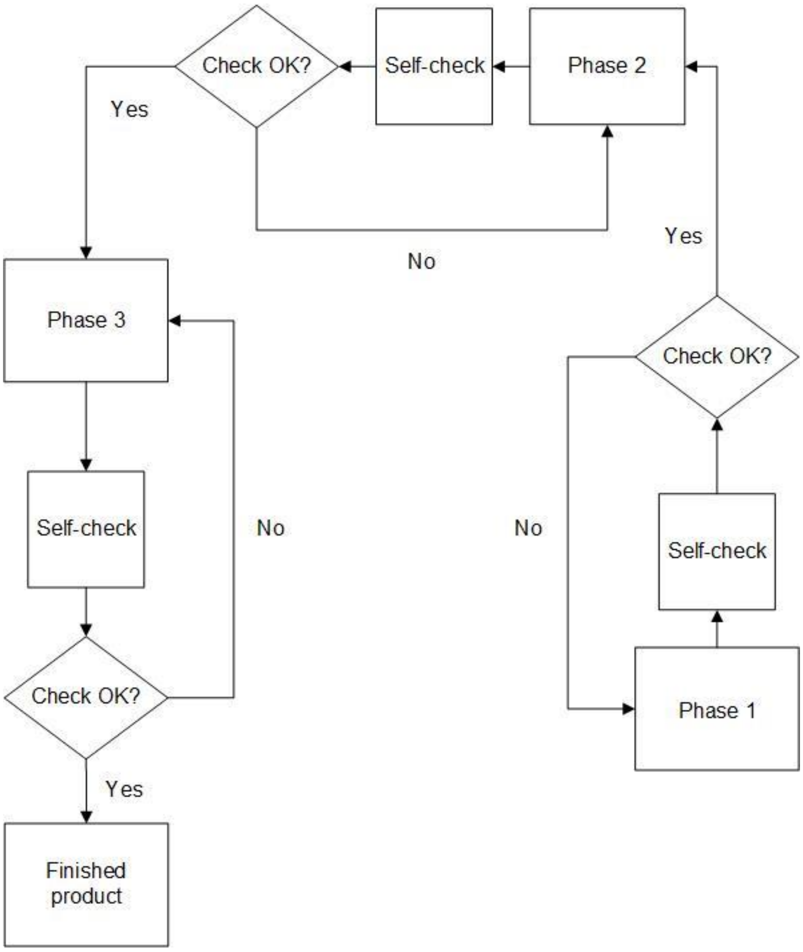

Figure 3. An Example of a Self-Check Process (adapted from Shingo 1986, p. 47).

Figure 3 illustrates self-checks in a three-phase manufacturing operation. After a phase is finished, a check is made before the product can move to the next phase. If corrective actions are needed, rework is done at the same phase. This way, the errors should not be able to leave the process and become defects. (Shingo 1986, p. 47)

The third inspection method is called source inspection. In source inspection, the conditions of the process are planned so that defects will not occur. Source inspection aims to improve process so that defected products cannot be manufactured. If excessive variation or damaged parts occur, the process cannot be started at all. Instead of discovering errors in products, source inspection aims to discover errors in the manufacturing process. (Shingo 1986, p. 82)

2.1.3 Problem Solving in Manufacturing

Problem solving is a critical part of continuous improvement process for successful companies to improve incrementally. There are several problem-solving tools that can be used in production environment. The plan-do-check-act (PDCA) and define-measure-analyze-improve-control (DMAIC) cycles can be applied in continuous improvement processes to solve problems. Both cycles have similar goals to recognize development targets, implement new improvements in processes, ensure that the improvements work, and start the cycle again to achieve continuous improvement. (Sower 2011, p. 87-88, 180-195) The PDCA cycle is presented in Figure 4.

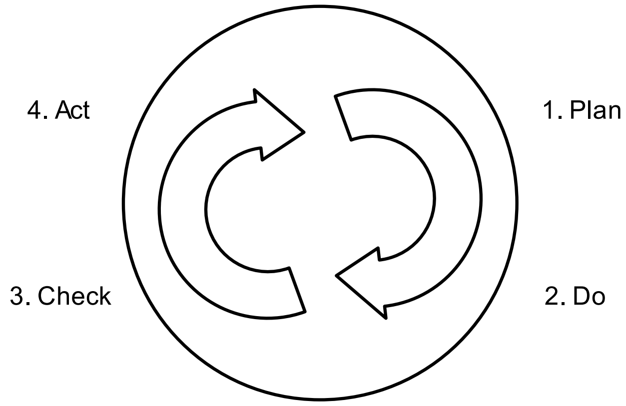

Figure 4. Plan-Do-Check-Act Cycle (adapted from Sower 2011, p. 194).

In the PDCA cycle, the plan phase is for determining the improvements that are wanted in the process. In the second phase, ideas are implemented as pilots. In the check phase, the pilot is analyzed to get an understanding of what kind of effect the pilot had on the process. In the act phase, the pilot is implemented if the results were favorable and the process was improved. The cycle starts again from the plan phase to address the idea that processes are improved continuously. (Sower 2011, p. 194)

Recognizing and solving the right problems in production is challenging because the actual problems are rarely easily visible. Symptoms are often thought to be the actual problems, which can lead to solving the wrong problem. Sower (2011) gives an example of high rates of scrap and rework in production, which are not the problems but symptoms of the actual problem. The reason to have high rates of scrap may happen because a machine is defected, wrong tools are used, or employee is trained badly. These three alternatives are the potential problems or root causes of the process. (Sower 2011, p. 179) A systematic problem-solving process is required to find the actual problem so that they are recognized and solved.

According to Sower (2011) there are three types of errors that occur in problem solving:

1. solving a problem that does not exist
2. failing to recognize that a problem exists
3. solving the wrong problem. (Sower 2011, p. 180)

Several different tools are used to solve more complex problems in a production environment because the problem-solving tools presented earlier are too high-level tools in many situations. These problem-solving situations are often called root cause analyses. Common root cause analysis tools include 5 whys method, where why is asked until the actual problem has been found and 8 disciplines model created by Ford Motor company, which aims to identify and eliminate existing problems through eight discipline process. (Okes 2009, p. 3-9) Cause and effect diagram is used to find potential causes for an effect (Sower 2011, p. 191-192).

Okes (2009) thought that the common problem-solving tools should be improved to solve more complex problems and created a ten-step model for root cause analysis. Okes (2009) created a 10-step model that has two phases: the diagnostic phase and the solution phase. (Okes 2009, p. 3, 8-9) The model is presented in Figure 5.

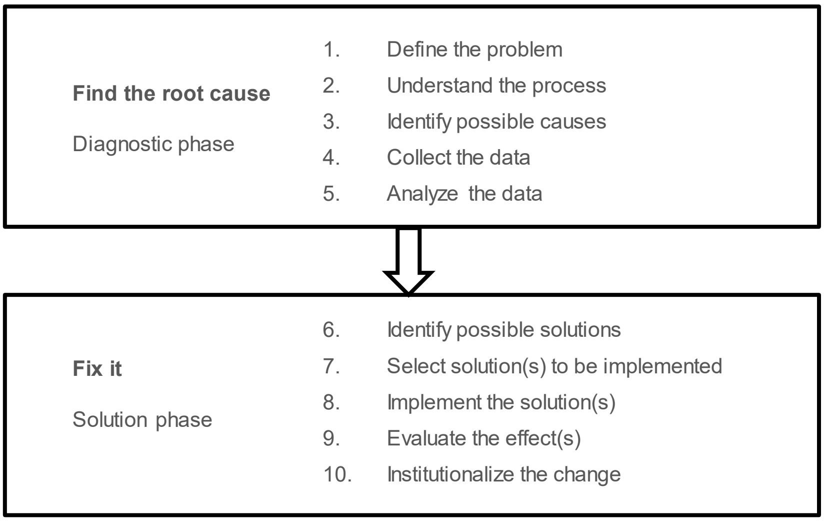

Figure 5. A Model for Root Cause Analysis (adapted from Okes 2009, p. 8).

According to Okes (2009), the steps 1-7 can be included in the plan phase of PDCA cycle. Implementation is the eighth step and is similar to do phase. Similarly, the ninth step is for the same purpose as the check phase, and the tenth step matches with the act phase of the PDCA cycle. However, the do it model offers a more systematic way to recognize the root cause, which is required in complex environments. The model is suitable for customer complaints, product failures, and process failures so it can be used when manufacturing processes are improved. (Okes 2009, p. 8-9)

Okes (2009) points out that all the problems should not be faced with the same amount of attention but the impact of the problems on quality should be noted. The principle where the problem with the highest frequency is fixed first is called Pareto principle. (Okes 2009, p. 17) In problem solving, pareto diagram sorts the data of abnormalities from highest to lowest. By applying the pareto diagram, it is possible to show the occurrences with the biggest impact in a clear way so that attention can be addressed to the most important symptoms or problems. (Sower 2011, p. 189-190)

One potential conflict between Sower's and Okes's literature is the usage of definitions problem, cause, and symptoms. Sower uses the word problem to illustrate the cause and the word symptom to describe the effect of the problem. The first step of the Okes's model is to define the problem and the third step is to identify possible causes. It seems that Okes's definition of problem equals with Sower's definition of symptom and Okes's definition of cause equals with Sower's definition of problem. In this study, the definitions used by Sower are used, so the word problem is used to describe the cause. Therefore, the first step of Okes's model should be 'define the symptom(s)' and the third step should be 'identify possible problems'.

2.2 Mistakes, Defects, and Errors

Shingo (1986) made it clear that mistakes are something that humans make, and defect does not occur until a mistake is made. A cause-and-effect relationship between human errors and defects was highlighted in his work. (Shingo, 1986) This point of view has been accepted later in several research studies (Hinckley & Barkan 1996).

Hinckley & Barkan (1996) defined that mistake is "… (1) the execution of a prohibited action, or (2) the failure to perform a required action, or (3) the misinterpretation of information essential for the correct execution of an action." Mistakes are rare but the number of different types of mistakes is so large that they have a large impact on defect rates in production. (Hinckley & Barkan, 1996)

According to Shimbun (1987), all defects are caused by human errors. He classified 10 types of human mistakes in manufacturing and safeguards that could prevent those errors. Mistake types such as forgetfulness, errors in identification, and misunderstandings were recognized. He also defined 10 most important sources of defects in manufacturing (Shimbun, 1987). They are presented in Table 1.

Table 1. Sources of Defects (Shimbun 1987, p. 14).

Error types
Omitted processing
Errors setting up workpieces
Missing parts
Wrong parts
Processing wrong workpiece
Misoperation
Adjustment error
Improper equipment setup
Improper tools and jigs

Human errors and sources of defects are closely linked to each other. According to Shimbun (1987, p. 14), there is always a causality between defect and human error. None of the defect types can be connected to a human error without further investigation because most defects can be a consequence of several different human errors. Therefore, root causes for defects need to be done.

According to Stewart & Grout (2001), repetitive actions become routines overtime and mistakes are common in situations where routine action activities are triggered in false situations. In manufacturing, an example could be making similar products in a repetitive manner. A slightly different product might trigger the routine action activity, which would lead into mistake in manufacturing. (Stewart & Grout, 2001)

Fast-Berglund et al. (2013) recognized in their case study that the number of errors in manufacturing increases when the products become more complex. It was recognized that the most common error types in automotive industry included forgetting to connect and tighten parts, fitting parts incorrectly, and missing parts. In their research, these error types covered almost 80 percent of all errors. They suggested that mistake-proofing methods should be used so that decision-making could be done automatically. (Fast-Berglund et al., 2013)

2.3 Poka-Yoke

Poka-yoke systems existed already in the 1960s, but they did not get much attention until in the 1980s when Shigeo Shingo introduced Zero Quality Control (ZQC) as a substitute for SPC in his book called Zero Quality Control: Source Inspection and the Poka-yoke System. Poka-yoke has been generally accepted concept, but it did not become widely popular among academic researchers in the 20th century. Stewart & Grout (2001) found two reasons for this. The first reason is that poka-yoke cannot be researched the same way as the other quality approaches are researched. In general, operations activities can be researched by using quantitative methodologies whereas poka-yoke research has a need for human psychology, too. Poka-yoke has not been interesting topic for those who would have the ability to understand poka-yoke, so the topic has been left uncovered. (Stewart & Grout, 2001)

According to Stewart and Grout (2001), the second reason for the lack of academic research is the set-up where ZQC and SPC approaches are considered as competitors. Shingo (1986) argued that SPC is only able to reduce defects, while ZQC is able to remove them entirely and making SPC unnecessary (Shingo 1986). However, academic researchers have preferred approaches with variation and statistics. It remained unnoticed that SPC and ZQC have strengths that complement each other. Therefore, ZQC should be seen as a complementary approach instead of a substitute for SPC. (Stewart & Grout 2001)

In a more recent literature study, Lazarevic et al. (2019) found a steady increase of articles, books, and conference papers on poka-yoke. The number of publications peaked in 2017 with 16 publications. (Lazarevic et al. 2019) Vinod et al. (2015) thought that more research on poka-yoke especially in real time situations is still needed.

2.3.1 Definition of Poka-Yoke

Multiple definitions for poka-yoke can be found in the literature. While many of them are similar to each other, some inconsistencies exist. Some researchers think that definitions are too broad, and a more precise definition is needed. Shingo (1986) defined poka-yoke as a mechanism that detects errors and defects by inspecting 100 percent of the products and giving immediate feedback. Saurin et al. (2012) gathered multiple definitions and concluded them in in the following definition: "... a poka-yoke is defined as a device that either prevents or detects abnormalities, which might be detrimental either to product quality or to employees' H&S [health and safety]." Lazarevich et al. (2019) called poka-yoke a control system that prevents defected products ending up with the customer either in a passive or active way.

The word poka-yoke is Japanese and means mistake-proofing. Human mistakes are unavoidable so production systems must be designed so that defected products are not delivered to the customer. Poka-yoke devices are tools that eliminate the effect of human error. Poka-yoke devices do this by shutting down the system when defect is about to occur or make defect obvious to identify after they have been made. The two main benefits that poka-yoke devices offer are immediate feedback and 100 percent inspection.

Immediate feedback makes it possible to make corrective right after the error has occurred. The benefit of 100 percent inspection is that defected products will not end up to the customer. (Shingo 1986) These benefits make it possible to apply poka-yoke applications in self-checks, successive checks, and source inspections.

2.3.2 Poka-Yoke Functions

Shingo (1986) divided poka-yoke applications into three functions: shutdown, control, and warning. All the three functions can be used in predictive and detective applications (Shimbun, 1987). In the shutdown function, the operation is stopped when a defect is predicted or detected. Warning applications use e.g. buzzers or lights to signal that operator's attention is required. Because human action is needed in these situations, a warning is not often the most reliable poka-yoke method. (Shingo 1986) Control functions are usually the most effective poka-yoke applications because predictive control methods are even able to prevent intentional errors. In detective poka-yoke applications, control method prevents the product from moving to the next phase in the manufacturing process if an error is detected. (Bayers 1994; Shimbun 1987)

Shingo (1986) also used a term setting function to describe the way how poka-yoke applications work. Contact methods take advantage of shapes and dimensions that ensure that parts are assembled correctly. Fixed-value methods rely on numbers. Systems that ensure that a certain number of parts are collected and a counter that ensures that the right number of products are packed are such examples. Motion-step methods are used to detect errors in motions. (Shingo, 1986; Shimbun, 1987)

Lazarevich et al. (2019) used the terms passive and active poke-yoke devices to describe the way they work. An example of a passive poka-yoke application was mentioned where wires were color coded to visualize operators to install the right wires together. If wrong wires were attached, colors would make it obvious for the operator that the attachment was not done right. In an active poke-yoke application, the wires could take advantage of shapes so that the wires could only be attached in one way. (Lazarevich et al. 2019)

According to Fisher (1999), poka-yoke devices are ideally rather simple and mentioned visual indicators that show replenishment levels and mechanical devices that prevent incorrect assembly as such examples. According to Bayers (1994), useful poka-yoke methods take advantage of weight, shape, dimension, or other measurable factors.

2.3.3 Poka-Yoke Applications in Literature

Both Shingo (1986) and Shimbun (1987) presented over a hundred of different poka-yoke applications in manufacturing environment. Applications with different inspection methods and poka-yoke functions were presented. (Shingo 1986; Shimbun 1987) Vinod et al. (2015) described the number of real-time examples of poke-yoke applications as dismal. However, Lazarevich et al. (2019) were able to introduce a variety of poka-yoke applications in their comprehensive literature review that have been implemented over-time. Case studies were made in manufacturing, construction, automotive, software, and service industries. In addition, poka-yoke methods have been used in healthcare and to help individuals with disabilities. (Lazarevich et al. 2019)

Many poka-yoke applications in manufacturing that Lazarevich et al. (2019) introduced, solved a problem, where parts were put to a wrong position, which would lead to a wrong assembly or drilling. Solutions included sensors to detect holes, jigs to ensure the right assembly, and pallets that ensure the right positioning. Several examples in the automotive industry were introduced, where automated tools helped operators to do tasks correctly. Sensors and cameras were used to detect parts and ensure the quality of the painting process. To prevent the usage of wrong parts, the lids of the part containers were opened and closed automatically so that the operator was not able to use wrong parts. Scanning barcodes were used in manufacturing and healthcare to ensure that parts and medicines are used in the right place. (Lazarevich et al. 2019)

Fast-Berglund et al. (2013) researched how poka-yoke applications could be applied in a complex manufacturing environment. Their results indicated that automated solutions support the manufacturing process the best way. A light system that helps the operators to use the right parts was given as an example of a successful poka-yoke application that was able to decrease human errors and defects. (Fast-Berglund et al. 2013)

Saurin et al. (2012) created an evaluation system for poka-yoke applications so that the best poka-yoke applications can be choose. Eight different attributes are used, and each attribute is scored from 0 to 4 points. (Saurin et al. 2012) The attributes are presented in Table 2.

Table 2. Attributes for Poka-Yoke Implementation Evaluation (adapted from Saurin et al. 2012).

	0 points	1 point	2 points	3 points	4 points
Poka-yoke function	No warning or control function	Warning function with low visibility	Warning function	Control function	Control and visible warning
Inspection method	No inspection	Judgment inspection	Successive check	Self-check	Source inspection
Inspection rate	Poka-yoke does not inspect		Poka-yoke inspects less than 100%		100% poka-yoke inspection
Operator action required to start the poka-yoke device	Two or more actions from the operator required		One action from the operator required		Does not require additional actions by the operator
Possibility of new errors	Creates opportunities for new errors		Creates opportunities for minor errors		Does not create opportunities for new unintentional errors
Health & safety	Creates major risks to the operator's health and safety		Creates minor risks to the operator's health and safety		Does not create any health and safety risks
Long-term maintenance plan	No maintenance plan		Even if both calibration and replacement is required, only one of the activities is performed		Poka-yoke device is calibrated or replaced regularly
Short-term maintenance plan	No systematic test plan		It is not specified how often the tests are carried out		Poka-yoke device is tested at the beginning of every shift

The score system measures how effective a potential poka-yoke system is by evaluating several attributes like the poka-yoke function, inspection methods, error-proofing abilities, and health and safety. The score system supports the company when new poke-yoke applications are designed. (Saurin et al. 2012)

2.4 Production Environments

Production environments can be classified based on the point where products are tied to specific customer orders. The point is referred as a customer order decoupling point or order penetration point. (Olhager 2010) Customer order decoupling point influences order fulfilment time, which can give a competitive advantage to the company (Stevenson 2018, p. 673). Based on customer order decoupling point, four generally used production environments are used: make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), and engineer-to-order (ETO). Production environments and their customer order decoupling points are presented in Figure 6. (Jacobs et al 2018).

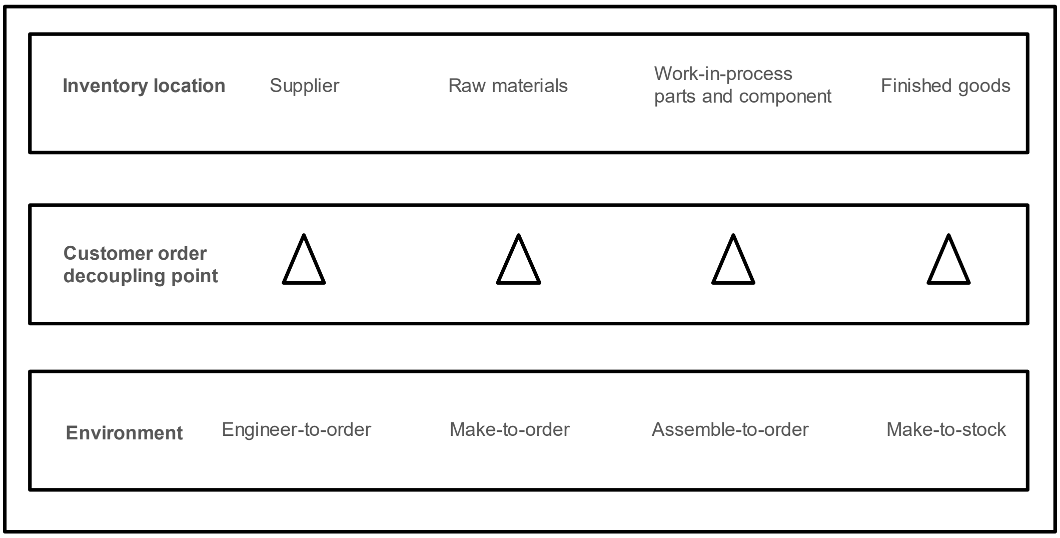

Figure 6. Production Environments Based on Customer Order Decoupling Point (adapted from Jacobs et al. 2018).

As can be seen in Figure 6, the customer order decoupling point defines the point where inventory is held. In MTO production, the inventory consists of raw materials whereas companies that manufacture products to stock, have inventories filled with finished goods. Companies do not necessarily manufacture all the products in the same production environment, but it is common to use a combination of different environments. (Jacobs et al. 2018)

Decisions related to production environments are strategically important. Production environment has a big impact on the capability of the company to customize its products and have a wide product range. Production environment also defines where production is forecast-driven and where it is customer order-driven. (Olhager 2003) It can be seen in Figure 6 that production is forecast-driven on the left side of the customer order decoupling point and customer order-driven on the right side of it.

2.4.1 Make-to-Order Production

MTO production is a customer order-driven production approach so its inventory consists of raw materials. This makes it possible that customers can make product specifications related decisions. MTO production makes it possible to customize products and offer wider product range than MTS production-based companies. The level of customization is the defining factor when it is decided, which production environment is the most suitable. According to Olhager (2010), companies with low-volume and customized products are generally expected to use MTO strategy but ATO production might be suitable for smaller level of customization.

Flexibility is anticipated in a customer order-driven operation. Flexibility in manufacturing includes capabilities to cope with changes in level of demand, launch new products, and adjust volumes of customer orders (Slack & Lewis 2017). Other critical factors include on-time deliveries and lead times. In manufacturing, the focus is on processes because they need to adapt to different products. (Olhager, 2010) Variety of products increases the complexity of the manufacturing process. At the operational level, complexity can be detected by the increased complexity of choices that needs to be done by operators. (Fast-Berglund et al. 2013)

Fast-Berglund et al. (2013) measure the complexity of a production environment by a factor of Operator Choice Complexity (OCC). OCC is calculated by setting a level of difficulty for each choice and adding them up to create a weighted sum. The hypothesis was tested in a vehicle factory in Sweden that was identified to be a mixed-model assembly line. The production environment contained a high number of variants and parts, so finding the riskiest phase was important. It is suggested in the study that higher complexity can be combated with usage of cognitive automation to ensure higher performance of human operators. (Fast-Berglund et al. 2013)

2.4.2 Mass Customization

One challenge that manufacturing companies meet is the ability to keep manufacturing costs low while offering a certain amount of variety in their selection at the same time. Standardization is important for manufacturing companies because high volumes can be produced, which again lowers manufacturing costs. Customization serves customers because they want variety, but they also want low-cost products. According to Stevenson (2018), the challenge for manufacturers that want mass customization is to keep the benefits of standardization and avoid problems that tend to follow variety. For some companies, the solution is mass customization. It can be defined as a strategy, where somewhat standardized products have a certain degree of customization. Delayed differentiation and modular design are examples of mass customization tactics. (Stevenson 2018 p. 154-155).

In the delayed differentiation tactic, products are not fully completed until customer needs and specifications are known. The customization is done in the end of the manufacturing process. The tactic makes it possible to manufacture work-in-progress product units to inventory and finish them after customer orders are received. Therefore, manufacturing process can be mostly standardized. Ideally, to achieve variety and short delivery times, customizable features can be produced quickly. (Stevenson, 2018 p. 154-155)

In modular design tactic, modules are grouped from component parts so that variety can be accomplished easily. Modularity makes it possible for customers to customize their products but also changing defective parts is easier. According to Stevenson, another benefit modular design tactic has is the simplicity of manufacturing that follows from modularity. Simple manufacturing and assembly make production more routine and standardized, which again lowers the production costs. Disadvantages of modular design include lower number of possible configurations and possible challenge of replacing a faulty part in a module. (Stevenson 2018, p. 154-155)

2.5 Synthesis

2.5.1 Inspections in Make-to-Order Production

All products should be inspected to be certain that defected products will not end up to the customers. Traditionally inspections have been considered as a job of a certain quality control unit that in many cases only inspects a selected sample of finished products. The method is not a guarantee of a defect-free production system and it should be improved. (Shingo 1986)

Production environment partly determines how products are inspected in manufacturing processes. The defining factor is likely to be the production volume of the factory, which is often closely linked to production environment: more product units normally lead to a fewer share of products that are inspected. Similarly, a smaller production volume makes it possible to inspect a bigger share of finished products. However, as Shingo (1986) declared, inspecting finished products does not improve quality nor guarantee defect-free products if every product is not inspected. Therefore, source inspections should be applied.

In MTO production, products are often customizable, in which case there is variation in the manufacturing process. This might make it difficult to apply source inspection methods. As Grout & Hinckley (2001) mentioned, the biggest risk for mistakes is at the work phases where non-routine tasks are done. If that is the case, those work phases should be the phases where products are inspected. Shingo (1986) suggests that a self-check or successive check should be made after a work phase and that the check should focus on a couple of potential mistakes at the work phase. These two views fit well into together and give a good perspective how inspections could be done in MTO production.

Using self-checks and successive checks does not mean that quality control teams would be replaced. As it was mentioned earlier, Shingo's idea of ZQC as a substitute for traditional quality control approaches can be questioned. Hinckley & Barkan (1996) proved that 100 percent inspection combined with SPC reduces defects in a more effective way than one of those quality tools alone would reduce them.

2.5.2 Poka-Yoke Applications in Make-to-Order Production

Grout & Hinckley (2001) argued that poka-yoke applications are most desirable in environments where a set of mixed products is manufactured. Applications should be used in manufacturing phases where products start to differ from each other to ensure that human errors are not made. Also, beginnings of processes where multiple different processes could be started and locations where configured parts are used were mentioned as promising poka-yoke application locations.

The argument for poka-yoke applications in mixed-product manufacturing seems valid. Grout & Hinckley (2001) recognized that mistakes are made when work is unusual from routine tasks. This is common in mixed-product manufacturing and applies to MTO production as well. Shingo (1986) also mentioned that poka-yoke applications are effective in high-mix low-volume production, which also applies to MTO production.

The challenge is to create poka-yoke applications that support manufacturing in a more complex production environment. A repetitive task is likely to be easy to mistake-proof because it is always done in a similar way. However, when customized products are manufactured, the task depends on the product or a configuration of the product. To work properly, the poka-yoke application should take into account which version of the product is manufactured. In these scenarios, it is likely that physical jigs and other mechanical tools that ensure the right assembly will not work.

Fast-Berglund et al. (2013) recommended to use cognitive automation in a complex production environment so that human operators would not need to make decisions by themselves. This can be combined with the idea of routine tasks presented by Hinckley & Grout (2001): if production environment is complex, there are not that many routine tasks, which again causes errors and defected products. They found out that a control system controlled by lights was helpful for operators. The light system guided the operators to choose the right parts. Another example of cognitive automation was to use screw drivers that helped operators to attach the parts in a right way. According to Fast-Berglund et al. (2013) the results indicate that automatic solutions should be used as poka-yoke applications in a complex production environment. (Fast-Berglund, 2013)

3. METHODOLOGY

3.1 Research Design

The thesis has two goals. As the first goal is to find poka-yoke methods that can be used to improve product quality in manufacturing. This goal benefits the financer of the thesis but also provides new knowledge for academic audience. More academic relevance is gained by researching the quality issues that exist in MTO production environment. Therefore, the latter information is valuable to answer the first research question, but it is also valuable as its own.

The two research questions require different methodological decisions. The research onion used by Saunders et al. (2016) can be used to present a comprehensive design for the study. The research onion includes several choices that affect the study: philosophy, research approach, methodological choices, strategy, time horizon, and data collection. (Saunders et al. 2016) The methodological choices are presented in Table 3.

Table 3. Methodological Decisions Made in the Study.

Philosophy	Pragmatism
Approach to theory development	Deductive
Methodological choice	Quantitative research
Strategy	Action research
Time horizon	Longitudinal
Data collection	Customer complaint data, work standards, work instructions

The philosophical worldview chosen in this thesis is pragmatism. According to Saunders (2016), pragmatism focuses on problems and solving them. Practical solutions are often desired, and researcher’s views influence the results. (Saunders 2016, p. 145-151) Pragmatism allows to apply qualitative, quantitative, and mixed methods research approaches. In the pragmatic worldview, it is sought what works right now. (Creswell 2011, p. 42) In the context of this study, the thesis aims to improve processes of the case company and find solutions that work.

Deductive approach generalizes from general to the specific whereas inductive approach generalizes from the specific to the general. In the deductive approach, data is used to evaluate propositions related to an existing theory, and on the contrary in the inductive approach data is used to identify themes and to create a conceptual framework. This way, theory is either proven wrong or right in deductive approach whereas theory is generated and built in inductive approach. (Saunders et al. 2000, p. 84-88)

Both approaches were evaluated, but the deductive approach is used to answer both research questions. To answer the first question, what kind of defects occur in MTO production needs to be understood. In the study, the defects are analyzed to get an understanding of mistakes in a specific production environment. This data is compared to existing mistake categorizations.

To answer the second research question, a literature review is conducted to better understand poka-yoke methods that are general quality tools that are tested in a specific production environment. This way it can be evaluated, how poka-yoke methods can be applied in MTO production environment. This creates a more detailed model for poka-yoke methods in certain production environment. This is important because poka-yoke research has mainly focused on manufacturing in general and service business.

Quantitative research method is used in this study. Quantitative research includes numerical data or data that can be quantified to answer research questions. Quantitative data is based on meanings that are derived from numbers, its results are collected in numerical and standardized data, and it is analyzed through the use of diagrams and statistics. Quantitative research is a suitable method to find out the significance of different problem types in production. In practice, the more common the mistake type is, more important it is to prevent it from occurring. Suitability of solutions can be measured in a quantitative way by comparing data before and after improvements. (Saunders et al. 2000, p. 326-327)

The study is action research. Three characteristics are common in action research: their purpose is to manage a change, involvement of practitioners, and set-up where researcher is a part of the research organization. The results from an action research should not only benefit the organization but results should inform other contexts as well. (Saunders et al. 2000, p. 95)

The time horizon in this thesis is longitudinal, which means that the study is a representation of events over a certain time period. Longitudinal study studies change and development, and typically its research questions are related to change over time. (Saunders et al. 2000, p. 96) In this case, the time period is located at the situation before the improvements and after them. The customer complaint data of 2019 is the starting point of the study and this data is compared to the data after improvements in the fall of 2020.

The primary data of this research is the customer complaint data of eight production cells purposely chosen by the case company. The seven production cells that had most complaints in 2019 and one production cell that had a ramp-up in September 2019 were chosen. The population size of the sample is 80 customer complaints. The problem types are recognized to get an understanding of the issues in production.

3.2 Research Environment

The case company manufactures instrument and weather measurement devices. The research focuses on the instrument factory of the case company. The instrument factory consists of 37 production cells, which of eight are researched in this study. Manufacturing processes of the products are standardized in most cases. Work standard illustrates the flow of the product from the first work phase to the end. Separate work phases are done in separate workstations, so the work standards also illustrate the actual geometry of the production cells. An example of a work standard is presented in Figure 7.

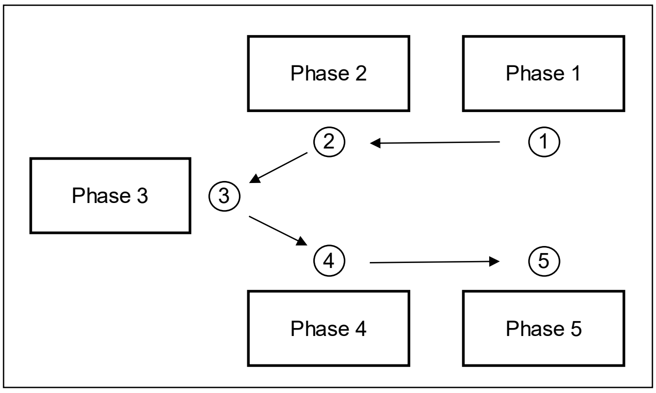

Figure 7. Illustrative Layout of a Production Cell at the Case Company.

Figure 7 represents the ideal flow of goods in the case company. Every phase of the manufacturing process is done in a separate workstation in a U-shaped production cell. Manufacturing process starts at the phase 1, where operator reviews the work queue and releases a job. After the job is released, the operator makes the product that is ordered. Common work phases include assembly, calibration, soldering and packing which are done in most production cells. Computer software tells, which parts are included in the configuration of the product and work instructions can also be used to make the product correctly. Ideally the process follows one-piece flow so that no more than one product is manufactured at the same time. In many cases, one-piece-flow is not possible to follow. Some work phases, such as calibration, are more time consuming than other work phases. In addition, usually more than one product unit is calibrated at the same time, so multiple products must be manufactured for one calibration. In these cases, one-piece-flow is followed before and after calibration, in which case two operators can operate at the production cell at the same time. Otherwise, only one operator works at the cell.

The outbound quality control team controls the quality inspections of finished products at the factory. Outbound quality control team performs visual and check list-based inspections of material samples, tests functionality of products, and gives feedback to manufacturing team. Inspections made by outbound quality control team are based on sampling, which depends on the defect rate of the product, customer, and product.

3.3 Data Collection and Analysis

The material used in this research include the customer complaint data of the case company in 2019, work instructions of the products, work standard sheets of the production cells, and order forms of the products. Additional information is gathered from the intranet of the case company. The data used in this research is presented in Table 4.

Table 4. Research Data.

Primary data	Customer complaint data
Secondary data	Work instructions
	Work standard sheets
	Product order forms

The customer complaint data is the primary data that is used to quantify the research. Other data is used to achieve better understanding of the defects and to find corrective actions to them.

3.3.1 Primary and Secondary Data Sources

The primary data consists of customer complaints of the products that are manufactured in eight production cells in 2019. The eight production cells were selected by the case company. Each customer complaint has its own document that tells, which product was defected and what was wrong with the product. In addition, documents may include information of the corrective actions and additional notes from the personnel at the case company. The production cells included in the thesis and the number of customer complaints in them are presented in Table 5.

Table 5. Customer Complaints in Each Production Cell.

Production cell	Number of customer complaints in 2019
Production Cell 1	9
Production Cell 2	10
Production Cell 3	11
Production Cell 4	17
Production Cell 5	11
Production Cell 6	11
Production Cell 7	3
Accessory Team	8
Combined	80

Seven of the eight production cells had the largest number of customer complaints at the factory in 2019. The eighth production cell is Production Cell 7, which had significantly less customer complaints. However, the ramp-up of the cell was not until in September of 2019 so it is not comparable with the other production cells.

The customer complaint data is analyzed to recognize the problem types that occur in production. Each complaint is categorized into one of the error types that were presented in Table 1.

The customer complaints are categorized into same error types as Shimbun (1987) categorized them and were presented in Table 1. The categorization method was selected for its clarity and universality. In addition, with the error types in Table 1, certificate issue is added as a new problem type. The addition is made because the certificate issue problem type is difficult to link with other alternatives and the issue would distort the results in missing part and wrong parts categories.

The secondary data consists of work instructions, work standard sheets and product order forms. Work instructions describe the manufacturing processes step by step and include all the alternatives for different configurations. Work standards describe the process flows and the steps that are included into manufacturing processes of the products. Customers use order forms to customize the products. Depending on the product, order forms include decisions such as displays, signal outputs, measuring settings, cables, and other accessories. These decisions form a code that is used in the manufacturing process to make the right product.

Root causes of some defects have already been analyzed by the case company and that information is also used in this research. Defining root causes afterwards requires combining all the primary and secondary data. Mistakes are located to the production cell by using the information included in the work standard and work instructions and defected product is compared to its order form.

The results include a pareto diagram of the problem types in production for the 80 customer complaints. In addition, data of error types in each production cell and the number of customer complaints by product and location of the production cells are gathered so that the second research question can be answered.

3.3.2 Data Analysis

Data was analyzed from the most common error types. Secondary data is needed to recognize the root causes for defects and locate the origin of them. The customer complaint data includes important information, but it is not linked to the manufacturing process in a clear way. After collecting all relevant data, the errors are categorized and re-categorized according to different criteria in order to find similarities. The process included groupings where all errors resulted from a similar first mistake, a root cause. However, the process was complete only when that root cause was split into groups where the errors would have the same fix. A theoretical model for the process is presented in Figure 8.

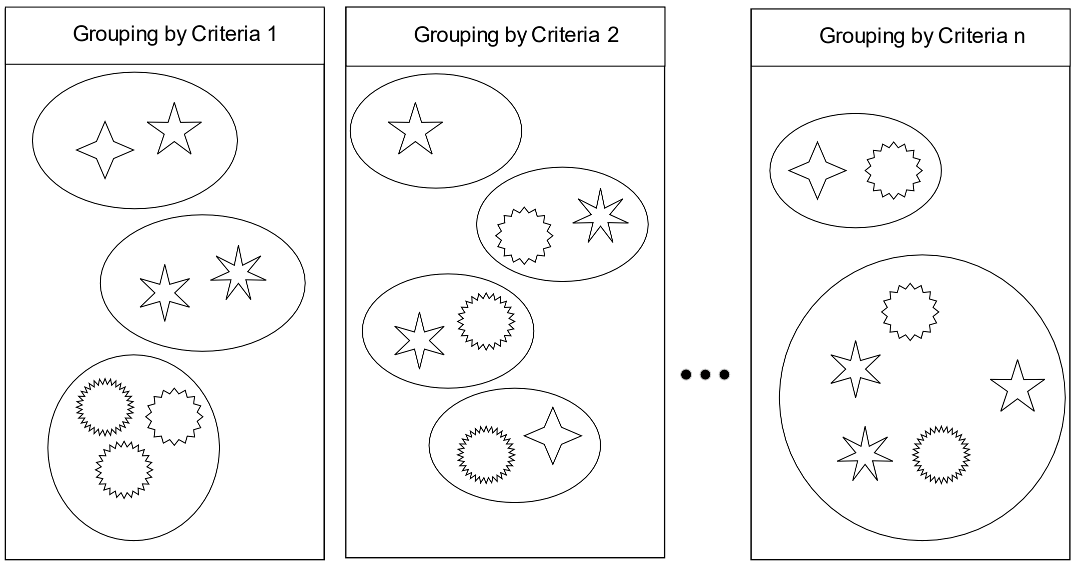

Figure 8. Theoretical model for error grouping.

The grouping that was found satisfactory included errors located in similar locations and for similar reasons in the manufacturing process. These similarities led to innovating solutions to fix errors from several error types simultaneously. It was discovered that location was the most important criteria, however some error types had to be excluded to create a large enough group with the same fix. After the root cause was found, brainstorming sessions were conducted with the engineers in charge of the process to find suitable poka-yoke methods, self-checks and successive check possibilities. It was necessary to ensure the corrective action would either prevent the defect before it happens (source inspection) or the defect is identified as close to the mistake as possible so that it would be corrected immediately (self-check).

3.3.3 Corrective Actions

If the root cause can be defined after the research previously mentioned, the ways to prevent it to be repeated are researched. This requires involvement in the improvement process, which makes this thesis an action research. Improvement project of the manufacturing process includes elements of managing change in a practical manner. Involvement on the shop floor is required to find sufficient solutions.

The research is categorized to be action research as the researcher participated in the brainstorming sessions identified in the previous chapter. The researcher also participated in the concrete construction of the pilots and helped the operators and engineers implement and use the systems selected. The piloted systems were improved by the researcher during the pilot, so the researcher had an impact on the pilots being successful. However, major changes were not made so it is arguable that the researcher had impact on the pilot launching but not as much the result of the pilot. According to Saunders et al. (2000, p.95), action research is defined as research “where the researcher is a part of the organization within the research and change process are taking place”. This definition is accurate of the research process as the researcher was employed by the organization and tasked with responsibilities outside, though related to, the research scope while the study was ongoing.

Due to the limited time frame, all possible corrective actions cannot be implemented. Therefore, corrective actions are planned only for mistakes, which have the biggest impact on the customer complaints. Corrective actions are planned based on the literature and observations on the shop floor. The poka-yoke methods presented in the literature are evaluated based on whether they are able to eliminate the possibility of the defect in certain problem types. The evaluation method selected is Saurin et al. (2012)'s framework for poka-yoke implementation evaluation. The framework is defined in more detail in subchapter 2.3.3.

After the corrective actions have been selected, they are piloted on the shop floor. Two actions were selected for piloting based on the recommendations from the framework and the researchers own deductions. As the research was done in co-operation with the case company, the case company's engineering team helped the researcher evaluate which actions would most likely be effective but also feasible. The device identified as most efficient by the framework would have left the company without a production cell as it was being modified for an extended period of time and was not selected for this reason. The action research nature of the study is clear in this method.

The two actions selected for piloting were implemented in the production cells where they would have the largest impact when counting the number of errors. The pilots lasted for ten weeks. At the start of the pilot the operators working with the pilots were trained to operate the systems correctly. Their work was observed, and their feedback recorded throughout pilot. During the pilot, the applications were fixed from time to time to ensure they worked as planned. After the initial piloting phase was over the systems remained in place and the observation tasks have been reassigned to a process engineer. The desired result of the pilot was a numerical value of the number of errors in the production cells.

4. RESULTS

4.1 Grouping of Customer Complaints by Production Cells

The customer complaints that occurred in the eight selected production cells in 2019 are presented in this chapter. The results include the number of customer complaints by product in each cell and the number of different error types in the cells. All the error types used are presented in Table 6.

Table 6. Error Types Used in the Study.

Error type	Description
Adjustment error	Customer received product with the wrong measurement scale.
Certificate error	Certificate was missing, some of the information did not match with the product, or the information was insufficient.
Missing part	One or several parts were missing from the delivery.
Omitted processing	Operator had forgotten to do a task in the manufacturing process.
Processing error	Manufacturing process led to the defect.
Unknown	Defect could not be solved.
Wrong part	One or several wrong parts were used.

Seven different error types were recognized. The customer complaint was categorized as a missing part type of problem when one or several parts in the bill of material of the order were missing. The wrong part category was used when assembly was not done according to the configuration. The wrong part error type was separated from the missing part type because of the possibly different reason they might have. A missing part error might be related to forgetfulness whereas wrong part might be a consequence of carelessness.

Every product requires at least one certification in the package, and if a certification was missing or the wrong certificate was included in the delivery, the certification issue error type was used. The processing error category was used if the customer complaint could be linked to the way the operator processed the product. The adjustment error type was used if the measurement scale for the instrument was not selected according to configuration chosen by the customer. The misoperation was the category used for cases where the product was not manufactured according to the process. The omitted processing type occurred when phases of the manufacturing process were not completed.

Those customer complaints that could not be identified were categorized as unknown defects. These cases were common in situations where the customer did not send the product back to the factory so investigations could not be made.

In addition with the error types, a location for each error is determined. The location is determined based on the complaint description, work instructions, and work standard. The errors are located in certain manufacturing phases in Figure 9.

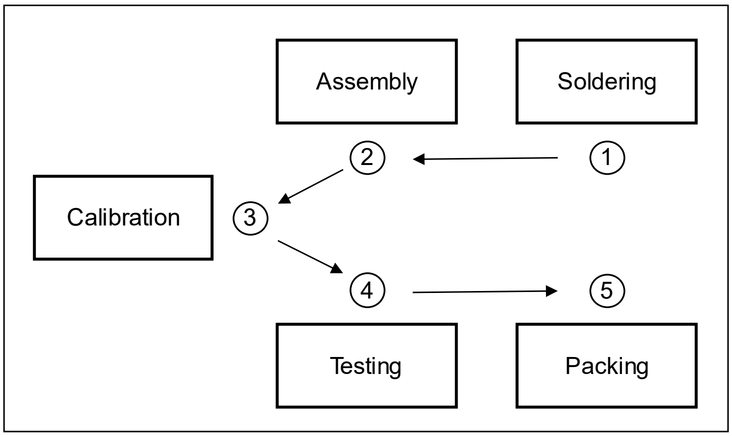

Figure 9. Manufacturing Processes of the Production Cells.

Soldering, assembly, calibration, testing, and packing are the phases that are used as error locations. Even though the layouts of the production cells are not exactly similar, the manufacturing phases that are presented in Figure 9 are included in most production cells.

4.1.1 Production Cell 1

Ten customer complaints occurred in Production Cell 1. All the complaints occurred with Product 1 even though another product is also manufactured in the cell. Error types and short descriptions of the customer complaints are presented in Table 7.

Table 7. Customer Complaints in Production Cell 1.

#	Product	*Error type*	Error location	Description
1	Product 1	Processing error	Packing	Information label was not attached to the unit
2	Product 1	Certificate error	Packing	Wrong certificate was included in the package
3	Product 1	Missing part	Packing	Missing accessory
4	Product 1	Processing error	Assembly	Faulty part
5	Product 1	Missing part	Packing	Missing accessory
6	Product 1	Missing part	Packing	Missing accessory
7	Product 1	Missing part	Packing	Missing cable
8	Product 1	Unknown		Defected product, the reason is not known.
9	Product 1	Missing part	Packing	Missing cable
10	Product 1	Missing part	Packing	Missing accessory

Six customer complaints occurred because parts were missing from the delivery. All the parts that were missing are accessories that are picked in the packing phase. Two processing errors occurred, one of which happened in the packing phase and the other in the assembly phase. A certificate error occurred once. Once the reason for the defect was not recognized. A count of error types in each location is presented in Figure 10.

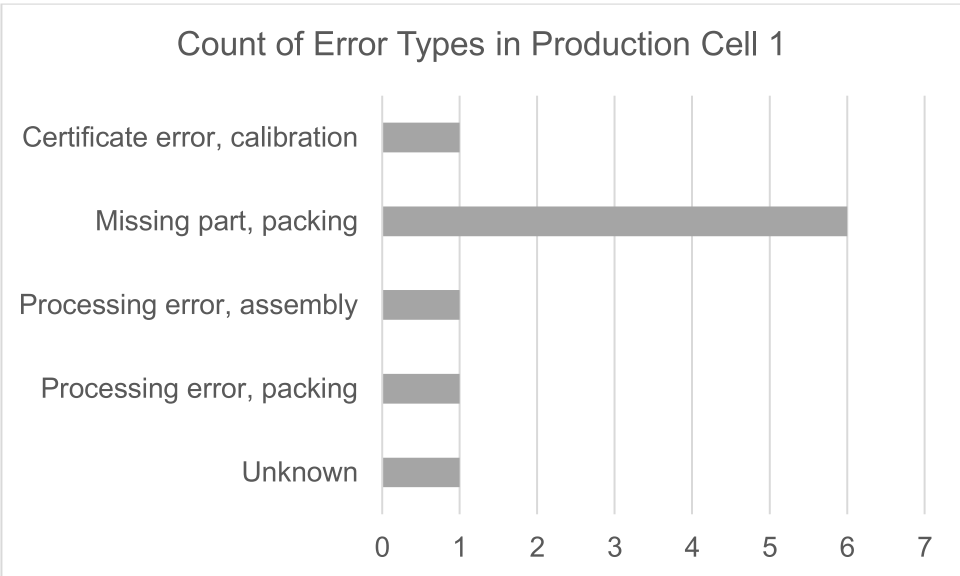

Figure 10. Count of Error Types in Production Cell 1.

60 percent of all customer complaints were missing part errors that occurred in the packing phase.

4.1.2 Production Cell 2

Three products are manufactured in Production Cell 2. At least one customer complaint occurred with each product. Error types and descriptions of the customer complaints are presented in Table 8.

Table 8. Customer Complaints in Production Cell 2.

#	Product	Problem type	Error location	Description
11	Product 2	Missing part	Unknown	Missing accessory
12	Product 3	Missing part	Packing	Missing manual
13	Product 3	Missing part	Packing	Missing filter
14	Product 3	Missing part	Packing	Missing filter
15	Product 3	Missing part	Packing	Several parts were missing
16	Product 3	Missing part	Packing	Missing cable
17	Product 4	Missing part	Packing	Missing cable
18	Product 4	Unknown		
19	Product 4	Missing part	Packing	Missing cable

Production Cell 2 had nine customer complaints with three different products. Product 3 had most customer complaints with five defects. Product 4 had three customer complaints and a part was missing in a Product 2 delivery once.

Eight times the reason for customer complaint was a missing part and once the complaint type was not recognized. The count of error types in Production Cell 2 is presented in Figure 11.

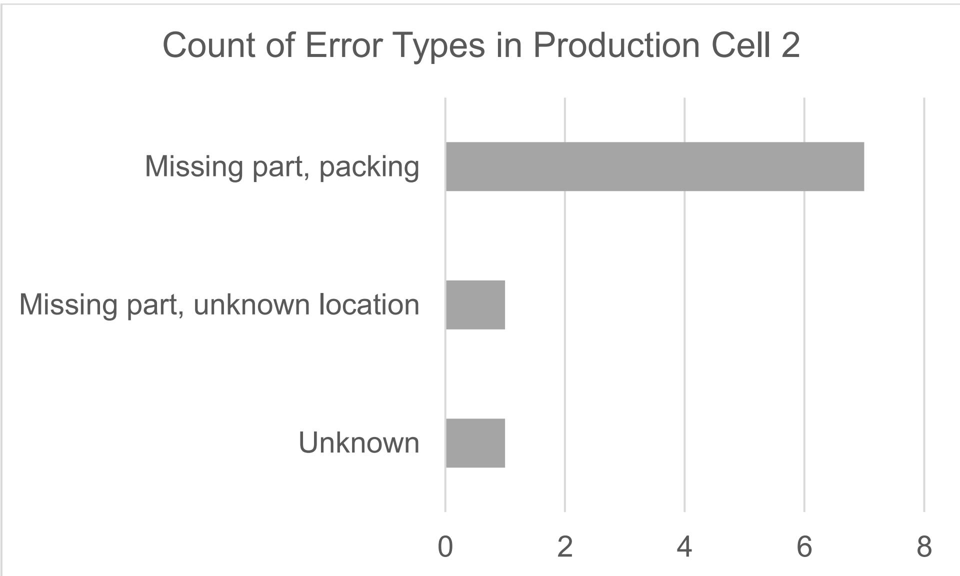

Figure 11. Count of Error Types in Production Cell 2.

Seven times the missing part was supposed to be installed in the packing phase. One time the location of the missing part error remained unknown.

4.1.3 Production Cell 3

Production Cell 3 had 11 customer complaints in five different products. Error types and descriptions of the customer complaints are presented in Table 9.

Table 9. Customer Complaints in Production Cell 3.

#	Product	Error type	Error location	Description
20	Product 5	Wrong part	Packing	Wrong accessory
21	Product 5	Certificate error	Calibration	Wrong certificate
22	Product 5	Missing part	Packing	Several parts missing
23	Product 6	Certificate error	Calibration	Wrong certificate
24	Product 6	Unknown		The customer did not return the product
25	Product 7	Missing part	Packing	Missing accessory
26	Product 7	Adjustment error	Calibration	Wrong dew point scale
27	Product 7	Missing part	Packing	Missing accessory
28	Product 8	Missing part	Packing	Missing charger plug
29	Product 8	Unknown		The customer did not return the product
30	Product 9	Processing error	Calibration	Units were tested with the same serial code twice

Mistakes in Production Cell 3 occurred in the packing and calibration phases in those cases where the location could be recognized. Error types and locations are presented in Figure 12.

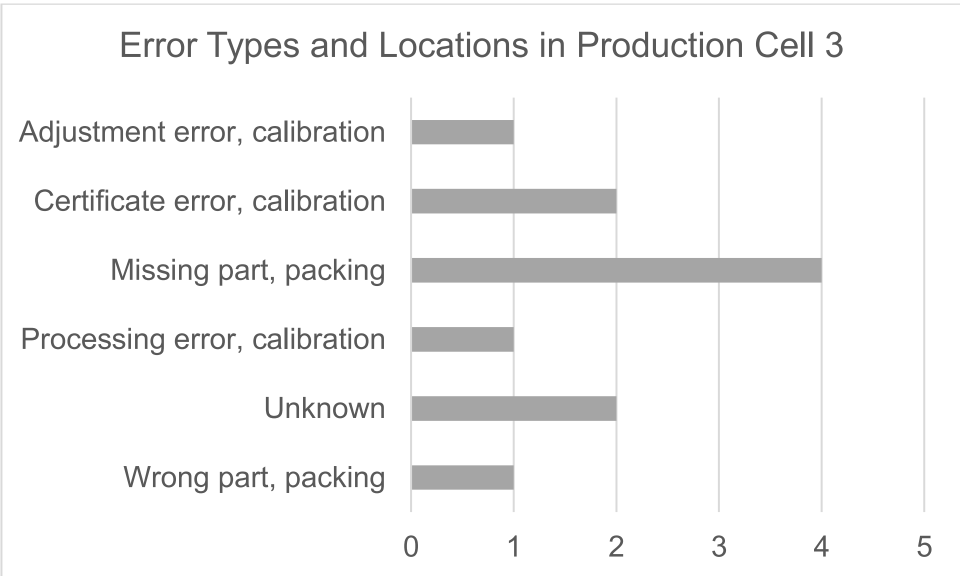

Figure 12. Error Types and Locations in Production Cell 3.

The missing part error was the most common complaint type with four customer complaints. A certificate error occurred two times and a wrong part, adjustment error, or misoperation occurred once. Complaint type was not known in two customer complaint occasion.

4.1.4 Production Cell 4

There were five products with customer complaints in Production Cell 4. The customer complaints are presented in Table 10.

Table 10. Customer Complaints in Production Cell 4.

#	Product	Error type	Error location	Description
31	Product 10	Wrong part	Packing	Wrong cable
32	Product 10	Processing error	Assembly	Jig was not used, so display was faulty
33	Product 10	Wrong part	Packing	Wrong filter
34	Product 10	Unknown		
35	Product 10	Wrong part	Assembly	Wrong parts used in base assembly
36	Product 10	Processing error	Assembly	Defected filter was installed
37	Product 11	Processing error	Assembly	Keypad bushing was too tight
38	Product 11	Certificate issue	Unknown	
39	Product 11	Wrong part	Packing	Wrong cable
40	Product 11	Missing part	Packing	Accessory
41	Product 11	Processing error	Assembly	Too tight bushing had damaged the device
42	Product 11	Missing part	Packing	Missing power cord
43	Product 12	Missing part	Unknown	Missing pressure head
44	Product 12	Unknown		Sales force information did not match with the order
45	Product 13	Wrong part	Packing	Wrong accessory
46	Product 13	Adjustment error	Calibration	Wrong dew point values
47	Product 14	Missing part	Packing	Missing power cord

17 customer complaints and six different error types occurred. Products 10 and 11 had the most customer complaints with six customer complaints. Errors are located in assembly, packing, and calibration. Error types and their locations are presented in Figure 13.

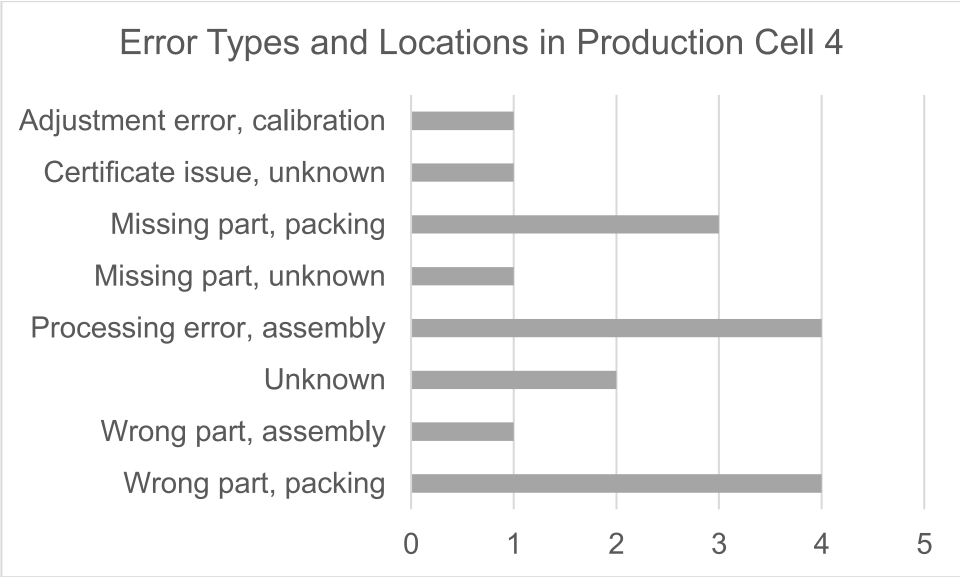

Figure 13. Error Types and Locations in Production Cell 4.

Missing part and wrong part errors were the most common error types with five customer complaints each. Eight of those customer complaints occurred in the packing phase.

4.1.5 Production Cell 5

There were 11 customer complaints with three different products in Production Cell 5. The customer complaints are presented in Table 11.

Table 11. Customer Complaints in Production Cell 5.

#	Product	Problem type	Error location	Description
48	Product 15	Processing error	Calibration	Wrong serial number printed when new labels were needed
49	Product 15	Missing part	Packing	Missing cable
50	Product 15	Adjustment error	Calibration	Wrong temperature scale
51	Product 15	Adjustment error	Calibration	Wrong scale in parameters
52	Product 15	Processing error	Calibration	Wrong label information
53	Product 15	Missing part	Packing	Missing accessory
54	Product 16	Missing part	Assembly	Plate around the connector was missing
55	Product 16	Wrong part	Packing	Wrong fitting
56	Product 16	Missing part	Unknown	Filter was missing, the reason is not known
57	Product 16	Certificate error	Calibration	Wrong certificate
58	Product 17	Certificate issue	Unknown	

11 customer complaints and five different error types occurred. Product 15 had six customer complaints, Product 16 had four customer complaints, and Product 17 had one customer complaint. Errors were located in assembly, packing, and calibration. Error types and their locations are presented in Figure 14.

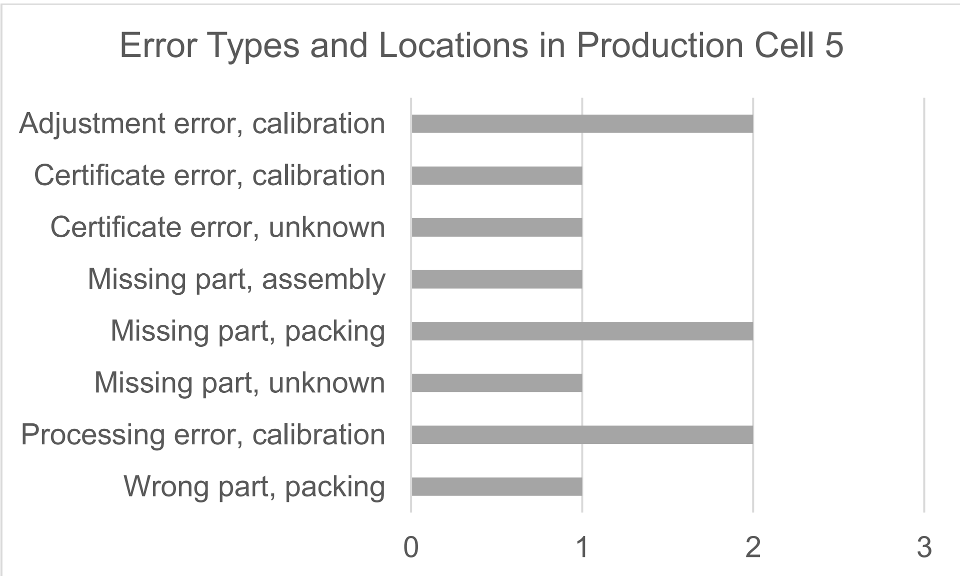

Figure 14. Error Types and Locations in Production Cell 5.

The missing part error was the most common error type with four customer complaints. A missing part error originated two times in the packing phase and once in the assembly phase. Once the missing part error could not be located.

4.1.6 Production Cell 6

There were 11 customer complaints with three different products in Production Cell 6. The customer complaints are presented in Table 12.

Table 12. Customer Complaints in Production Cell 6.

#	Product	Error type	Error location	Description
59	Product 18	Wrong part	Packing	Wrong cables
60	Product 18	Omitted processing	Assembly	Test filter was sent to the customer
61	Product 19	Omitted processing	Assembly	Test filter was sent to the customer
62	Product 19	Missing part	Packing	Missing cable
63	Product 19	Missing part	Packing	Missing accessories
64	Product 20	Processing error	Calibration	Same serial number was used twice
65	Product 20	Wrong part	Packing	Wrong able
66	Product 20	Missing part	Packing	Missing cable
67	Product 20	Processing error	Assembly	Tag was roped around the coil of the cable
68	Product 20	Unknown		
69	Product 20	Missing part	Packing	Missing filter

11 customer complaints and four different error types occurred. Product 20 had six customer complaints, Product 19 had three customer complaints, and Product 18 had two customer complaints. Errors are located in assembly, packing, and calibration. Error types and their locations are presented in Figure 15.

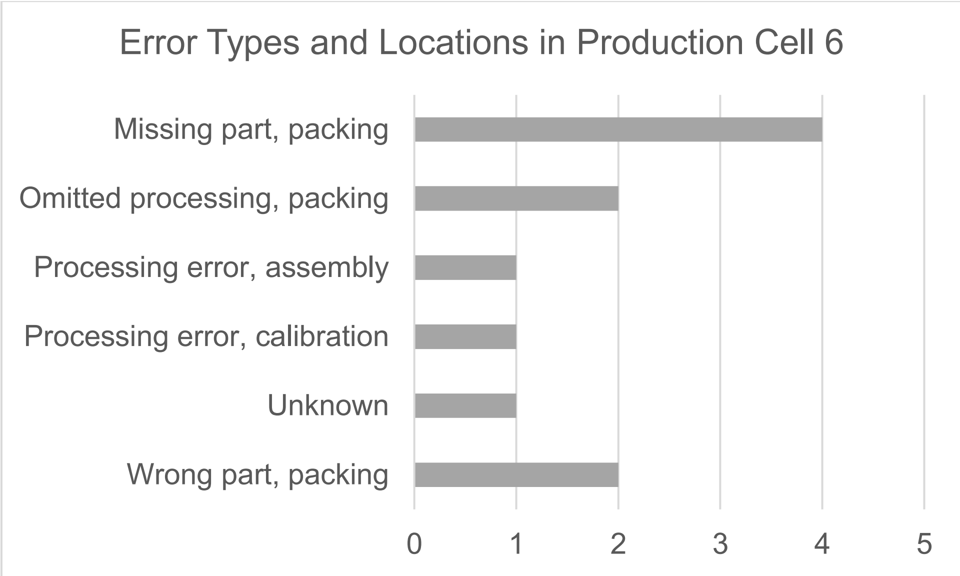

Figure 15. Error types and locations in Production cell 6.

The missing part error type occurred four times and all the error types originated in the packing phase. Two omitted processing errors and wrong part errors occurred in the packing phase two. Processing error occurred once in assembly and once in calibration.

4.1.7 Production Cell 7

Three customer complaints occurred in Production cell 7. The customer complaints are presented in Table 13.

Table 13. Customer Complaints in Production Cell 7.

#	Product	Problem type	Error location	Description
70	Product 21	Wrong part	Unknown	Wrong nozzle
71	Product 22	Wrong part	Unknown	Wrong nozzle
72	Product 23	Wrong part	Unknown	Wrong filter

All the three customer complaints occurred because wrong parts were used. Locating the errors is difficult afterwards because the manufacturing processes were not precisely designed when the mistakes occurred.

4.1.8 Accessory Team

The manufacturing process is different in Accessory team than it is in the other production cells because it consists only of packing and delivering accessories so there is no manufacturing at the cell. Therefore, all the error types are either missing part or wrong part errors. Error types are presented in Table 14.

Table 14. Customer Complaints in the Accessory Cell.

#	Problem type	Error type
73	Missing part	Accessory
74	Missing part	Accessory
75	Missing part	Accessory
76	Wrong part	Accessory
77	Missing part	Accessory
78	Wrong part	Accessory
79	Missing part	Accessory
80	Wrong part	Accessory

The cell had eight customer complaints, five of which were missing part errors and three were wrong part errors.

4.1.9 Summary of Customer Complaints

80 customer complaints occurred in the eight selected production cells. The number of customer complaints in each error types is presented in Table 15.

Table 15. Number of Customer Complaints by Error Type.

Error type	Count	Share
Missing part	35	43.8%
Wrong part	15	18.8%
Processing error	12	15.0%
Certificate issue	6	7.5%
Unknown	6	7.5%
Adjustment error	4	5.0%
Omitted processing	2	2.5%
Combined	*80*	*100%*

Missing part errors were the most common error type with 35 customer complaints. Other error types with over 10 customer complaints were wrong part error type with 15 customer complaints and processing errors with 12 customer complaints. A pareto diagram of the customer complaints by error type is presented in Figure 16.

Figure 16. Pareto Diagram of Customer Complaints by Error Type.

Figure 16 illustrates the share of customer complaints from the most common error type to the least common error type. Missing part error, wrong part errors, and processing errors are the three most common error types, and they cover almost 78 % of all customer complaints.

4.2 Root Cause Analysis for Customer Complaints by Error Type

The three most common error types presented in chapter 4.1.9 represented 77.6 % of all customer complaints in 2019. In addition, each selected error was several folds compared to those excluded from the study. Therefore, those error types were prioritized. A root cause analysis for missing part and wrong part errors, and processing errors was completed.

4.2.1 Missing Part Errors

There were 35 missing part errors. They occurred in three different locations: in the accessory cell, assembly, and packing. The number of missing part errors in each location are presented in Table 16.

Table 16. Missing Part Errors in Different Locations.

Error location	Count	Share of missing part errors	Share of all customer complaints
Assembly	1	2.9%	1.3%
Packing, Acces-sory team	5	14.3%	6.3%
Packing, other	26	74.3%	32.5%
Unknown	3	8.6%	3.8%

There was one error in the assembly phase. Most errors were made in the packing phase to total 26 errors. Five missing part errors occurred in the Accessory team. The location of the error could not be determined on three occasions.

The results of the Accessory team are presented on their own row because it differs from other production cells in that there is no production but only product picking and packing. For this reason, the solutions selected for the production cells are most likely not useful for the Accessory team.

For all the missing part complaints, the symptom is the same: the customers do not receive all the parts they have ordered. The problem that causes the missing part errors is analyzed separately in all error locations.

Missing part errors in the Accessory team

Each operator has their own packing desk where accessories are packed. The picking is done by reading the material lists that include the item information such as the item code. The operator locates the right supermarket box that has the same item code and picks the item. After all items are picked, they go back to the packing desk and pack the items into small bags.

The picking process is rather simple, but it requires constant attention from the operator, so mistakes are difficult to avoid. Item codes are long and similar with each other and many parts also look similar with other parts in the same accessory category.

The work environment is fast-paced, and several operators work at the area, so it is likely that there are distractions regularly. It is also impossible to be constantly 100 percent focused, which is required to manually pick the right items every time. Though human errors are understandable, they are unacceptable in a production environment. Two possible causes for the mistakes are that operators do not get enough assistance to pick the right items (i.e. source inspection) and there is not a system that checks (i.e. self-check) that the right items were picked. Therefore, additional systems must be applied to ensure human errors do not happen.

Missing part error in assembly

One customer complaint occurred in the assembly phase. In the case, a plate should have been attached around the connector of a probe, but the plate was missing. The customer complaint is difficult to analyze afterwards but it is likely that there has been a distraction that has forced the operator to stop the manufacturing for a while. For instance, if a supermarket box has been empty, they may have been taken the empty box away from the shelve and forgot to continue from the phase they were. Because the case is a one-time error, which has not occurred before or after the case, no corrective actions have been designed yet.

Missing part errors in packing

Missing part errors occurred 26 times in the packing phase. As it turns out, parts that were missing were usually accessories that are packed in the end of the manufacturing process. Therefore, the core units were assembled correctly but the accessories that are packed in the phase were missing.

The accessories that are packed vary, so the operator needs to pay attention to the packing every time. To name a single cause for forgetting to pick up all the parts is challenging. The operator might have been distracted, they might have read the instructions wrong, or just missed a line on the picking list. Picking up accessories is a repetitive task, but it includes a lot of variation. Therefore, the manufacturing process should assist the operator so that picking up accessories would not constantly require operators to make decisions.

Unknown

Three missing part errors occurred that could not be located to a specific phase of the manufacturing process. The only customer complaint for Product 2 occurred because a bushing that is assembled in the second phase was missing. The bushing should be attached every time, so it is not clear why it was not done this time. There is a possibility that the bushing had detached from the unit. However, it is so easy to see that a missing bushing should get the operator’s attention.

One missing part error occurred because a pressure head was not delivered to the customer. Pressure heads are not kept at the production cell by default, but they need to be ordered to the production cell when they are needed. The operator had ordered a pressure head, but it was not found from the production cell afterwards. The error may have occurred elsewhere, but the root cause is impossible to define in hindsight.

In one case, a filter was missing around the probe. The filter is kept around the probe the entire manufacturing time and it has never been missing before. The filter may have been accidentally removed at the same time when the protection cap was removed. The cause is not known and not investigated due to onetime occurrence.

4.2.2 Wrong Part Errors

There were 15 wrong part errors and they occurred in three different locations: in the Accessory team, assembly, and packing. The number of missing part errors in each location are presented in Table 17.

Table 17. Wrong Part Errors in Different Locations.

Error location	Count	Share of wrong part errors	Share of all complaints
Accessory team	3	20.0%	3.8%
Assembly	1	6.7%	1.3%
Packing	8	53.3%	10.0%
Unknown	3	20.0%	3.8%

Most errors were made in the packing phase. One error was done in the assembly phase error and three errors were made in the Accessory team. Three times the location of the error could not be determined.

Wrong part errors in Accessory team

Wrong part errors in Accessory team are really similar to the missing part errors even though the error type is not the same. Similarly, the operator does not read the material list correctly. In the wrong part errors, the error occurs right before the parts are picked from the supermarket boxes. Each part type has its own item code, but the parts can look very similar. It is possible that the operator reads, which part should be picked and does not pay enough attention to the item code. And even though they paid attention to the code, it is written in the supermarket boxes in a small font and codes can have only one different number. Mistakes are easy to make because the environment is fast-paced, and the operators need to pay attention to the picking the whole time.

Wrong part errors in the assembling phase

Once wrong parts were used in the base assembly phase. The operator has a procedure instruction form in an Excel table. The table includes a lot of information and can be confusing to read. Poor instructions are the likeliest cause for the customer complaint. The instructions were already improved before the research process started so no further analysis is made.

Wrong part errors in packing

Eight wrong part errors occurred in the packing phase. The errors are similar to the missing part errors. Wrong cables were delivered four times and the wrong case, installation kit, filter, or connector were delivered once. The operator checks the parts from a bill of material list on the computer screen. The process is simple in this case too, but the item codes are the only thing that guide the operator to make the right choice. The correct part type was chosen in all studied cases, so the operators know which part types are needed. It is possible that the operators read the item codes and the part description from the bill of materials but do not remember the code correctly when they pick the parts. It seems that support is needed to guide the operators so that it is easier to make the right decision in the picking process.

Unknown

All the three unknown errors were made in Production Cell 7. They are difficult to analyze afterwards because the ramp-up of the production cell was done right before the errors occurred. The processes were not defined well at the time, which is the likeliest reason the mistakes were made.

4.2.3 Processing Errors

There were 12 processing errors and they occurred in three different locations: in the assembly, calibration and packing phases. The number of processing errors in each location are presented in Table 18.

Table 18. Processing errors in different locations.

Error location	Count	Share of processing errors	Share of all complaints
Assembly	5	41.7%	6.3%
Calibration	4	33.3%	5.0%
Packing	1	8.3%	1.3%
Unknown	1	8.3%	1.3%

Five errors were made in the assembly phase and in the calibration phase, and three error occurred in packing. Once the error location could not be recognized.

Processing errors in assembly

Three customer complaints occurred because of too tight bushings that had caused a faulty product. A grounding flake got broken after it had been pressed too tightly when it was bended around the device. The error occurred because there is not a way for the operator to be sure how hard the grounding flake should be pressed. Two processing errors occurred for Product 11 because the bushings had damaged some parts of the devices. The defects were possible because nothing informs the operator how tight the bushings should be. Ideally, the tool that is used for pressing would ensure that the press would be optimal.

In one processing error case, the device had a defected display. It turned out that there is a jig for display assembly, which protects the display. The jig was not used this time, which caused the defect.

In one case, a defected filter was installed to the product. Filters are picked from a supermarket box and the operator should make a visual check when a filter is picked. However, the operator should be able to trust that parts are not faulty.

Processing errors in calibration

Three processing errors occurred in the calibration phase. In the first error, one of three labels was missing from the product. It is likely that the missing label had bad printing quality and new label should have been printed, but it was not done. The error would have been prevented if the printer had printed the labels properly. The reason why a new label was not printed and used is not clear.

The second customer complaint occurred because the customers received two products with the same serial numbers in the product labels. In both cases, the operator had not changed the serial number between two calibrations. The software does not prevent the operator to use the same serial number twice.

The third error occurred because the products had wrong label information. The test program prints labels automatically, but poor label quality may force the operator to print a new label. In this case, the serial number needs to be written manually, which is a potential situation for a human error. In the other case the test program had a default serial number, which was not correct. According to the process, the operator should remove the wrong code and input the correct code.

Processing errors in packing

A processing error occurred because a tag in the cable was roped around the coil of the cable, which damaged the tag. The operator was not aware that the tag has to be visible and it must not be faulty. The customer complaint has not occurred again after the operator was informed about the complaint. However, the possibility of the mistake still exists and there is a risk that the same error might occur with a new operator.

Unknown

One customer complaint occurred because sales information did not match with the order that the operator used for the manufacturing. The information about the case is inadequate for further investigations, so it has not been researched further.

4.2.4 Summary of Error Types

The three most common error types were missing part, wrong part, and processing errors. 62 customer complaints occurred because of those three error types. Out of those 62 customer complaints, 34 errors were missing part or wrong part errors in the packing phase. In addition, 8 similar errors occurred in Accessory team. Those errors cover 53 % of all customer complaints that occurred at the instrument factory.

The missing part errors and wrong part errors have similar causes in the packing phase and in Accessory team. The biggest differences between the packing phase and the Accessory team are that several operators pick materials at the same time. In addition, the process in the Accessory team consists only of material picking.

The processing errors did not have as many common factors that had caused the customer complaints. Poka-yoke methods could be used for some of the errors, but their impact would be much smaller than focusing on the missing part and wrong part errors in the packing phase and possibly in the Accessory team. Customer complaints can be reduced the most by applying poka-yoke methods in manufacturing phases where mistakes are most common. The first poka-yoke applications should be applied so that they eliminate as many errors at once as possible. Therefore, poka-yoke applications were designed only for missing part and wrong part errors in the packing phase.

4.3 Poka-Yoke Application Design for Eliminating Packing Errors

Poka-yoke applications were planned to prevent the operators from packing wrong parts or forgetting to pack parts. Four possible poka-yoke methods were created. They are presented in this chapter. The evaluation was made in the brainstorming earlier in the implementation process so it was not taken into account whether implementing all the poka-yoke applications would be possible at the case company.

4.3.1 Light System

A light system could make material picking easier for the operator by guiding which parts should be picked. Small lights would be located under each supermarket box. Each supermarket box contains certain items, and they are always kept at the same positions. The light would indicate, which items the operator should pick. A potential light system process is presented in Figure 17.

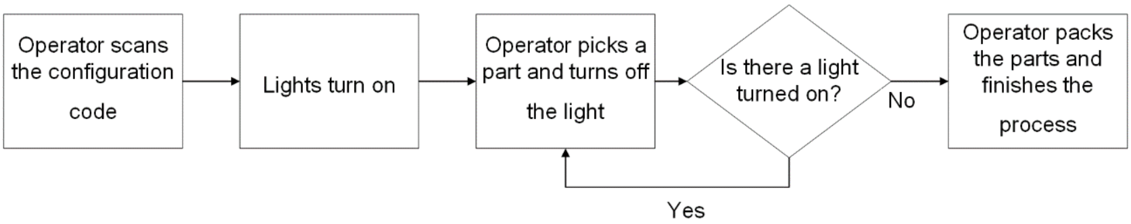

Figure 17. Process Chart of the Light System.

In the light process, the operator scans the configuration code of the product to feed the information to the light system. The lights under those items that need to be picked will light up. Every time the operator picks an item, they push the button next to the light to inform the light system that the item has been picked and the light can turn off.

The light system would improve the conditions of the manufacturing process, so it would be a source inspection system. The lights would make the packing process much easier for the operator than the current packing process because the system guides the operator to make the right decision. However, the lights would not error-proof the packing phase entirely because the light system does not prevent the operator from picking a wrong part.

Only one operator packs parts in the other production cells so the system might be viable in those. The light system is probably not an ideal application in the accessory cell because only one operator could control the light system at the same time.

4.3.2 Automatic Lids for Supermarket Boxes

An automated lid solution could guide the operator even better than the light system. Each supermarket box would be closed by a lid that prevents the operator from picking parts from the boxes. The process description is presented in Figure 18.

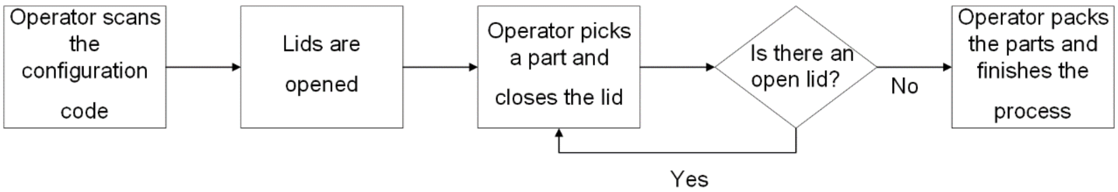

Figure 18. Process Chart of the Lid System.

In the system, the operator scans the configuration code similarly as in the light system to feed the information to the system. The lids of those supermarket boxes that contain the parts that need to be picked, will open up. After the operator has picked the part, the lid can be closed by using a acknowledge button. This way the operator knows, which parts are yet to be picked.

The system would be a source inspection system that would entirely error-proof the wrong part error type. Missing part errors would not necessarily be prevented because too few parts could still be picked in situations where more than one part is required.

Same limitations as with the light system applies for the accessory team. Lids cannot be opened for multiple picking processes at the same time if the lids are used to error-proof the picking system.

4.3.3 Scale System

A scale could be used to ensure that the right parts are packed into the package. A scale system process is presented in Figure 19.

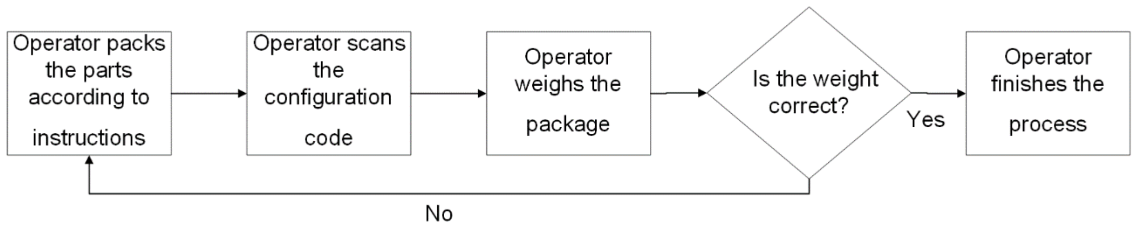

Figure 19. Process Chart of the Scale System.

In the scale system, the operator picks all the parts into the package. When they are finished, the operator scans the configuration code of the product and weighs the package. The scale system compares the package to a standard and tells whether the package is packed correctly or not.

The system would check that the right parts are picked after the process, so the system would be a self-check system. Potential problems with the case system are the variation in the weights of the parts and the possibility that some alternative parts have the same weight. The scale system could be used in the packing phase and in the Accessory team because each operator could have their own scales.

4.3.4 Barcode scanning system

Barcode scanning could be used to ensure that every part is picked, and wrong parts are not picked. A barcode scanning system is presented in Figure 20.

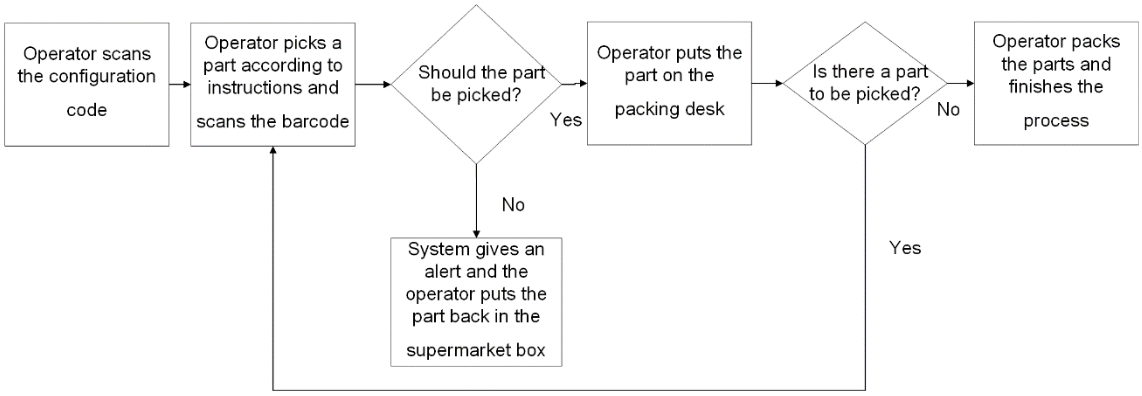

Figure 20. Process Chart of the Barcode System.

In the barcode scanning system, the operator scans the configuration code in the beginning of the packing process so that the information of the product parts is fed to the scanning system. The operator uses the scanner every time they pick a part either by scanning the code in the supermarket box or the code on the part. The system gives an alert if a barcode of a wrong part is scanned.

The system would be a source inspection system and it could prevent the wrong part and missing part errors entirely. Barcode scanning would also be possible to apply in the Accessory Team because each operator could have their own scanner. The barcode scanning may slow down the process because scanning every part would take time.

4.3.5 Grading the Poka-Yoke Applications

The grading framework created by Saurin et al. (2012) is used to evaluate the effect of different poka-yoke applications on customer complaints. Categories of the framework were presented in Table 2. As explained in Chapter 2.3.3. Saurin et al's framework is used to grade poka-yoke applications with the help six categories. The researcher selected to grade each category out of four, with four being the best possible score. The results are presented in Table 19.

Table 19. Results of the Poka-Yoke Applications.

	Poka-yoke function	Inspection method	Inspection rate	Operator action	Possibility of new errors	Health & safety	Score
Lid system	3	4	4	2	4	4	**3.50**
Light system	2	4	4	2	4	4	**3.33**
Scale system	2	3	4	2	4	4	**3.17**
Barcode scanning system	3	3	4	0	4	4	**3.00**

The lid system got the best result with 3.50 points. It has a better poka-yoke function than the light and scale systems have because it controls the process. Only two points were given in the operator action attribute because the operator needs to make an extra task to use the lid system. The operator would have to scan the barcode, which would require an action from the operator.

The light system got 3.33 points. The score is lower than the score of the lid system because the light system would only warn the operator with lights. This means that the process would not be entirely error-proofed because it would still be possible to pick wrong parts. The light system still has a good rating because the inspection method would be a source inspection system, which could be identified how the process guides the operator. The lights would be used on every occasion so 100% of the products are inspected. The operator needs to do an extra task with the light system, too.

The scale system got 3.17 points. It is also a warning system and requires the same scanning action from the operator. The scale system did not get as good result in the inspection method category than the lid and light systems. The packages would be checked after the parts are picked, which makes the scale system a self-check system. The scale cannot ensure that right parts are used in advance, but they have to be checked after the picking process.

The barcode scanning system got 3.00 points. It got 3 points in the poka-yoke function category because the barcode scanning includes a warning function and a partial control function. The warning is given after every scanning to indicate, whether the right part was scanned. It is not an actual control function because picking the wrong part is still possible. It is better than merely a warning system though because the feedback of the scanning is immediate. A proper control function would prevent the operator from picking the wrong part entirely so four points cannot be given. In the inspection method category, the system got three points because scanning is a self-check inspection method. The feedback is faster than in the scale system, but the scoreboard does not take that into account. Its problem is the bad result in operator action category. Zero points were given because the barcode scanning process requires the operator to scan every part. Therefore, multiple extra actions are needed while the other applications could be used by adding one extra task.

4.4 Poka-Yoke Applications for Eliminating Errors

Four different poka-yoke applications were evaluated in chapter 4.3. The lid system got the best results with 3.50 points. However, the system could not be implemented at the case company. The lid system would require major changes in the production cells because the existing cell infrastructure would not support the change. The supermarket shelves in the cell are inflexible and would need to be replaced. Indeed, the packing portion of the cell would need to be redesigned. The implementation would take a longer time than the light system implementation and the production would have to be interrupted for a longer time due to major modifications. This would lead to having to halt production in the cell. The costs of the pilot were likely to be high, which is not ideal for a pilot. When investing in this kind of change it is important for the company to know the result. All in all, the solution was an overcompensation to the amount of errors.

The light system got 3.33 points and was implemented to Production cell 2. The implementation consisted of programming a system that would illuminate lights under selected supermarket shelves according to the order form scanned by the operator before beginning their task. The programming was done in-house by test engineers and lasted two weeks. The installation of the system was done by the researcher and the process engineers. The cell was out of use for only a couple of hours, so the works cannot be seen as invasive. Seven missing part errors occurred in the packing phase of the cell in 2019. The light system was implemented in August 2020 and has been in usage for 10 weeks. During the pilot, zero customer complaints about missing parts or wrong parts have occurred. However, the system had several faults and was not reliable by the end of the pilot. The researcher had to fix the system regularly to keep it running. The results of the pilot were successful enough to prove the idea behind the solution worked. Based on the pilot, the company decided to invest in a commercial solution by an external company specialized in similar solutions to ensure reliability.

The scale system got 3.17 points and was implemented to Production Cell 1. In this pilot the operator would pack the products, then scan the order form and last weigh the package. The implementation consisted of programming an Excel Macro Application to ensure the input of the scale was compared with the statistical sum of the products listed in the order form. Six missing part errors in the packing phase of the cell were recorded in 2019. The scale system was implemented at the same time as the light system. During the pilot, zero customer complaints about missing parts or wrong parts have occurred. The scale system itself worked well, but during the pilot it was discovered that some of the items have variation in weight and are difficult to compare to the item weight in the database. This would cause the system to call false negatives. The researcher and the process engineer had to change the system to have a larger allowance for error i.e. if the weight were off by less than five grams the system would accept it. There is a risk that some faulty packages are accepted, but the system does decrease the amount of packing errors significantly. The system was implemented as a part of the process because it has increased reliability of the process and does not require too much from the operators.

The barcode scanning system got 3.00 points, which was the worst results of the four poka-yoke applications. The system was not piloted because creating barcodes to every item requires negotiating with the suppliers and implementation would also be a time-consuming process. The challenging implementation combined with the worst score compared to other applications, the decision to not implement the system was made.

5. DISCUSSION

5.1 Comparing Discovered Mistakes and Their Causes in Make-to-Order Production to Existing Literature

The first research question is as follows:

Research question 1: What kind of mistakes operators make in MTO production?

The subchapter 5.1.1 includes a definition of the kind of mistakes operators make in MTO production and 5.1.2 includes reasoning behind the causes of those mistakes.

5.1.1 Mistakes Operators Make in Make-to-Order Production

It was suggested in the literature that operators make mistakes in situations where tasks do not follow routines and manufacturing becomes more complex (Fast-Berglund et al. 2013; Stewart & Grout 2001). The results of this study support the previous findings. The first research question was answered in Table 15 and Figure 16: mistakes at the case company were wrong part and missing part errors and they covered 62.6% of all customer complaints. After empirical research, it turned out, the errors occur in situations where constant decision making is required by the operators. In MTO production environments, these situations are common in phases where products are customized according to customers' wishes; in the case company, mistakes were made in tasks where parts are picked. To prevent errors from occurring, the process should be improved so that the operators get support from the process: manufacturing becomes intuitive and poka-yoke applications ensure mistakes cannot be made.

In the packing phase, the whole process is a non-routine task because it varies in every customer order. Based on some literature mistakes are made in environments where variation is only momentary, because variation helps operators remain alert (Stewart & Grout 2001). It could have been possible to make a hypothesis that a manufacturing phase with only non-routine tasks would make the operators alerted all the time, which would make the packing phase almost defect-free. The case company was not defect-free, but that does not mean the operators were not alerted and performing well. It would appear variation in what is being packed is not enough to make the task "non-routine" and ensure a defect-free environment. It could be argued that the problem is not in the alertness of the operators. Instead the variation in the products being packed and the amount of decisions being made was so large, that mistakes were bound to happen for that reason alone.

5.1.2 Causes for Mistakes in Make-to-Order Production

Based on existing literature it is a difficult question to answer exactly why less mistakes are made in some phases and more in others. According to Fast-Berglund et al. (2013) mistakes are correlative with Operator Choice Complexity (OCC). By definition OCC is "a measure developed to quantify human performance in making choices". (Fast-Berglund et al. 2013) In this study the variation in complexity of choices is not studied, and therefore cannot be evaluated. However, there seems to be a correlation between the number of decisions made and the number of mistakes made. The biggest number of decisions are made in the packing phase, so errors are most common there. If this is the case, it could be possible that the defining factor for mistakes is the "Decision-Making Density", which would mean that the tasks where decision making by the operator is required the most are the most potential tasks for mistakes. Therefore, the phases in the manufacturing process that require the biggest amount of decision making would be those that should be improved the most. It can be suggested that the risk of mistakes is mitigated when the "Decision-Making Density" (decisions/production phase) is alleviated, and thus decreasing decisions decreases mistakes.

The reason for mistakes in the packing phase is at least partially expected. Picking accessories is not a very complex process to describe, but it is more demanding on the shop floor than it may appear. For almost every part, there are alternatives that could be used instead of the part that the customer wants. An example is picking the right cable, which can be ordered in several different lengths and there are even different cables that have the same length. Almost always, the operator can make the right decision and chooses the right cable. However, it is not very likely that the operator could make the right decision every time.

5.2 Poka-Yoke Methods in Make-to-Order Production

The second research question is as follows:

> *Research question 2: Which poka-yoke methods could prevent operators from making mistakes in MTO production at the case company?*

The subchapter 5.2.1 includes a definition of the kind of methods applicable in MTO production. In the subchapter 5.2.2 the researcher evaluates existing tools for comparing methods. The subchapter 5.2.3 includes a summary of the pilots implemented and an analysis of their success.

5.2.1 Applicable Poka-yoke Methods in Make-to-Order Production

Poka-yoke methods are needed in manufacturing phases where mistakes occur so that defects can be prevented or detected immediately after they occur. Based on the results, poka-yoke methods should be used to help operators in manufacturing phases where they need to make manufacturing related decisions. It was recognized that the biggest need for poka-yoke applications is in the packing phase. There is a need to support operators so that the material picking process would be intuitive and a routine task-like even though different parts are picked each time.

It was proved that mistakes could be reduced by using by at least two inspection methods: source inspection and self-check. The light system added reliability into the process so that mistakes became more difficult to make. A system that fixes the mistake before it happens is a source inspection system. The scale system was an example of a self-check system because it helped the operator to ensure that right parts were packed but the process itself did not become easier than before.

Source inspections are generally valued more than self-checks because they prevent the mistake from happening all together (Shingo 1986). Source inspections are not always possible, especially when dealing with existing production environments. For instance, the results implicate that the scale system was a useful poka-yoke application in cells where light systems could not be applied due to a tight schedule. The scale could be implemented quickly with existing resources. There is no one solution for every mistake, but both source inspection and self-check solutions are valuable tools in decreasing mistakes in MTO environments.

5.2.2 Selecting the Appropriate Poka-yoke Method in Make-to-Order Production

The framework for poka-yoke implementation evaluation (Saurin et al. 2012) was tested in practice in this research, and some improvements were discovered. The framework proved useful when different poka-yoke applications were evaluated. However, it seems that the eight attributes in it are not enough to determine which application would be the best solution to a certain problem. The cost structure of the application could be an important aspect to consider when a new poka-yoke application is designed. In addition, implementation time and suitability of the poka-yoke application for existing infrastructure are important if the score is wanted to be used as a defining factor for application selection. The lid system got the highest score when four potential poka-yoke applications were evaluated. However, the framework does not take into account the applicability or the costs of the applications so the "most-implementable" solution could not be implemented.

Another practical issue came up in the Accessory team, where several operators work at the same station. It was recognized that the light system would not work because the operators would not know who the light was for. This could not be concluded from the results where the light system received the second highest score. The framework did not take the number of operators using the supermarket shelves into account. If the number of processes that can be done at the same time without the poka-yoke failing would be measured in the framework, the barcode or scale systems could have received higher points in the Accessory team. The barcode or scale systems should not break down if several operators are doing their own processes in the same space.

The point scale of the framework might need adjustments because all the attributes are considered to be equally important in the framework. Saurin states that the weights of the categories can be adjusted before the evaluation begins, but nevertheless some adjustments should be made for the default points. For instance, one extra task by the operator drops the operator action category points from four to two points but a self-check inspection is only one point smaller than source inspection. Source inspections are the best way to design poka-yoke applications, so the one-point difference should have been bigger. In addition, the health & safety category was considered as important as other categories. A poka-yoke application should not be worth the investment if it might create even a minor safety risk in the manufacturing process; this should not be up to the evaluator.

5.2.3 Implementation of Poka-yoke Applications in Make-to-Order Production

Based on the results, the challenge with poka-yoke applications in MTO production is that there are so many different errors that multiple poka-yoke applications are needed to prevent them. The other error types that did not lead to corrective actions covered 37.5% of the customer complaints so together they form a significant amount. For example, processing errors were the third most common error type in the research, but several poka-yoke applications would have been required to prevent them all from occurring. It must also be remembered that a poka-yoke application might create a possibility for another error. In MTO production this is especially valid because different configurations and products need to be taken into account in poka-yoke design.

The value in poka-yoke applications is that they provide 100% inspection. By testing every product before it leaves the production cell, the company can find every mistake with minimal resources. It is important to make sure the time between the mistake happening and the check is as short as possible to eliminate useless tasks. The most important thing is to make sure the company is testing the right criteria: the analysis of the mistakes must focus on identifying what is similar in the most common mistakes. As there is never an answer which would cover every mistake, companies should prioritize: start from the most common mistake or easiest fix and work down. A manufacturing environment is never ready, instead continuous improvement is needed. For this reason, the importance of solving problems and improving systems in the right order is key.

5.3 Implications for the Case Company

The research was conducted in cooperation with a case company. The following subchapters include reasoning for future investments into poka-yoke applications and a recommendation as to what those investments should be.

While it might be a good idea to focus on the customer complaints to reduce them in the short term, all the defects should be researched to understand the big picture of defects, error types, and suitable poka-yoke applications. If more common error types are found in the inspection data of the quality control team, suitable poka-yoke applications should be created for these error types. This would create a possibility to move the focus of the inspections on other products and this way improve the overall quality in the long term.

5.3.1 Reasoning for Corrective Actions in the Case Company

When the complaints are observed statistically the scale of the mistakes is clear. The customer complaint rate of 0.5% means that one in 200 deliveries is somehow faulty. The average size of one delivery is not known, but order sizes at the case company vary from one to hundreds of product units and one product includes several accessories. As one wrong or missing part leads to a customer complaint, it is fair to say that mistakes in the packing process are extremely rare. Nevertheless, since the customers are given the opportunity to customize their orders, they expect the order to be filled exactly as requested. It can be assumed most customers complain if the order is defected, because they order products for specific needs.

Even though the operators perform well, better quality is needed to fulfil the customer expectations. The case company manufactures high-end products and aims for high quality, which means that the company pursues a differentiation strategy, and the customers expect to get products with high quality. Therefore, every customer complaint can have a negative impact on the reputation of the company and investments on quality improvements can be expected.

5.3.2 Recommendations for Corrective Actions for the Case Company

The assignment given by the case company identified customer complaints as primary data for detecting mistakes. However, there is an Outbound Quality Control (OQC) team, who inspect products based on sampling. The data compiled by this team is not considered in this research. In future projects, it would be beneficial to use all possible data sources. From a long-term perspective, it is important to focus not only on mistakes that lead to customer complaints, but all mistakes as a whole. The first recommendation is to improve comprehensive data analysis in the whole factory to prevent partial optimization.

The most common mistakes identified by the OQC team could be mitigated with poka-yoke solutions, and thus the resources of the OQC team could be concentrated on less-common mistake types. The most common mistakes would be eliminated by poka-yoke applications and the less-common mistakes inspected by the OQC. New mistake-proofing methods would be continuously implemented, and the mistakes inspected by the OQC would get rarer and rarer. This would lead to the customers receiving less and less defected products. The second recommendation is to inspect most common mistake types through poka-yoke solutions and incrementally free up human resources of the OQC and ensure sampling is conducted elsewhere, where it is most needed. Through continuous improvement and addition of poka-yoke applications the areas requiring human inspection will decrease over time.

By far the most problematic phase was the packing phase. It could be proved that at least 42.5% of all customer complaints occurred because parts that should be packed there were either picked wrong or they were not picked at all. The share is even higher if the Accessory team is counted in, which has a slightly different manufacturing process that consists only of material picking. However, data related to Production Cell 7 was very limited as it only consisted of a few months due to production starting late 2019. It could be observed on the shop floor, that the Cell was not functioning as planned. The third recommendation is to analyze Production Cell 7 separately with data from the year 2020.

In packing phases, both the light system and the scale system tested well in the pilots. The light system was superior and should be preferred wherever possible. The pilots should be increased to all production cells where picking or packing mistakes occur in order from most mistakes to least mistakes. The fourth recommendation is to firstly evaluate every production cell separately, implement either system (or both) accordingly and follow-up to tweak the systems to work as designed.

The accessory team turned out to be difficult to fix. Though the barcode systems were deemed difficult to implement it should be considered in the Accessory team, because the packing is so different there, and other poka-yoke applications have not been possible. The scale system could be implemented in the Accessory team in the meanwhile, but it is not completely mistake-proof. With this said, the fifth recommendation is to conduct a thorough study on the Accessory team alone, as it functions in a very different way than the other productions cells and this research does not provide enough information to fix the quality issues.

The value of poka-yoke solutions in the assembly process is not explored since the statistical analysis led to focusing on errors in picking and packing activities. Packing is a mandatory part of the process, and from the customers' perspective the missing articles are just as problematic as defects in the base unit. However, if taking into account the company's reputation, it could be that faulty manufacturing would have larger indirect consequences. After the mistakes in the packing processes have been eliminated, the sixth recommendation is to conduct a thorough data analysis to find which assembly errors could be eliminated with poka-yoke applications.

6. CONCLUSION

6.1 Academic Contribution of the Study

This study researches the characteristics of MTO production and locates the mistakes made in MTO production to certain phases in the phases of the manufacturing process. This research was built on research of mistakes written by Stewart & Grout (2001), the poka-yoke implementation framework created by Saurin et al. (2012) and the idea of applying poka-yoke in a complex manufacturing environment studied by Fast-Berglund et al. (2013).

MTO production tends to be such a complex system so definition of routine task is rather lax. It is likely to be easier to define routine tasks in MTS production. In MTO production, even the most routine tasks are likely to include some level of customization. For this reason, research related to MTO production should include a spectrum of "routineness" instead of categorizing tasks to routine or not. For this reason, the definition of routine task in Stewart & Grout (2001)'s study is difficult to apply in MTO production even though the general idea seems to be in line with the empirical data presented in chapter 4.

This research provides suggestions for adjusting the framework for evaluating applicability of poka-yoke methods created by Saurin et al. (2012). In a field with little to none theoretical tools of evaluating methods, Saurin et al. (2012) provided an interesting tool to work with. This research proved that the framework is applicable though some adjustments are needed. Though this research cannot provide a conclusive alternative to the presented framework, it does provide valuable insight to anyone creating or applying such frameworks in production environments.

Poka-yoke applications were researched in a complex, manual, and small-part manufacturing process. The study proved that poka-yoke applications can be used especially in material picking processes. This is in line with Fast-Berglund et al. (2013)'s study where it was researched how a light system could be applied in a complex car manufacturing process. The biggest problem with the poka-yoke applications in MTO production seems to be that there are so many error types in MTO production that it is very difficult to eliminate all the error types by applying only one or two poka-yoke applications.

Though this research does not focus on creating an alternative unit or model for evaluating the complexity of production phases, it is suggested that Fast-Berglund et al. (2013)'s model of evaluating the complexity is more complex than necessary in certain production environment. This research suggests that the shear number of decisions is enough to evaluate the complexity of the production phase and the need for poka-yoke applications.

As poka-yoke and especially poka-yoke in MTO production environment are seldomly researched topics, this research adds to sparce knowledge on the topic. Especially research that takes into consideration customizability and its relation to mistake proofing is needed for the manufacturing industry to benefit from academic research. This enables access to real production environments and practical research in the future.

6.2 Managerial Implications of the Study

It is suggested in the literature that operators make mistakes in situations where tasks do not follow routines and manufacturing becomes more complex. This research is in with the hypothesis to some extent. The main findings are to make production tasks routine-like tasks by applying poka-yoke applications in the most problematic production tasks. Those tasks that cannot be mistake-proofed by applying poka-yoke applications, should be taken into the realm of human quality assurance such as sampling or even self-checks/successive checks completed by the operators as a part of the process.

In MTO production environment, complex, mistake-prone situations are common in phases where products are customized according to customers' wishes. In the case company, the customization is done in all manufacturing phases: the right sensors are selected in the first phase, later the base unit of the product is manufactured, which includes selecting the right base parts. Whenever possible, companies should try to split phases into those with customizability and those without. This, of course, is not always possible or even desirable dependent on the company's strategy.

This research suggest that the number of decisions made by the operators correlates with the number of mistakes made. As a general rule, it could be beneficial to try to decrease the amount of decisions operators have to make by applying poka-yoke systems into the process. In the best case poka-yoke applications can be used to make non-routine tasks routine. This in turn should make the task easier to mistake-proof.

When decreasing defects in production, poka-yoke applications should be applied in phases were there are plenty of defects that are caused by the same mistake. The poka-yoke applications should always be evaluated for the most common mistakes as a part of a continuous process. In the long run, this tends to free resources from quality control units to focus on less common mistakes.

6.3 Limitations of the Study

The study was conducted with a case company. The characteristics of mistakes and poka-yoke applications depends on the manufacturing process. More research of the topic is needed to make further generalizations.

This study was made as an action research, which makes it possible for the researcher to be an active actor on the shop floor. Four different poka-yoke applications were brainstormed but it does not mean that those four ideas would be the best solutions. The voice of the researcher had an effect on the selected poka-yoke applications. It is possible that the applications would have been different if the research would have been made by someone else.

The goal of this study was to find ways to reduce the number of customer complaints by applying poka-yoke methods and the goal was achieved. However, the set-up where the study focused on the customer complaints has its limits when the most common error types are researched. The study did not take the inspections of the quality control team into account, which could change the results. The quality control team makes inspections based on sampling and for some products 100% of the units are inspected. If the quality control team is able to find the defects in inspected products, they will not cause customer complaints and these quality issues will not be seen in the customer complaint data.

Two different solutions were tested in this study: a light system and a scale system. Both systems proved promising results because customer complaints have not emerged since launching the pilots. However, it needs to be acknowledged that the observation period of ten weeks is short. For instance, the light system was piloted in Production cell 2, which did not have any packing errors even ten weeks prior to the pilot. However, mistakes were made relatively often before the ten weeks prior to the pilot so it is difficult to say exactly how big of an impact the pilot had. No improvements were made before the light system pilot so better quality can be a consequence of the operators' manufacturing skills.

6.4 Future Research

This research applied poka-yoke methods to make material picking process easier for the operators. More research is needed to research whether poka-yoke methods could be applied in the manufacturing processes that include assembly. Applying poka-yoke methods in manufacturing phases where products are assembled seems difficult because the customization requires a certain level of modularity where several different parts can be used. Traditional physical poka-yoke applications tend to work so that only one part and position is allowed in manufacturing. Research in different manufacturing environments is needed to find out if the only way to prevent wrong assembly is to ensure that right parts are used in advance.

In this study it is suggested that the risk of mistakes is elevated when the amount of decisions made by human operators are elevated. This finding was unexpected by the researcher so the average number of decisions in every manufacturing phase was not counted in this study and the conclusion cannot be verified. However, it could be a potential research topic for mistakes in MTO production or production environments in general.

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