LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology Management
Department of Industrial Management

POKA-YOKE FOR MASS CUSTOMIZATION

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ABSTRACT

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Producing high quality products and services is one of the key concerns in order to keep up with the competition in the global markets. Companies are putting a great effort on preventing customers having faulty products and services by any means. However, the total elimination of mistakes in manufacturing processes has always been a great challenge for quality management.

In this thesis the applicability of *poka-yoke* methodology in reducing the number of quality failures in the case company has been studied. *Poka-yoke* stands for the mistake-proofing and is mainly developed for the purpose of eliminating human errors in manufacturing processes. Inspection techniques; *judgment, informative and source inspection* are in the core of this methodology.

Mass customization and large configurability of products leads to situation where the root causes of quality problems may vary a lot. To study the effects of these factors extensive analysis of quality failures was conducted. Recommendations and proposals for further actions regarding problem solving processes and utilization of mistake-proofing methods were provided on the basis of the analysis.

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Korkealaatuisten tuotteiden ja palveluiden tuottaminen on yksi tärkeimmistä edellytyksistä pysyä mukana kilpailussa globaaleilla markkinoilla. Yritykset tekevät jatkuvia panostuksia varmistaakseen keinoilla millä hyvänsä, että vialliset tuotteet ja palvelut eivät päätyisi loppuasiakkaalle asti. Tästä huolimatta, virheiden eliminointi valmistusprosesseissa on ollut ainainen haaste laatujohtamiselle.

Tässä diplomityössä tutkittiin *poka-yoke* metodologian soveltuvuutta laatuvirheiden vähentämiseen kohdeyrityksessä. *Poka-yoke* tarkoittaa virheiden ehkäisemistä ja se on alun perin kehitetty inhimillisten virheiden eliminoimiseksi. Menetelmän ydin on tarkastustekniikoissa, joita ovat toteava ja tiedottava tarkastus sekä lähdetarkastus.

Massaräätälöinnistä ja tuotteiden laajasta konfiguroitavuudesta johtuen juurisyyt laatuongelmiin liittyen voivat vaihdella paljon. Näiden selvittämiseksi toteutettiin kattava laatuvirheanalyysi. Analyysin perusteella annettiin toimenpidesuosituksia ja ehdotuksia ongelmanratkaisuprosessien kehittämiseksi sekä laitetehtaalla tapahtuvien vihreiden eliminoimiseksi kohdeyrityksessä.

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This research project and the writing of Master's thesis has been a culmination for my studies in Lappeenranta University of Technology. Many challenges have been faced during this project but at the same time it has been very interesting and rewarding.

Now that I am finishing this thesis, I would like to give my warmest thanks to the various people in the case company who have contributed to this work during these months. Without your valuable and professional comments and criticism and outright support this wouldn't have been possible.

Specially, I would like to express my gratitude to my supervisor, Professor Janne Huiskonen, for his constructive comments and guidance, and to my instructor M.Sc. Matti Pilviö, for his ideas and support throughout the research project.

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1 INTRODUCTION

This chapter introduces the background and motivation for the thesis, defines the research problem and set objectives for this study. An overall structure of this thesis is also provided.

1.1 Background and motivation

Producing high quality products and services to fulfil customers' requirements is the most pursued target of every company in the world. However, there is no such a company or a system where no mistakes are made or none faulty products are delivered to customer. This is the problem companies have to face every day; how to make sure that customers are receiving products and services exactly as they have ordered and how to detect possible quality non-conformances as early stage as possible in manufacturing processes.

Inspection is the most important element of quality control. The aim of inspection is to detect faulty products from non-faulty products. Although increasing the level of inspection may improve outgoing quality levels and help with controlling processes in high defect levels, it won't prevent defects from occurring. Decreasing the level of quality failures and producing high quality products comes not from the inspection but from the improvement of the process.

This master's thesis is conducted by the request of the case company to study the possibilities in declining the increased level of quality failures according to the chosen theoretical approach, known as poka-yoke methodology.

Case company develops, manufactures and markets products and services for environmental and industrial measurement in global markets. The mission is to provide basis for better quality of life, environmental protection, safety and productivity. Case company's major customer groups are meteorological and hydrological institutes, aviation organizations, defence forces, road and rail organizations, weather related private sector, system integrators and industry worldwide.

Mass customization and large configurability of products has its own problems and challenges regarding quality control. Especially, when the level of automation is low the possibility of making human errors exists if processes are not mistake-proofed. A large number of case company's existing quality failures can be considered to be caused by human errors. By utilizing the principles of poka-yoke methodology case company aims at lowering the level of quality failures by eliminating the possibility of making human errors.

1.2 Research problem and objectives

The main research problem of this thesis can be stated as follows:

"Recognition of the root causes of quality failures and their elimination by utilizing poka-yoke methodology in the production environment of mass customized products"

In addition, possibility to utilize poka-yoke methodology over the organizational boundaries is examined.

In order to provide a logical approach to the research problem the following objectives are set up for this study:

- to provide an extensive theoretical literature review of poka-yoke methodology and problem solving models
- to conduct a thorough analysis of case company's quality failures and problem solving methods
- to provide recommendations for existing quality failures according to the principles of poka-yoke methodology

- to define a model for the systematic utilization of mistake-proofing efforts in the case company

The greatest importance of this study is paid on the literature review of poka-yoke methodology and quality analysis conducted in the case company. In addition, to get familiarized with this specific methodology and its principles the analysis of quality failures is taken into the new level from the case company's point of view. Totally novel quality metrics are gathered and analyzed to provide a strong basis for the support of further recommendations and improvement efforts. The results of these analyses have also been utilized widely within the ongoing Production Quality-project in the case company.

However, due to limited time and resources the main emphasis was on providing recommendations for the quality problems, only few implementations were executed during the study and therefore the effectiveness of the efforts can't be largely assessed. On the basis of my study and experiences so far, poka-yoke methodology seems to be a considerable approach for many quality improvement efforts. The findings of the literature study can be generally applied to other contexts; however the findings of the empirical part are solely valuable and usable in this context due to case-specific characteristics of quality failures.

1.3 Structure of this thesis

This thesis consists of three main sections; the literature study, the empirical study and the summary. Results and recommendations are provided in the empirical part of the thesis. The third section summarizes the topics discussed and provides some future perspectives. Structure of this study is provided in figure 1.

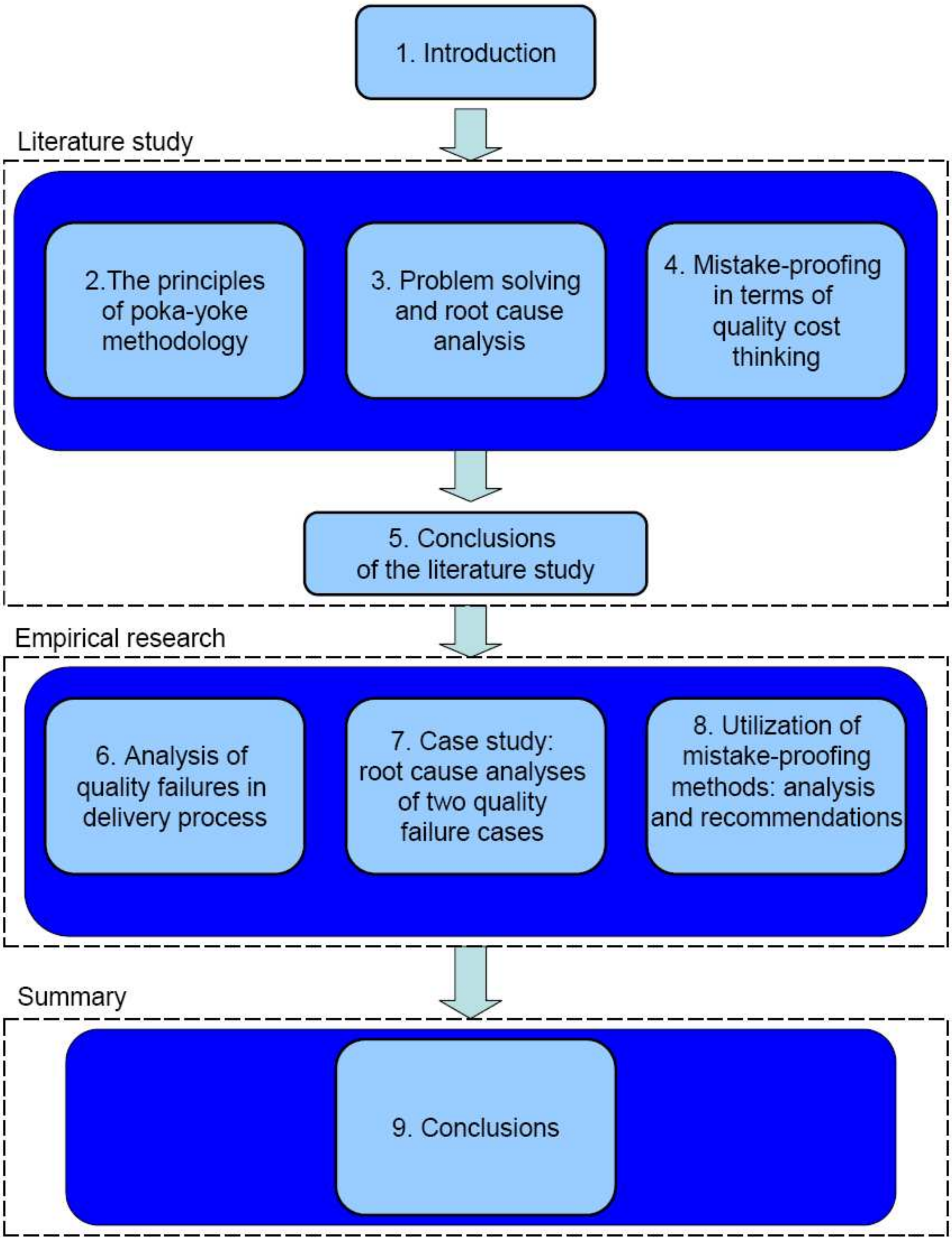


Figure 1. Conceptual structure of this study.

PART I: LITERATURE STUDY

2 THE PRINCIPLES OF POKA-YOKE METHODOLOGY

This chapter introduces a theoretical background of poka-yoke methodology. The main objective is to provide an extensive overview of the principles of poka-yoke methodology and to clarify its position in the field of quality management. Instead of concentrating on detailed characteristics of physical poka-yoke devices, clarifying main theses in the background of this methodology are in the core scope of this literature study.

2.1 History and definitions of poka-yoke

It was year 1961 when Dr. Shigeo Shingo, an industrial engineer at Toyota Motor Corporation, introduced the concept of poka-yoke. Based on Shingo's long-term experience and observations, he developed the concept of poka-yoke and turned it from the idea into a formidable tool; a tool for achieving zero defects and eventually eliminating the need of quality control inspections. Since then, "poka-yokes" have been an integral part of Japanese quality and manufacturing systems. (Manivannan, 2006; Shimbun, 1988)

In its early days, term *poka-yoke* was known as *baka-yoke*, meaning fool proofing. In the operator's point of view this term wasn't very attractive, because of term's dishonorable and offensive connotation. Soon after the name episode in one of the Japanese car manufacturing plants in 1963, the term to describe this methodology was changed to poka-yoke. The term "poka-yoke" stands for mistake-proofing; referring originally devices which serve to prevent (or proof, in Japanese "yoke") the sort of inadvertent mistakes ("poka" in Japanese) that anyone can make. (Manivannan, 2006; Shingo, 1986)

Many definitions for poka-yoke methodology can be found from the literature. The following statements describe best the idea of poka-yoke from different aspects:

> *"The original idea behind poka-yoke is to respect the intelligence of workers. Poka-yokes are for freeing worker's time and mind to pursue more creative and value adding activities" - N.K. Shimbun, 1988*

> *"Error proofing is not so much a lean "tool" as it is a way of thinking and evaluating problems. It is based on a philosophy that people do not intentionally make mistakes or perform the work incorrectly, but for various reason mistakes can and do occur" -*
> *J.K Liker and D. Meier, 2006*

> *"Defects = 0 is absolutely possible" - Shigeo Shingo, 1986*

Poka-yokes were originally developed for manufacturing, considered primarily physical devices to prevent mistakes from occurring. Nowadays the whole concept of poka-yoke has a much more extensive purpose; it can be seen as a tool, as an effective quality control technique and finally as a quality philosophy. The basic principle behind all these "levels" is the prevention of defects. The creator of poka-yoke concept, Shigeo Shingo, believed that defects could simply be eliminated in the first place, instead of relying on measures taken on after-the-fact. According to Shingo (1986), mistakes that lead to defects can be engineered out of the processes and defects can be eliminated this way.

The well-known quality guru, Edward Deming, has once stated that "quality comes not from inspection, but from improvement of the process" (Manivannan, 2006). This statement is also the heart of the poka-yoke philosophy. Rather than looking for defects after the fact, a true goal is to create processes that yield zero defects (Manivannan 2006).

2.2 Errors and defects in mistake-proofing

In order to have a thorough understanding of mistake-proofing, an understanding of why mistakes occur and what human factors make mistakes less likely is appropriate (Stewart & Grout, 2001). In addition, discussion of what do the words "mistake", "defect" and "error" mean in the context of mistake-proofing is provided.

Shingo has made a clear distinction between a mistake and a defect. Mistakes are inevitable; people are human and cannot be expected to concentrate all the time, or always understand completely the instructions they are given. Defects results from allowing a mistake to reach the customer, and are thus entirely avoidable (Fisher, 1999). Manivannan (2007) defines that a *defect* is any deviation from product specifications that may lead to customer dissatisfaction. To be considered defective, the product must deviate from manufacturing or design specifications, and it must not meet the expectations of internal or external customers.

According to Shingo (1986) the causes of defects lie in worker errors, and defects are the results of neglecting those errors. It follows that mistakes will not turn into defects if worker errors are discovered and eliminated beforehand. On the other hand, from the source inspection’s point of view, Shingo (1986) states that defects arise because errors are made and these two have a cause-and-effect relationship. Errors will not turn into defects if feedback and action takes place at the error stage.

2.2.1 Human error classification

Shimbun (1988) classifies 10 different kinds of human errors, which are presented in table 1. Also Grout (1995) states about mistakes that to err is human. According to these, we will sooner or later come to the conclusion that almost all defects are caused by human errors.

Table 1. Classification of human errors (Shimbun, 1988).

Type of human error	Example
Forgetfulness	Sometimes we forget things when we are not concentrating
Errors due misunderstanding	Sometimes we make mistakes when we jump to the wrong conclusions before we are familiar with the situation
Errors in identification	Sometimes we misjudge a situation because we view it too quickly or are too far away to see it clearly
Errors made by amateurs	Sometimes we make mistakes through lack of experience
Willful errors	Sometimes errors occur when we decide that we can ignore rules under certain circumstances
Inadvertent errors	Sometimes we are absentminded and make mistakes without knowing how they are happened
Errors due to slowness	Sometimes we make mistakes when our actions are slowed down by delays in judgment
Errors due to lack of standards	Some errors occur when there are no suitable instructions or work standards. For example, a machine might malfunction without warning
Surprise errors	Errors sometimes occur when equipment runs differently than expected
Intentional errors	Some people make mistakes deliberately

As this classification points out, the possibility of making a human error is very remarkable especially in manufacturing and assembly tasks. In order to obtain a satisfactory level of quality failures human errors should be eliminated or at least the making of them should be made very difficult.

Referring to Shingo's (1988) statement that the causes of defects lie in worker errors and defects are the results of neglecting those errors, both Shimbun (1986) and Hinckley (2001) have studied various types of defects and their relationship to human error types (see figure 2). They are particularly useful for anticipating mistakes and mistake-proofing the product design and production process.

◎ Strongly connected ○ Connected

Causes of defects \ Human errors	Intentional	Misunderstanding	Forgetful	Misidentification	Amateurs	Willful	Inadvertent	Slowness	Non-supervision	Surprise
Omitted processing	◎	○	◎	○	○	○	◎	○	○	
Processing errors	◎	◎	○	○	◎	◎	◎	◎	◎	
Errors setting up workpieces	○	○	◎	○	○		◎	○	○	
Missing parts	◎	○	○		○	○	◎		○	
Wrong parts	◎	◎	◎	◎	◎	◎	◎		◎	
Processing wrong workpiece	○	◎	◎	○	○	◎	◎		○	
Misoperation			○				○		○	◎
Adjustment error	○	○	○	◎	○	◎	○	○	○	○
Improper equipment setup			○				◎			◎
Improper jigs and tools			○				◎			○

Figure 2. Cause-and-effect relationship (Shimbun, 1988).

Based on the cause-and-effect relationship between defects and mistakes there can be seen clear connections between them. Some types of defects occur more frequently than others. This frequency of each type of mistake varies by the each task, organization and individual. (Hinckley, 2001)

2.2.2 Classifying mistakes

Mistakes can also be classified in many ways. Hinckley (2001) has collected a wide range of classification methods used in mistake-proofing literature (see table 2). Although the underlying principles for mistake-proofing are extremely simple, a large fraction of mistake-proofing solutions require unique adaptations to specific problems. Thus, the point of mistake-proofing is not only to classify mistakes and defects unambiguously, but to find best available solution to the problem. Hinckley (2001) points out that the classification schemes have led to better understanding of mistakes and human limitations; however they are not independently useful for mistake-proofing. The great value of mistake-proofing is that, independent of the cause, psychological factor, production stage, or potential consequences it blocks or warns about an undesired outcome at a stage in the process when the consequences can be minimized.

Table 2. Classification methods of mistakes (Hinckley, 2001).

Mistake category	Cause examples
Causal factors	fatigue, poor lightning, urgency, interruption
Project phase	design, fabrication, assembly
Ergonomic factors	perception, decision, action, skill, training
Human error probability	error frequency, human performance
Stress factor	workload, occupational change, or frustration
Mistake consequences	injury, loss, damage
Function or task	welding, milling, detailing, inspecting
Behavioral factors	communication, motor processes, perception
Corrective action	rework, repair, scrap

2.3 Inspection techniques in the field of quality control

Inspection is the most important element of the mistake-proofing and quality control. Inspection is essentially comparison between a product or a service and proper requirements; any deviation from these requirements might be considered as an abnormality (Ghinato, 1998).

Most people have only a narrow view on what "inspection" really is in the context of quality control. According to Shingo (1986), inspection systems consist of three inspection methods: *judgment inspections*, *informative inspections* and *source inspections*. These inspection methods will be presented more thoroughly in the following sections. Compared to Shingo's view on inspection methods, many plants have traditionally executed only one of these inspection methods; judgment inspections. The purpose of this inspection type is only to categorize finished products as defective or acceptable (Shingo, 1986).

According to Shingo (1986), each inspection method has a different objective:

- judgment inspection for discovering defects
- informative inspection for reducing defects
- source inspection for eliminating defects

The objective of inspection is closely related to the nature of the abnormality to be detected. Inspection for discovering defects is designed to identify defects resulting from abnormal processing. Inspection for eliminating defects in turn depends on detecting errors during processing and taking immediate corrective action in order to avoid such error-originated defects. (Ghinato, 1998)

As mentioned earlier, judgment inspection is most widely used method in quality control purposes. However, for no matter how accurately and thoroughly it is performed, it can not in any case contribute a lowering of the defect rate in the plant itself. This inspection method has no value for bringing down the defect rates in the plants (Shingo, 1986). According to Shingo's classification, judgment inspection is the lowest order of inspection. The effective use of informative and source inspection will itself keep defective goods from moving on either to customers or to subsequent processes.

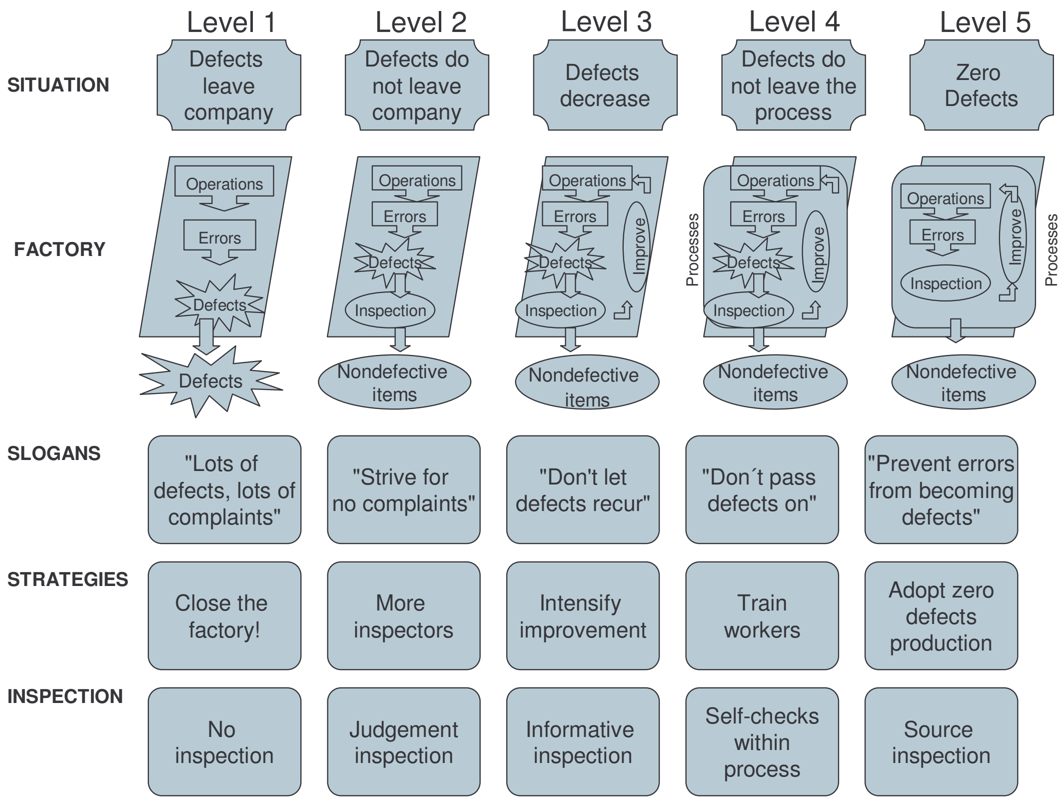


Figure 3. Levels of quality control (Shimbun, 1988).

The field of quality strategies is summarized in the figure 3. It illustrates how the utilization of specific inspection method effects on the number of detected defects. In the worst case (level 1) any kind of inspection process doesn’t exist, which results that customers receive lots of faulty products. On the level 3, informative inspections have been utilized in different stages of manufacturing processes and defects are detected effectively in-house processes. Only handful of faulty items may pass to the customer. In the most desired stage (level 5), errors do not turn into defects while they are detected already at their source. As this comparison also points out, the movement is from corrective mode to gradually more and more preventive mode.

2.3.1 Judgment inspection

Judgment inspection is the traditional inspection process of identifying products that are defective before they are released for distribution. This is sometimes referred to as "inspecting in quality" (Fisher, 1999). From the cause-and-effect point of view the judgment inspection is solely based on detecting defects (effects) in the products rather than detecting errors (causes) during processing (Ghinato, 1998). An example of this type of inspection could be a "go" or "no go" test for electronic components. Usually the information obtained from judgment inspection is generally not useful in controlling the upstream processes (Hinckley, 2001).

It has slowly started to gain acceptance in the modern world that achieving world-class quality is not done by detecting every defect and removing or repairing the defective products (Hinkley, 2001). Firstly, it is extremely huge waste of money to inspect every finished product and secondly, another drawback of judgment inspection according to Ghinato (1998) is the inefficiency of feedback function: the execution of counter-measure takes a long time.

2.3.2 Informative inspection

The second type of inspection process is the informative inspection. The aim of the informative inspection is as soon as a defect has occurred transmit all the relevant information to the person in charge of that particular process and start corrective action immediately (Ghinato, 1998). As Shingo (1986) describes informative inspection method suggest that continuous correction and improvement of processing leads to a gradual decrease of defect rate. According to Shingo (1986), informative inspection methods can be divided into three categories:

- Statistical Quality Control (SQC) (also known as Statistical Process Control SPC)
- Successive Checks
- Self-Checks

Statistical Quality Control (SQC)

Statistics and its related quality control tools were and are still widely used in the manufacturing companies around the world already since 1950s. SQC is a sort of informative inspection technique; it uses statistically based control charts to reduce future defects by feeding back information about defects to the offending processes. Typical to SQC is also the use of statistics to set control limits that distinguish between normal and abnormal situations. (Shingo, 1986)

Compared to judgment inspection, SQC provides advancement in quality control because feedback from the inspection can be used to guide upstream processes (Hinckley, 2001). Robinson and Schroeder (1990) have stated that perhaps the most profound impact of SQC has been the rationalizing and systematization of the information gathering and feedback processes. However, SQC has also some limitations. Problems in processes cannot be reacted or detected until some process deviation has occurred (Hinckley, 2001).

Successive Checks

The birth of successive check method was in 1960, when Shingo suspected that there should be an inspection method more effective than the statistical quality control. Sampling inspection should be replaced by 100 % inspection. The problem concerning 100 % inspection is that it is expensive and takes a lot of time and trouble. But if low cost 100 % inspections could be devised, wouldn't it be preferable? That's the point where Shingo realized that solution for the problem would be the effective use of poka-yoke mechanism. (Shingo, 1986; Ghinato, 1998)

Successive checks involve having each operation inspect the work of the previous operation. Each operation therefore performs both production and quality operations. This kind of inspection is very useful for example in assembly lines, where one person performs one operation. The power of successive checks is the immediate feedback. The corrective action could be taken immediately after the detection of any abnormality. (Stewart & Grout, 2001; Shingo, 1986)

Harmon (1992) introduces in his book "Reinventing the factory II" features of the effectiveness and cost-efficiency of successive checks:

- The inspection performed by the following worker is automatic and free. It does not require additional and sophisticated resources for pre-processing inspection.
- The rate of defects which occur due to the lack of attention of the first worker decreases enormously when 100% inspection is executed by the worker of the following process.
- Defects originated from previous processes interfere in positioning, assembling and processing at subsequent stages, what ensures compulsory and costless appraisal.
- Inspection performed by people independent from the particular is more effective and reliable.

Self-Checks

The third and the most effective informative inspection method is self-check system. Self-checks use poka-yoke devices to allow each operation to assess the quality of their own work. Because they check every unit produced, they may be able to recognize what circumstances changed that caused last unit to be defective (Stewart et al., 2001). The effectiveness of self-checks is due to instantaneous feedback; the detection of abnormality performed by the worker is immediate, and the corrective action can be quickly applied.

There are a few aspects which separate self-checks form successive checks. For workers it has less psychological resistance to discovering abnormal situation themselves than having them to be pointed out by others. Also, being able to see the reality of abnormal situation with ones own eyes allows one to understand its true causes, and more appropriate and effective countermeasures can be worked out and implemented. (Shingo, 1986)

2.3.3 Source inspection

Source inspection is the most effective form of inspection techniques. It determines beforehand whether the conditions necessary for high quality production exists (Stewart et al., 2001). According to Shingo (1986) the occurrence of a defect is the result of some condition or action, and it would be possible to eliminate defects entirely by pursuing the cause. Source inspection uses poka-yoke devices to detect improper operating conditions prior to actual production.

Essential to the method of source inspection is the identification and the control of causes and defects. Effective utilization of source inspection method depends on acknowledging the existence of cause-and-effect relationships between errors and defects, the identification of errors and the application of counteractive techniques. (Ghinato, 1998)

The main difference between source inspection and judgment or informative inspection is in the viewpoint of control function. Control function is illustrated in the frame of management cycle in the figure 4. Normally quality management systems carry out control or management in large cycles with following steps:

- an error (cause) happens but is not noticed;
- a defect (effect) consequently occurs and is then detected;

- feedback is prompted;
- corrective action is implemented.

Instead, in source inspection, the control function occurs in smaller loop, having more effect on causes rather than effects:

- error (cause) takes place and is detected;
- feedback is promoted at the error stage;
- proper corrective action is then implemented

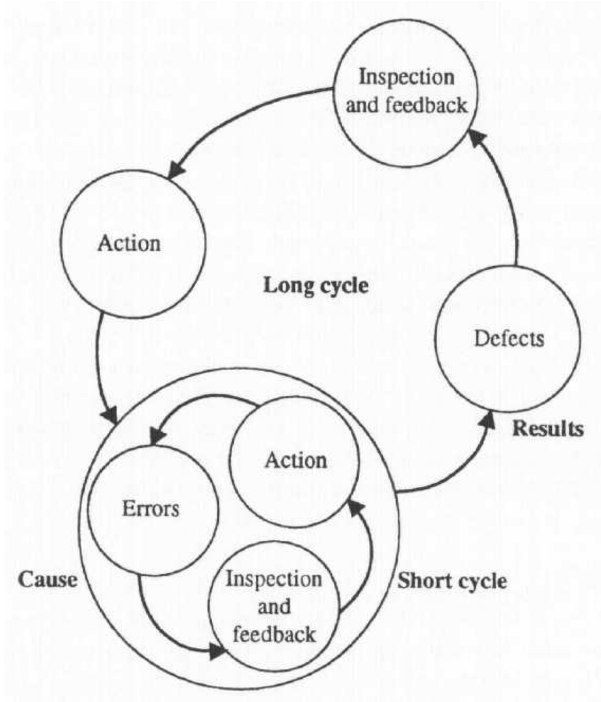


Figure 4. Control function and inspection methods (Shingo, 1986).

As this comparison points out, putting the focus of control on the cause of abnormalities, the corrective actions are always directed to processing rather than to products as it occurs in the long control cycles of judgment and informative inspection. (Shingo, 1986; Ghinato, 1998)

2.3.4 Summary of inspection methods

As the examination of inspection methods points out the effectiveness of inspection methods is based on three major aspects, summarized in the figure 5.

The first aspect covers the inspection technique; whether the inspection is executed through sampling method or by 100 per cent inspection. According to poka-yoke methodology 100 % inspection is the only way to control human errors effectively enough and thus recommended.

Objective of Inspection	Inspection method		Inspection technique		Feedback			Focus of inspection	
			Sampling	100 %	Long	Short	Immediate	Effect (defects)	Causes (errors)
Inspection to discover defects	Judgement inspection		☆	☆	☆	—	—	☆	—
Inspection to reduce defects	Informative inspection	Statistical methods	☆	—	—	☆	—	☆	—
		Successive inspection	—	☆	—	—	○	○	—
		Self-inspection	—	☆	—	—	☆	☆	—
Inspection to eliminate defects	Source inspection		—	★	—	—	★	—	★

Poka-yoke (100 % – Immediate)

Zero Defect Quality Control (ZDQC) (Short – Causes (errors))

Figure 5. Characteristics of quality control methods (Shingo, 1986).

Feedback function describes the delay between the occurrence of a defect and detecting a defect. In judgment inspection an error may have turned into a defect in very beginning of the production process, but is noticed until inspecting the finished products. Due this it may be challenging to localize the point where a defect has occurred and what where the existing circumstances. In addition, the information obtained may be useless to control upstream processes anymore. In informative and source inspections feedback is provided much faster, almost immediately; which makes immediate corrective actions possible. The number of faulty WIP (work-in-progress) products can be thus minimized.

The latest aspect concentrates on the focus of inspection. In jugdement and informative inspection detection is based on existing defects while source inspection concentrates on possible errors. The latter inspection method is naturally preferable because it detects errors before they even have turned into defects.

2.4 Types of poka-yoke systems

Poka-yoke devices can perform three useful operations in defect prevention. These operations or functions are conducted from three stages mistakes can occur. Combining Bayers (1994) and Hinckley (2001) the state of mistake and specific related functions of poka-yokes are as follows:

- Mistake is about to occur - Warning
- Mistake has already occurred but has not yet resulted in a defect - Control
- The mistake has caused a defect - Shut down

Mistake-proofing methods have three basic functions to use against mistakes; control, shutdown and warning (see figure 6). Control prevents mistakes, defects, or the flow of defective items to the next process. Shutdown stops normal functions when mistakes or defects are detected or predicted. Warnings signal that an abnormality, mistake or defect has been detected. Recognizing that a mistake is about to occur is "prediction", and recognizing that a mistake or defect has already occurred is "detection". (Hinckley, 2001)

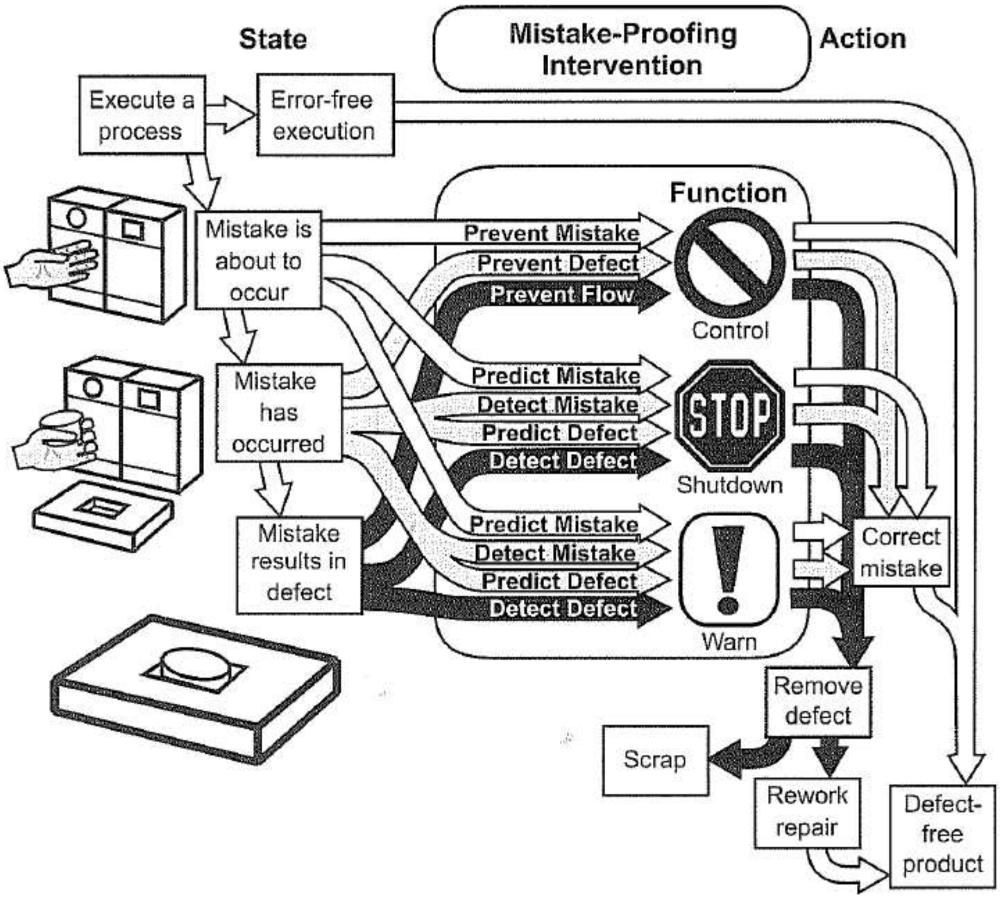


Figure 6. Three possible states of mistakes with three functions of poka-yoke (Hinckley, 2001).

Warning function is a less powerful function compared to the other functions. It demands that worker's attention is captured; otherwise defects will continue to occur. Typical examples of warning methods are lights and noises. The use of warning methods may be considered either where the impact of abnormalities is slight or where technical or economical factors make the adoption of control methods extremely difficult. (Shingo, 1986)

Control and shutdown functions are the most effective mistake-proofing methods. By deploying poka-yoke devices throughout a process in order to prevent errors, defects will not occur. Also when an error is detected, an operation can be shut down preventing defects from occurring. This is very typical approach to Japanese manufacturing which encourages workers to stop the line immediately when a problem or defect is detected (or is about to occur) and then correct it quickly as possible. (Bayers, 1994; Liker & Meier, 2006)

Control, shutdown and warning are functions which all use specific techniques to work. The most common types of setting function techniques, according to Shingo (1986), are *contact method*, *fixed-value method* and *motion-step method*. Contact methods are usually sensing devices to detect abnormalities in product shape or dimension by whether or not the contact is made between the products and sensing devices. In fixed-value method, abnormalities are detected by checking for the specified number of motions in cases where operations must be repeated a predetermined number of times. In motion-step method abnormalities are detected by checking for errors in standard motions in cases where operations must be carried out by predetermined motions.

2.5 Design principles for poka-yokes

Physical and operational poka-yokes involve installing devices that eliminate conditions that may lead to an error or making modifications that reinforce the correct procedure sequence. Bayers (1994) states, that the most difficult part of the poka-yoke process is getting started. After that, deployment is usually easy because workers and management can see immediate benefits. Shingo (1986) presents three elements which help at getting started when designing poka-yoke methods:

- Characteristics
- Process deviations and omissions
- Value differences

2.5.1 Characteristics

Bayers (1994) takes a closer look to design tips of poka-yokes in his article "Using poka-yoke (mistake-proofing devices) to ensure quality". According to him (conducted originally from Shingo) characteristics can include measurable or descriptive factors such as *weight, shape* or *dimension.* Weight is used widely in assemble, for example detecting a missing parts or otherwise incomplete packaging. Of course this requires that physical materials should be heavy enough to be detected.

Concerning the *shape* of physical component, different kinds of jigs and guide rails are deployed to prevent insertion of the assembly into a machine if it is not positioned correctly. Also the idea of making component leads in different shapes to ensure proper positioning falls within this category. *Dimension* is also very practical characteristic for the basis of poka-yoke design. For example automobiles that accept only unleaded fuel have a fuel port that will not accommodate a fueling nozzle from a leaded fuel source. (Bayers, 1994)

2.5.2 Process deviations and value differences

Process deviations refer to situations where, for example, some phases of certain process are skipped intentionally or unintentionally resulting in defects. This can mean that products are delivered without testing to the customers. A typical poka-yoke solution for this kind of situation could be that shipping labels would not be printed until the final test has been passed. (Bayers, 1994)

Differences of values can be used in design basis for example in the case of omitted parts. In complex assemblies where certain number of different parts should be manually added this poka-yoke design approach is very useful. An example of this is packaging kits of parts for each unit assembled. If any of the parts is left over to packaging kit, you'll visually see that something is omitted from assembly. By all its simplicity, this poka-yoke method is effectively employed by surgeons, using it to indicate if all instruments have been removed from patients prior to closing an incision. (Bayers, 1994)

2.6 Zero Quality Control

Zero quality control (ZQC) is the ideal production system - one that does not manufacture any defects, developed by Shigeo Shingo. Zero quality control ensures that a manufacturing system is able to produce defect-free products consistently through the identification and control the causes (errors) of defects. (Ghinato, 1998)

Zero quality control has three main components that according to Shingo lead to the elimination of defects:

1. *Source inspection* to detect errors at their source - before they cause defects.
2. *100 percent inspection* – use of inexpensive poka-yoke (mistake-proofing) devices to inspect automatically for errors or defective operating conditions.
3. *Immediate corrective action* - Operations are stopped instantly when a mistake is made and not resumed until it is corrected.

Achieving zero defects is possible to achieve only by combining all of these components. These components, according to Shingo, are weighted in importance as follows:

- source inspection - 60 %
- 100 percent inspection (poka-yoke) - 30 %
- immediate action - 10 %

2.7 Company-wide mistake-proofing

Many people think of poka-yoke techniques only as the application of limit switches, guide pins or automatic shutoffs implemented by the engineering department. As Manivannan (2006) states, this is only a narrow view of poka-yoke mechanism. Poka-yoke mechanism can be electrical, mechanical, procedural, visual, human or any other form that prevents incorrect execution of a particular process. Thus poka-yokes can be implemented in the areas such as sales, order entry, purchasing and product development where the cost of mistakes is actually much higher than the cost of mistakes that occur on the shop floor. (Manivannan, 2006)

There are large varieties of possible mistakes that can be found from the areas mentioned above. For example from the sales point of view it should be mistake proofed to prevent sales persons to sell wrong products to wrong applications. According to VTT survey in 2004 of quality defects in subcontracted products, the results show that the large amount of delivery delays were caused by defective documents and instructions (Pötry, 2004). This points out that mistakes and neglects in design and administration become visible until after a long period of time and the making of corrective action is then much costly.

2.8 Poka-yoke implementation process

Implementing poka-yoke devices or mistake-proofing processes in a company can be executed in many ways. Implementation process can vary a lot; depending on the application mistake-proofing efforts will be used. Thus, if poka-yoke effort is only to implement a tool instead of implementing mistake-proofing methods covering a large process, the approach will be different.

Various ways and stages of implementation process are presented in the literature. The following framework summarizes a few important steps which are recommendable to follow at some level:

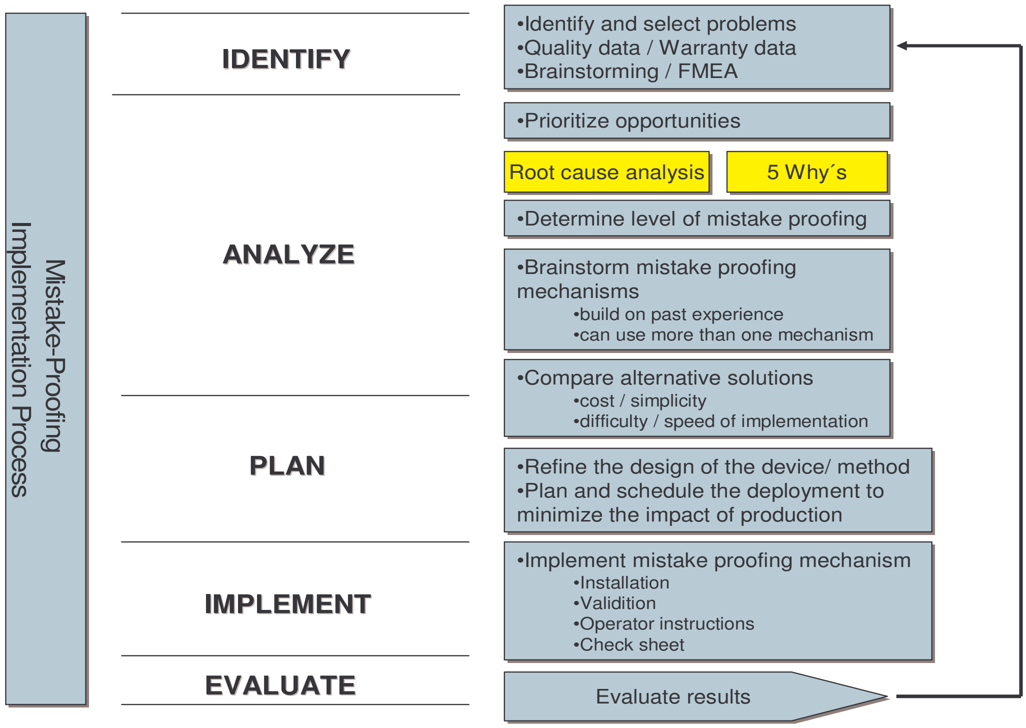


Figure 7. Framework of implementation process (Adopted from Smith (2004) and Hinckley (2001)).

As above framework shows, there are certain steps that can be followed when implementing mistake-proofing efforts. First step is to identify and select problems, using for example existing quality data. Second step is to analyze the urgency of solving the problem and identifying the root causes of observed defects. The following steps concentrate on generating, comparing and selecting the right mistake-proofing efforts and after that planning and scheduling deployment. In the last phase mistake-proofing method will be implemented, with familiarizing and training operators. After short period of time it is time to evaluate the results. It is important to determine if a problem has been solved and if the solution is incomplete then identify other actions that need to be taken. If the solution has broad application, the company should work to standardize implementation across a company. (Hinckley, 2001)

Poka-yoke mechanism can be a very effective tool for improving quality. However, it is important to remember that using poka-yokes have some constraints and it is not an effective solution for every quality problem. Wherever possible, the use of poka-yoke mechanism is anyway very advisable. Brownhill 2005) states, that if mistakes cannot be completely designed out of the product or process, then the highest mistake-proofing level possible for the application should be used (see figure 8).

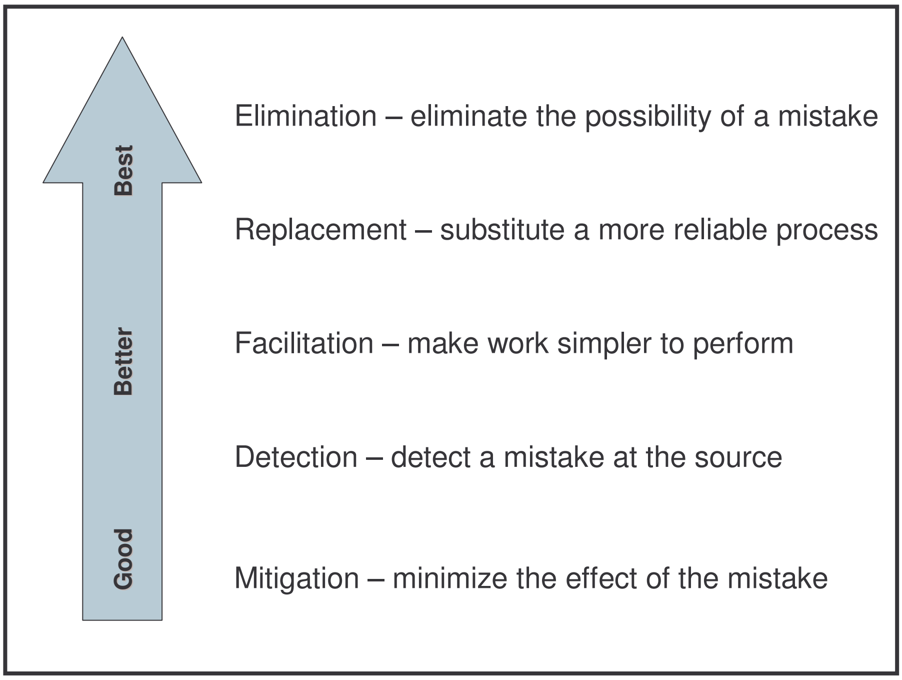


Figure 8. Mistake-proofing levels (Brownhill, 2005).

An American mistake-proofing expert, John Grout, has experience on a few situations where mistake-proofing efforts have not worked well. According to his article "Mistake-proofing production" (1997), these situations can be found from the area of very high-speed production, destructive tests and where the use of control charts is very effective. When the production process has output rates that are very rapid, inspections must be nearly instantaneous to be effective. Even, if the inspection process slows down production slightly, the cost over the long run may be substantial. Concerning destructive testing the use of 100 % inspection has no sense at all. In this case, use of statistical sampling and inference is required. Also effective use of control charts replaces the need for self-checks when products have well-defined specifications and they use accurate measurement system.

2.9 Objectives of poka-yoke implementation

Implementing poka-yoke methods have both short and long-term objectives. Thus, the benefits can be direct and indirect. Usually the most obvious benefits are seen in the assembly floor. According to Hinckley (2001) the amount of scrap material will be reduced and also rework and repair costs will be cut. Manivannan (2006) summarizes four types of long-term objectives for implementing poka-yokes:

- Competitive advantage: Cost of quality is an important part of company’s competitive advantage in the global markets; it costs far less to prevent defects occurring in the first place
- Knowledgeable workers: Understanding the principles of mistake-proofing helps to participate defect elimination
- Predictability: Poka-yoke devices and methods assures defect-free products and services and thus reduce the need for traditional inspection and rework operations
- Reduced variation: Mistake-proofing devices ensure that all sub-assemblies and completed assemblies are exactly the same. There will be little chance of part-to-part variation (standardization)

Mistake-proofing efforts also enhance safety issues because more attention is paid on working environment and execution of operations (Superior Controls, 2007). What is also important and useful for the whole company is that people in all levels and across all functions begin to think in a preventive mode rather than an "after-the-fact detection" regarding process errors.

3 PROBLEM SOLVING AND ROOT CAUSE ANALYSIS

Beneath every problem there is a cause for the problem. In order to solve a problem one must identify the cause of the problem and take steps to eliminate the cause. If the root cause of the problem is not identified, then one is merely addressing the symptoms and the problem will continue to exist. (Doggett, 2005)

This chapter introduces a short literature review of the principles of problem solving methods and root cause analysis tools. The main objective is to present some methods for correcting problems and emphasize why identifying and eliminating the root causes of the problems is of utmost importance. At first, in section 3.1, an introduction of two different philosophical approaches in the background of the problem solving processes is provided.

3.1 Philosophical approaches for problem solving

"The problem solving methodology is a skill that runs deep and strong at all levels of the organization across all functions" - states Liker & Meier (2006) when describing how problem solving is seen in Toyota; one of the world class pioneers in quality. According to Liker et al. (2006) the term "problem solving" may be a misnomer, since the process usually goes well beyond the basics of problem solving. It requires thorough evaluation and reflection, careful consideration of various options, and a carefully considered course of action, all leading toward measurable and sustainable goals.

Very often, after a problem has occurred, main effort is put only on correcting that particular existing problem rather than focusing on finding preventive and long-term solutions. As a traditional approach for correcting problems (see figure 9) illustrates, basic principle of this method is to avoid stopping the production to the last and correct problems “off line”.

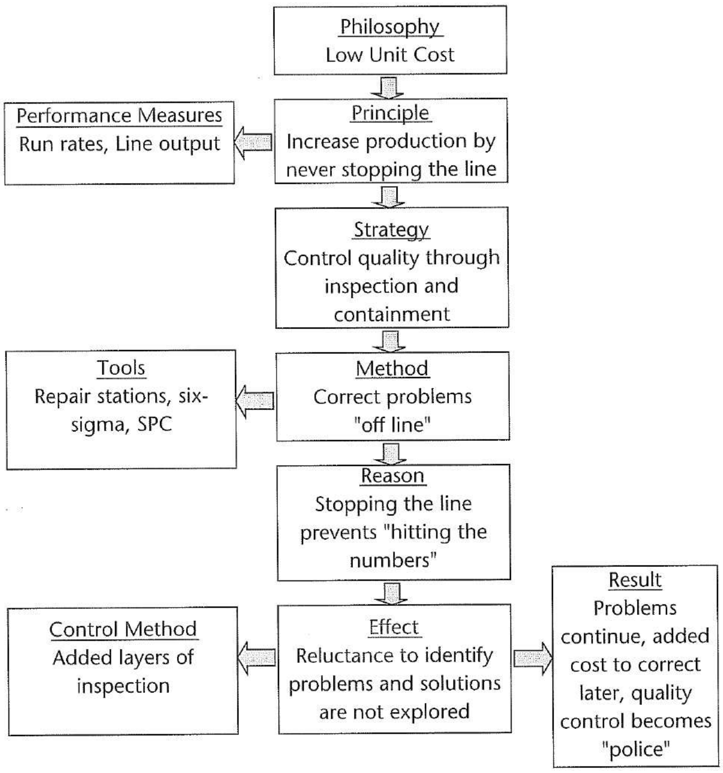


Figure 9. Traditional method of correcting problems (Liker et al., 2006).

In many companies this kind of attitude towards correcting problems is very common. Any problems that arise can be corrected later and according to this approach quality is controlled by additional inspection and containment. And even if people may have good ideas to solve the problem they are said that it is not your job to worry about it. This erroneous thinking creates an attitude among the workforce that identifying problems and possible solutions is not important.

Toyota's core philosophy is based on eliminating waste. Figure 10 presents an outlook of Toyota method of stopping to fix problems. Compared to traditional method of correcting problems this method totally differs from many aspects.

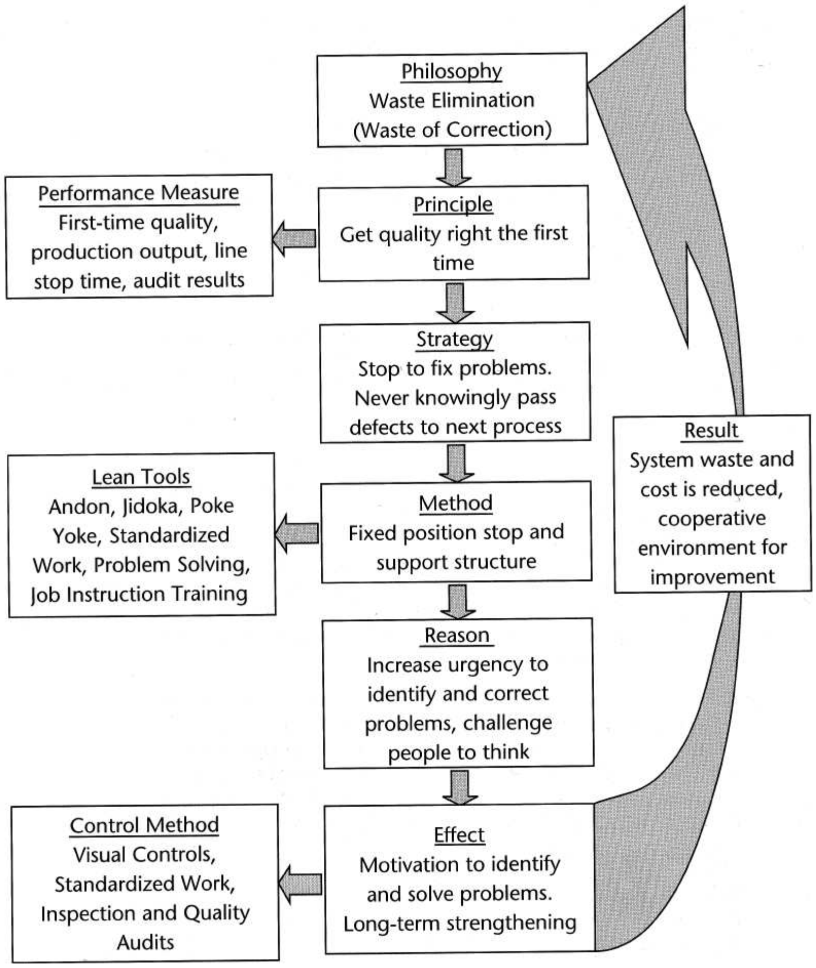


Figure 10. Toyota method of stopping to fix problems (Liker et al., 2006).

Whereas traditional method aims to keep run rates and line outputs high, even at the expense of quality, one of Toyota's main principles is to get right quality from the first part produced. This is reached by the extensive support system which provides tools and resources to identify and solve the problems. The effect of the Toyota method is to motivate workers to identify and solve problems which in the long run build a strong base for continuous learning and improvements. (Liker & Meier, 2006)

The role of problem solving has also an effect on organizational learning. Some literature studies have shown that the success of improvement efforts depends on how problems are addressed. This approach leads us to the concept of *single* and *double loop learning*. Loop learning concept makes a distinction between fixing problems (first order solutions) and diagnosing and altering underlying causes to prevent recurrence (second order solutions). First-order problem solving allows work to continue but does nothing to prevent similar problems from occurring. Second order problem solving, in contrast, investigates and seeks to change underlying causes. (Tucker et al., 2001)

3.2 Frameworks for problem solving processes: PDCA, DMAIC and Toyota's cycle

Problem solving process is a simple process which provides certain steps needed to be followed in a way from "problem-faced"-state to "problem solved"-state. Literature presents several models and frameworks for problem solving used largely in quality control efforts. In this section, a short introduction of three problem solving methods, PDCA-cycle, DMAIC and Toyota's cycle, is provided.

PDCA

PDCA-cycle stands for the words *Plan-Do-Check-Act*. PDCA was made popular by Dr. W. Edwards Deming who is also known as a father of modern quality control by many. The PDCA cycle is a serie of activities pursued for improvement. It begins with a study of current situation, during which data are gathered to be used in formulating a plan for improvement. Once plan has been finalized, it is implemented. After that, the implementation is checked to see whether it has brought about anticipated improvement. If so, a final action is to standardize it and ensure that the new methods are practiced on a large scale. (Imai, 1986)

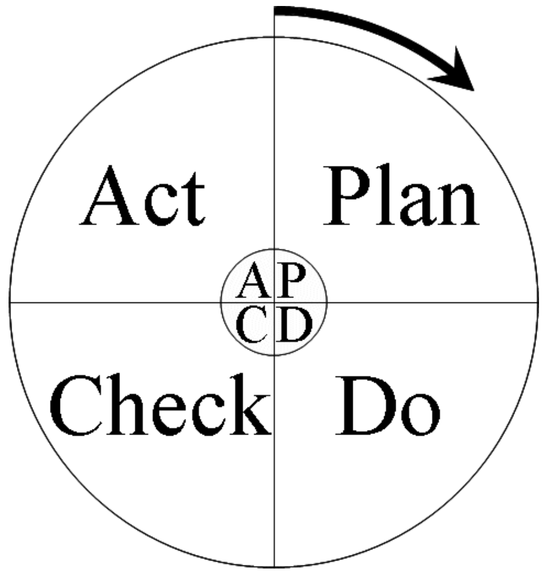


Figure 11. Plan-Do-Check-Act cycle.

DMAIC

DMAIC is a widely used problem solving method inspired and originated from PDCA. DMAIC stands for the words Define, Measure, Analyze, Improve and Control (see figure 12). It is a problem solving method developed originally as a tool for Six Sigma methodology. Six Sigma is a set of practices, developed by Motorola to systematically improve processes by eliminating defects. The core of the Six Sigma methodology is a data-driven, systematic approach for problem solving, with a focus on customer impact. Statistical tools and analysis are often useful in the process. (Pande & Holopp, 2002)

The strength of DMAIC method is based on Six Sigma teams, which consist of people from different positions, for example from different job levels, skills and seniority (Six Sigma Belts). Thus, the problem will be handled with expertise but also many different aspects will be taken into consideration. (Pande & Holopp, 2002)

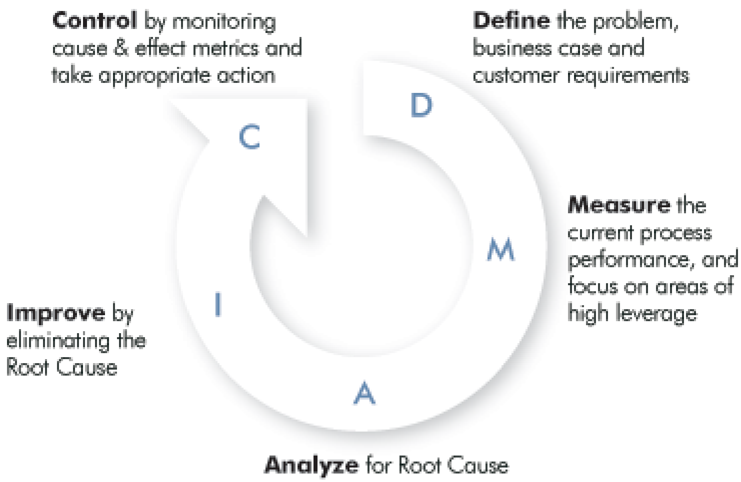


Figure 12. DMAIC problem solving cycle (IIL, 2007).

In defining stage, the problem is identified, goals are stated and also possible constraints and assumptions are set up. Measure is a logical follow-up to define and it is a bridge for a next step: analysis. The measure stage has two main objectives; firstly, to gather data to validate and to quantify the problem/opportunity and secondly, begin teasing out facts and numbers that offer clues about the causes of the problem. In the analysis stage the understanding of the process and problem is enhanced and resulting finally in the identification of the root causes. Then it is time to implement the solution and finally control the cause & effect metrics if goals set in the first place are achieved. (Pande & Holopp, 2002)

Toyota's problem resolution cycle

Toyota has developed its own method for problem solving (see figure 13). The aim of this method is to build a culture that stops to fix a problem. This approach has its roots in Toyota Production System (TPS) ideology (*principles presented in Jeffrey K. Liker´s book: The Toyota Way: 14 Management Principles from the World´s Greatest Manufacturer*), and specially in its first principle, which advises to base your management decisions on a long-term philosophy, even at the expense of short-term financial goals. Even though Toyota's problem resolution cycle aims at long-term solutions this entire cycle is repeated many times throughout the day in Toyota plants. This describes not only method's simplicity but also its effectiveness. (Liker et al., 2006)

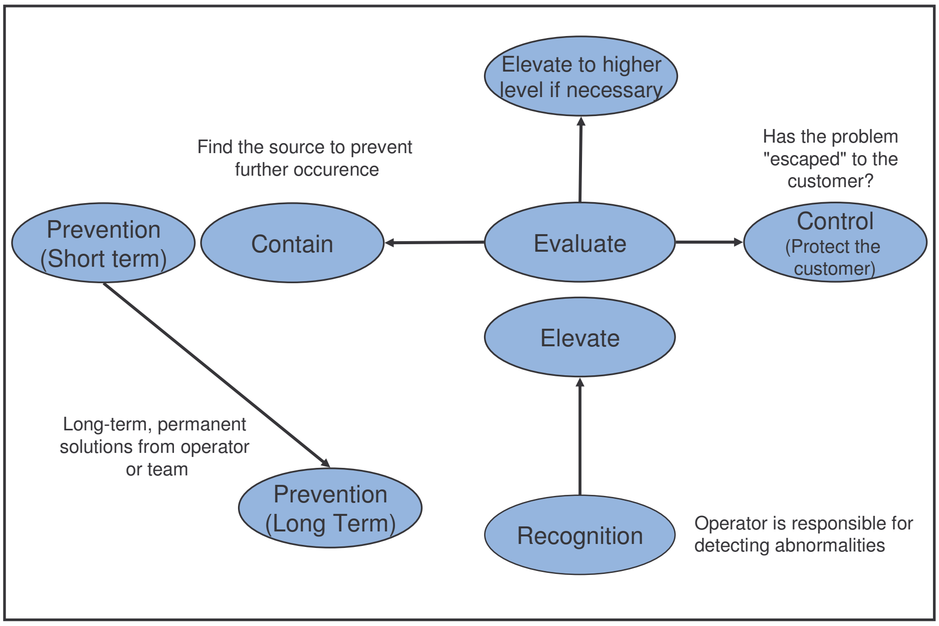


Figure 13. Toyota problem-resolution cycle (Liker & Meier, 2006).

In Toyota's problem resolution cycle there are a few steps which might be unusual for many. In this model "elevating" stands for signaling the need for assistance e.g. when operator is not able to solve the problem by him/herself. In Toyota, support people are always designated beforehand and thus assistance is quickly available. At the control stage the main task is to ensure that the problem will not go any further and especially do not reach the customer. In containment stage the source of a problem is identified and controlled. (Liker & Meier, 2006)

After the problem has been controlled and contained and production has returned, the focus shifts to prevention. In some cases preventive measures are short term in nature, meaning they are temporary measures until more effective and permanent (long-term) measures can be implemented. Usually long-term solutions are generated by a team, where all participants are responsible for the development of effective countermeasures. (Liker & Meier, 2006)

Similar processes for problem solving as presented above can be found a wide variety from the literature. Some of them emphasize the importance of testing and evaluating solutions before making them permanent, others focus on involving those who know the problem best in solving it, while some point out the importance of seeing the problem solving as part of a larger improvement effort. (Andersen & Fagerhaug, 2000) From a company point of view a strict following of some problem solving method is not the point, but combining and finding a practical and effective model which serves the company's specific needs best.

3.3 Root cause analysis

Root cause analysis is a collective term used to describe a wide range of approaches, tools and techniques used to uncover causes to problems. Some of the approaches are more geared toward identifying the true root causes than others: some are more general problem solving techniques while others simply offer support for the core activity of a root cause analysis. Therefore there is not a streamlined process of a fixed number of steps for a root cause analysis. (Andersen & Fagerhaug, 2000)

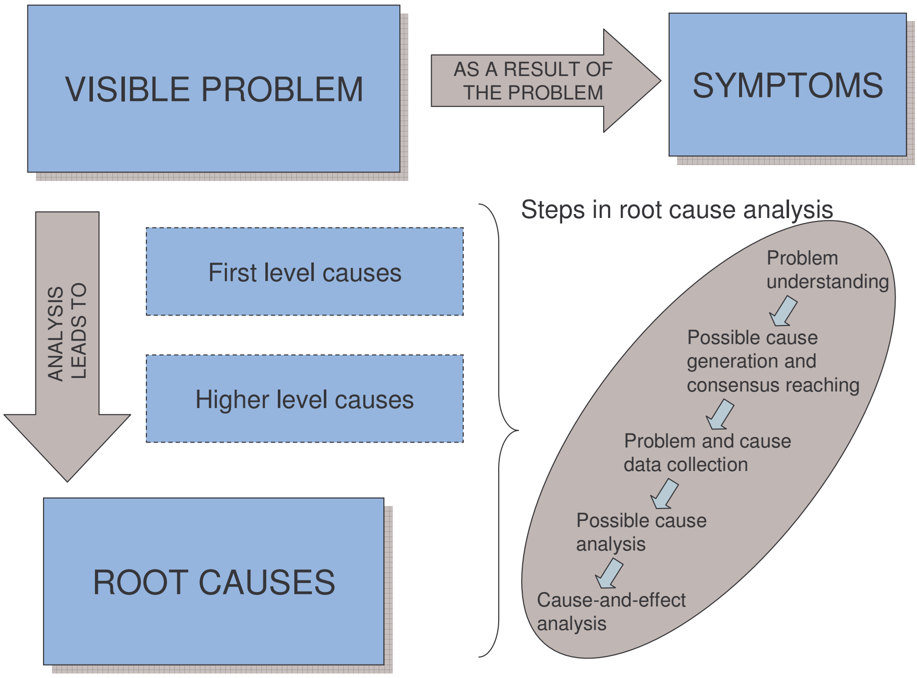


Figure 14. Symptoms versus root causes and possible steps in root cause analysis (Adopted from Liker & Meier, 2006 and Andersen & Fagerhaug, 2000).

A problem is the result of multiple causes at different levels. This means that some causes affect other causes which, in turn, create the visible problem. According to Andersen et al. (2000) causes can be classified as following (see also figure 14):

- Symptoms: these are not regarded as actual causes, but rather as signs of existing problems.
- First level causes: causes that directly lead to a problem.
- Higher level causes: causes that lead to the first level causes. While they do not directly cause the problem, higher level causes form links in the chain of cause-and-effect relationship that ultimately create the problem
- Root cause: the highest level at the bottom which sets in motion the cause-and-effect chain that creates problems.

Conducting a root cause analysis may have many objectives. As presented in table 3, Andersen et al. (2000) points out that different root cause analysis tools can be grouped according to their purpose. In each group there is a great variety of tools available. Depending on the situation, steps can be applied sequentially or others can be applied on many points in the analysis.

It is usually difficult to know which tool should be used when, and how the tools relate to one another in an overall root cause analysis. The main objective, however, is to find the root causes of the problem and eliminate them. The tools used are aids that help to reach this goal (Andersen et al., 2000). In table 3 there are presented some general and widely applied tools, categorized according to presented steps in overall root cause analysis.

Table 3. Tool summary for root cause analysis (Andersen & Fagerhaug, 2000).

Stage/Tool	Purpose
Problem understanding	
Flowchart	Understand the flow of activities in a process
Critical incident	Understand what are the most troublesome symptoms
Spider Chart	Compare performance with external references
Performance matrix	Priritize problems or symptoms to attack
Possible cause generation and consensus reaching	
Brainstorming	Generate as many ideas as possible
Brainwriting	Generate as many ideas as possible
Nominal group technique	Prioritize ideas
Paired comparisons	Prioritize ideas
Problem and cause data collection	
Sampling	Gain a representative sample from a large population
Surveys	Collect data from respondents
Check sheet	Register data in a systematic fashion
Possible cause analysis	
Histogram	Portray data graphically
Pareto chart	Find the few elements causing most effects
Scatter chart	Find relationships between two variables
Relations diagram	Find relationships among many elements
Affinity diagram	Find relationships otherwise not easily seen
Cause-and-effect analysis	
Cause-and-effect chart (with 4Ms)	Generate and group problem consensus
Matrix diagram	Analyze causal relationships
Five whys	Identify chains of cause-and-effect

According to Bringslimark (2006) documenting "operator error" as a root cause is an action which occurs very often. This conclusion to a problem is usually achieved by little or none of deeper inspection of root causes. Bringslimark (2006) states also that the label "operator error" sends a blatant message that training has not been effective and that operations are not under control. Therefore, companies must recognize that identifying operator error as a root cause strongly suggests that things are not right, and that the real root cause needs to be more thoroughly analyzed and effectively addressed by the organization to demonstrate that the training and corrective/preventive action systems are performing as planned.

Table 3 presents only a short list of available tools. However, in order to achieve satisfactory results, the most critical issue is selecting the right tool for the right application. It helps not only to ensure that the desired results are achieved, but it also ensures wrong decisions don't cause time to be wasted on the wrong solutions (Okes, 2002).

According to Andersen et al. (2000) and Okes (2002) there are some recommendations that need to be taken into consideration concerning analysis tools. Firstly, you must not to become a slave to one or more tools and secondly you must remember that a tool is not the solution in search of a problem to solve. Also concerning the use of quality tools, one challenge is to learn whether a particular tool fits for the degree of quality maturity of the organization. The level of maturity describes the company's attitude and understanding of quality issues. Thus, depending on the level of maturity the tools used in quality issues varies a bit; in a low maturity level very basic tools are used whereas in a high level of maturity more emphasis is paid on quality management tools and the quality is monitored very closely.

4 MISTAKE-PROOFING IN TERMS OF QUALITY COST THINKING

Scrap and rework are common terms in many manufacturing companies. Nevertheless, it is quite difficult for many to address what the true costs of quality are. This chapter introduces main principles of quality cost thinking, different components of quality costs and a comparison of two theoretical models of defining the optimum of quality costs. In addition, the effects of mistake-proofing efforts have in accumulating quality related costs are examined. Any emphasis on how to measure these costs and what kind of reporting system it requires won't be taken.

4.1 Quality cost system

Quality costs are the measures of the costs specifically associated with the achievement or non-achievement of product or service quality. More specifically, quality costs are the total of the cost incurred by

a) investing in the *prevention* of non-conformances to requirements
b) *appraising* a product or service for conformance to requirements
c) *failing* to meet requirements

According to American Society of Quality (ASQ) definition, quality costs represent the difference between the actual cost of a product or service and what the reduced cost would be if there were no possibility of substandard service, failure of products, or defects in their manufacture.

Why understanding the elements of quality costs and regular monitoring is useful for a company? Campanella (1999) presents in the book "Principles of quality costs" that the goal of any quality cost system is to facilitate quality improvement efforts that will lead to operating cost reduction opportunities, in other words, producing high quality products with lower costs.

Philip B. Crosby (1979) states in his book "Quality is Free" that the cost of quality has two main components: the cost of good quality (the cost of conformance) and the cost of poor quality (the cost of non-conformance) As presented in figure 15, these two forms of quality can be divided even further:

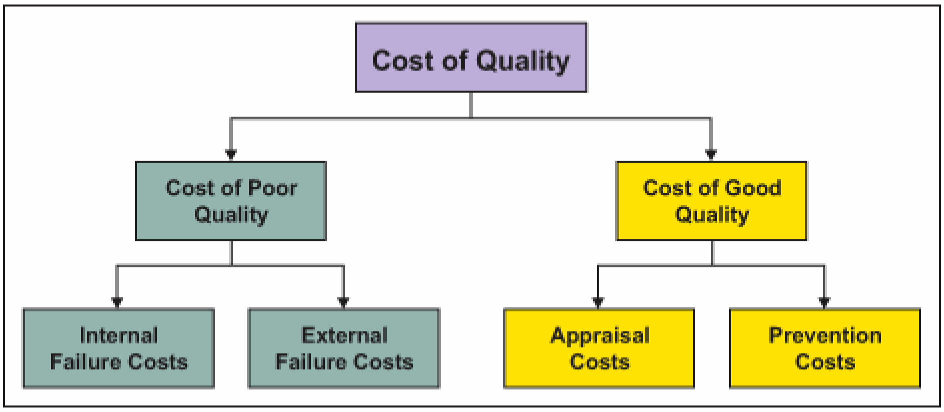


Figure 15. Components of quality costs (Buthmann, 2007).

The costs of poor quality consist of both internal and external failure costs, which results from failing to meet the requirements. The costs of good quality consist of appraisal and prevention costs. Appraisal costs are associated with measuring, evaluating or auditing products or services to assure conformance to quality standards and performance requirements. Prevention costs are the costs of all activities specifically designed to prevent poor quality in products or services.

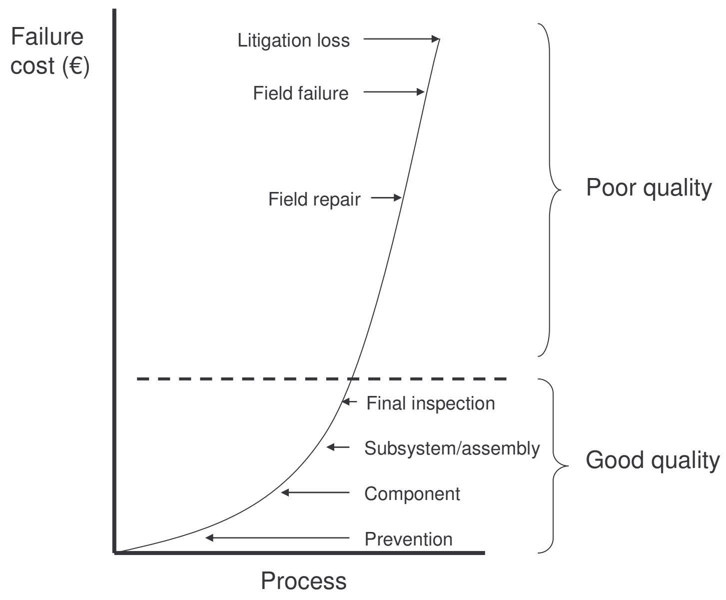


Figure 16. Failure cost as a function of detection point in a process (Campanella, 1999).

The difference between the elements of a good and poor quality can be presented from the failure cost point of view (see figure 16). Normal distinction between the good and poor quality is made on the point when a product or service is delivered to a customer. Due this, all efforts done to avoid the customer having a defective product is referred as a good quality. Many companies are normally satisfied with the situation where customers do not receive defective products, no matter what the costs of good quality will be. The aim of figure 16 is still to point out that is not the most admirable state and by taking a closer look to the elements of good quality shows that there is still a remarkable chance to reduce quality costs. The earlier a defect is detected in the process, the cheaper it will be to correct it. (Campanella, 1999)

4.1.1 Optimum models for quality cost thinking

The most argued issue of quality costs is propably concerning the models of optimum of quality costs. There are two different theoretical models available which both tries to find the optimum between the costs and the quality. In the classic model of optimum quality costs, illustrated in figure 17, achieving 100 % defect free products is not reasonable because appraisal and prevention costs are assumed to increase exponentially when approaching 100 % quality level. Thus, the optimum is found somewhere below the 100% quality level.

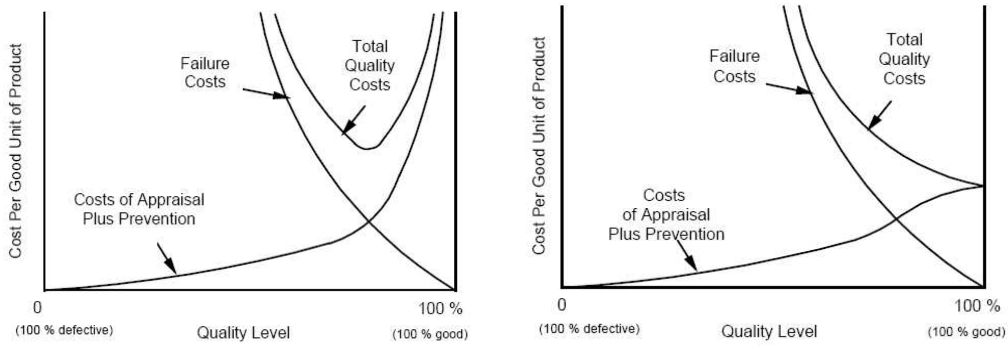


Figure 17. Traditional vs. new model of optimum quality costs (Campanella, 1999).

In a few last decades the new model of optimum quality costs has gained ground. The new model suggests that approaching 100 % quality level does not necessarily increase the total quality costs. This model has two arguments. Firstly, does it really take infinite investments (for appraisal and prevention) to reach zero defects (Schneidermann, 1986) and secondly, according Pyzdek and Keller (2003), the loss of sales could so remarkable under 100 % quality level. With these arguments the model suggests that total quality costs have its minimum at the 100 % quality level.

4.1.2 Iceberg model

Many of the elements of quality costs are hidden and thus difficult to identify by formal measurement systems. The iceberg model, presented in figure 18, is very often used to illustrate this matter. Only a minority of the costs of poor and good quality is obvious and they appear above the surface of the water. According to the survey of identifying the cost of quality conducted by VTT (1999) in Finland many companies estimating their level of cost of quality listed only most concrete "here and now" costs as true costs of quality and not even tried to estimate the hidden costs. Referring to the iceberg model this survey shows that there is a huge potential for reducing costs under the water. This basically means that, by identifying and improving the area of hidden costs it is possible to reduce the costs of doing business significantly.

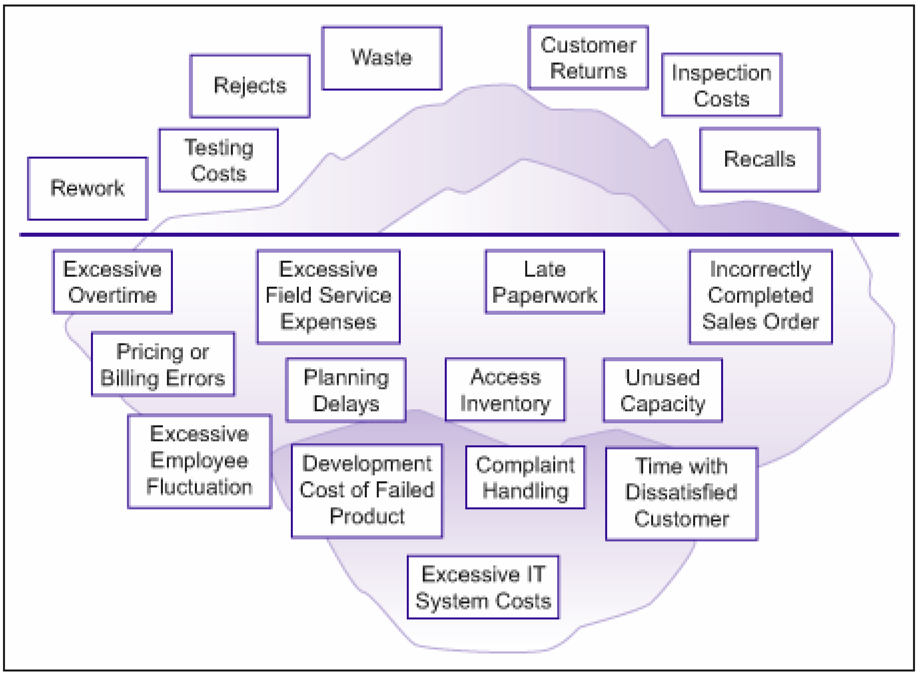


Figure 18. The iceberg model of cost of quality (Buthmann, 2007).

4.2 Components of quality costs

As mentioned earlier, costs of quality can be separated to conformity and non-conformity costs. Conformity costs are usually considered as necessary costs of quality consisting of primarily quality assurance and prevention costs. Non-conformity costs consist of fault costs and inspection costs which are held unwanted and can be avoidable. Most of the quality costs cumulate from non-conformity costs because the later the defect is detected the more expensive it is to correct it. The following figure illustrates this approach to quality based costs.

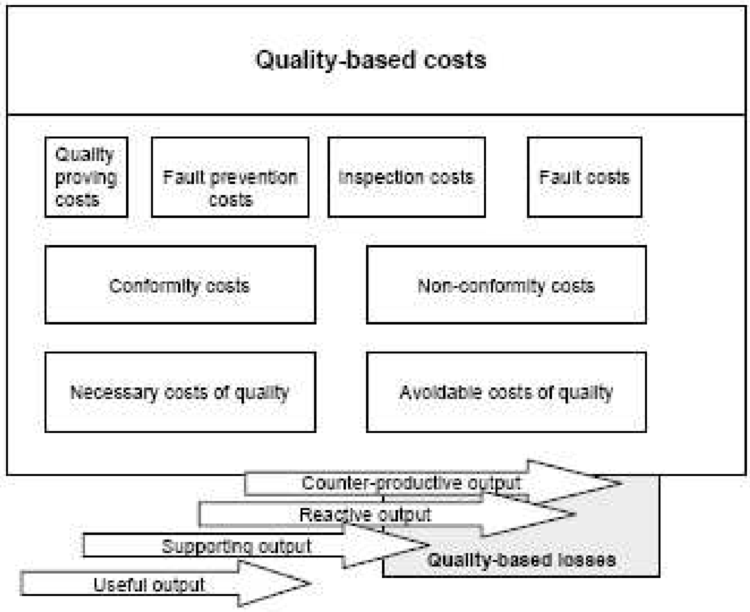


Figure 19. Necessary and avoidable costs of quality (Pfeifer, 2002).

The "1-10-100 Rule" describes well the accumulation of quality related costs, even though this "rule" has no specific research background. This widely used rule of thumb suggests that a quality problem costing 100€ to resolve in the field would cost only 10€ to correct if discovered during in-house processes and only 1€ to prevent in the first place.

4.2.1 Prevention costs

Prevention costs are the costs of all activities specifically designed to prevent poor quality in products or services (Campanella, 1999). Examples includes the costs for quality planning, supplier evaluation, new product review, mistake-proofing, process capability evaluations, quality improvement team meetings, quality improvement projects and naturally also quality education and training. (Buthmann, 2007)

4.2.2 Appraisal costs

Appraisal costs consist of measuring, evaluating or auditing products or services to assure conformance to quality standards and performance requirements (Campanella, 1999). Costs occur mainly because of the need to control products and services to ensure high quality level in all stages (Buthmann, 2007). Appraisal costs include:

- checking and testing purchased good and services
- in-process and final inspections and tests
- field testing
- product, process and service audits
- calibration of measuring and test equipment

4.2.3 Internal failure costs

Internal failure costs are costs that are caused by products or services not conforming to requirements or customers/users needs and are found before delivery of products and services to external customers. These non-conformities would otherwise have led to the customer not being satisfied. Deficiencies are caused both by errors in products and inefficiencies in processes. Typical forms of internal failure costs are

- scrap
- rework
- reinspection
- retesting
- material review
- downgrading
- delays and shortages

(Campanella,1999)

4.2.4 External failure costs

Concerning traditional quality cost systems, external failure costs are the most obvious and thus easiest to measure and monitor. External failure costs occur after delivery or shipment of the product, or during or after furnishing of the service, to the customer. Examples include the costs for:

- complaints
- product recalls/ repairing goods and redoing services
- warranty claims
- customers' bad will
- losses due to sales reductions

External failure costs are the most expensive ones to correct and thus prevention of mistakes beforehand is much more preferable than correcting afterwards. (Campanella, 1999)

4.3 Quality costs and mistake-proofing

Mistake-proofing is a method which systematically aims at decreasing the possibility of making mistakes in manufacturing processes and thus prevents producing faulty products and services. As defect levels drop, failure costs naturally decline while appraisal and prevention costs may increase (Schneiderman, 1986). This approach was very dominant even few decades ago and striving for zero defect -state was not seen acceptable in the belief that reaching 100 % quality level would require enormous increase of appraisal and prevention costs. Nowadays, however, the situation is somehow opposite; all failure costs are considered to be some sort of waste which causes expenditures and need thus to be avoided. More and more attention is paid on the importance of appraisal and preventive actions which are considered necessary forms of good quality.

Mistake-proofing efforts can be considered to be very favorable in terms of quality costing. Referring to figure 16 about failure costs as a function of detection point in a process, the basic principle behind mistake-proofing is to detect an occurred mistake as on early stage as possible. In every action the basic approach is preventive rather than corrective. This conclusion can be drawn up when contrasting Shingo's inspection methods to this context; by source inspection the circumstances behind correct execution are checked and possibility for making a mistake is erased or by informative inspection the flow of defected products is halted immediately. In both cases the amount of rework and scrapping costs are minimized.

When combining Crosby's (1979) two main quality cost components and the accumulation of failure costs according to the detection point in a process (figure 16) the effects of continuous mistake-proofing efforts to the accumulation of total costs of quality can be presented as follows:

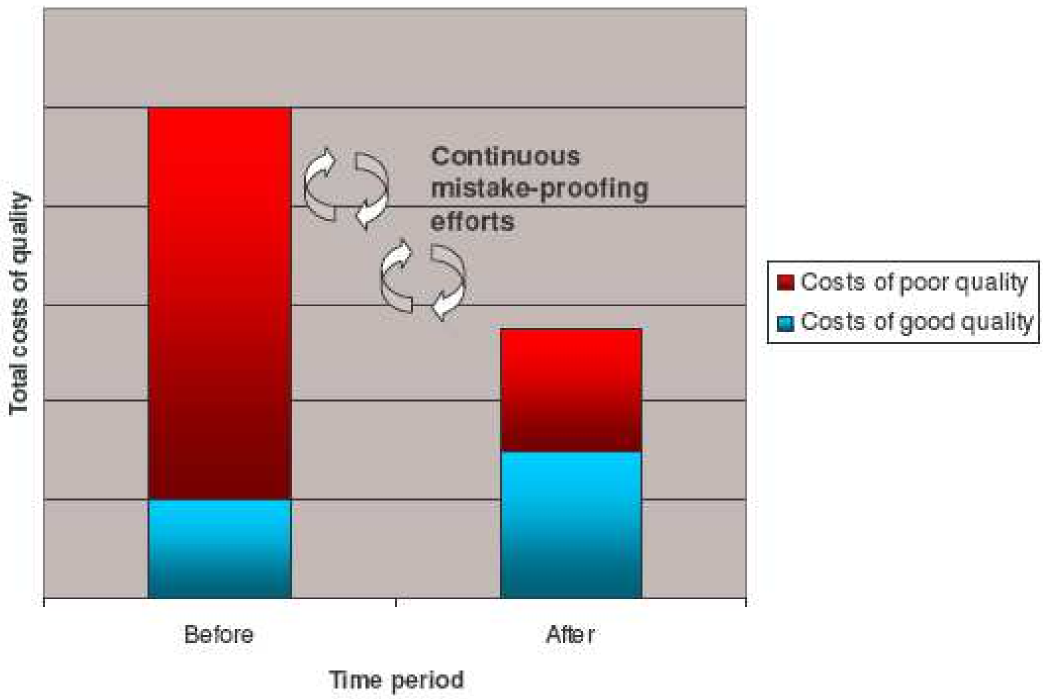


Figure 20. The effects of the continuous mistake-proofing efforts on total costs of quality.

As figure 20 summarizes, in a theoretical situation where defect rates are high most of the quality related cost can be considered as form of poor quality costs such as repairing goods, handling of customer complaints and warranty claims. Only minor actions are taken to develop processes and quality control systems towards preventive mode. However, with systematic mistake-proofing utilization total costs of quality can be cut. Firstly, due the number of defected products achieving customers decrease remarkably, it follows that the costs of poor quality decreases too. Even the costs of good quality may increase considerably due to investments on preventive methods of mistake proofing, the overall cost level still remains at much lower level compared to initial state.

5 CONCLUSIONS OF THE LITERATURE STUDY

Every company operating in the global markets must be able to produce high quality products and services that fulfil customers' requirements in order to keep up with the competition. In addition, "making of quality" needs to be executed as cost-efficiency as possible.

Traditional Western approach for "making of quality" has been to eliminate the possibility of customer receiving a faulty product or service, no matter what the costs would be. When the percentage of external customers receiving faulty products has increased, as a corrective action more inspections for finished products have been arranged. Of course, this approach will increase the number of defected products detected in-house and thus non-conforming products reaching the customer is eliminated. However, if the causes of the problems are not solved or any corrective actions made to processes, processes continue to produce defective products at the same level as before.

In this study so far, a detailed overview of the principles of poka-yoke methodology has been introduced. This concept aims at systematic improvement of the processes and eliminating the mistakes from occurring with very simply methods. In the heart of this methodology are the three levels of inspection (presented thoroughly in section 2.3):

- Judgment inspection (for only detecting mistakes)
- Informative inspection (immediate feedback of detected mistake)
- Source inspection (eliminates mistakes at their source)

As Edward Deming has once stated "quality comes not from the inspection, but from the improvement of the process"; poka-yoke also stands for this statement. Especially informative inspection and source inspection are forms of inspections which informs which part of the process needs to be corrected and do not allow processes to continue before correcting. Poka-yokes are also in the great importance in the “lean”-concept of the Japanese quality management. Through source inspection is it possible to produce high quality products from the first part on and thus avoiding producing waste in form of any kind of scrap and rework. With informative inspection producing waste can be minimized due the faulty unit can be detected almost immediate and allowing it to continue to next process is halted.

If I reflect the advices of this methodology to my experiences I found the approach of inspection methods very useful. Firstly, it gives a totally new insight of how mistakes in in-house processes can or could be detected and what are remarkable benefits achieved through the utilization of this methodology. Secondly, the implementation of poka-yokes is not tied on any strict procedure rather than they are very simple and inexpensive methods which any of us can develop.

To obtain remarkable results in quality improvement it requires effective and systematic use of problem solving methods. The main theses of chapter 3 is to point out that problem solving methods should be executed in all levels of the organization and the main emphasis should be paid on generating long-term solutions. Lots of theoretical models for problem solving are provided in the literature, however, every company should try to identify the tools and models most suitable for their purposes.

Customer complaints, recalls of faulty products, scrap and rework all the forms of unwanted costs associated with quality costs. The aim of quality cost thinking is to assist in recognizing the elements of quality costs, especially hidden ones, and to highlight the importance of good quality costs, such as prevention and appraisal costs. In a classic model of optimum quality costs (see figure 16) the optimum was found somewhere below the 100 % quality level due to assumption that appraisal and prevention costs would increase exponentially when reaching the 100 % level.

However, in a new model the optimum is at the 100 % quality level, due to 100 % quality inspection can be executed cost-effectively with the help of different methods, such as poka-yoke inspection methods.

PART II: EMPIRICAL RESEARCH AND ANALYSIS

This is the empirical part of the thesis. Chapter 6 introduces the results of different quality analyses conducted in the case company. In chapter 7 the analysis is taken even further with a detailed examination of two typical case examples. With the results of these, a framework for systematic utilization of poka-yoke efforts will be defined and modified to meet the needs of the case company. Proposals and recommendations to quality improvement efforts are provided in the chapter 8.

The conducted quality analyses are very basic measurements, but still very novel in the case company. Due to insufficient level of relevant quality data available, lots of emphasis is also paid on improving and developing quality reporting systems during the study.

6 ANALYSIS OF QUALITY FAILURES IN DELIVERY PROCESS

This chapter provides an extensive analysis of quality failures in case company's delivery process. The content of this chapter is two-fold: at first, a general description of the existing characteristics of delivery process and production environment is presented to provide an overall view of the context. The latter part concentrates on different analyses of quality failures. Main focus is to point out the main problem areas from different aspects and appraise them according to their type and severity. This helps finding out explanatory factors and consistency to rationalize data and in the later phase to generate solution models to existing quality problems.

6.1 Case company description

Case company develops, manufactures and markets products and services for environmental and industrial measurements in the global markets. The major customer groups are meteorological and hydrological institutes, aviation organizations, defense forces, road and rail organizations and system integrators. The core competency can be identified as a superiority of sensor manufacturing and calibration technology.

Case company consists of three business divisions. Divisions vary from others in the nature of their businesses. This analysis is carried out in one business division which provides products for the measurements of humidity, dew point, barometric pressure, wind, rain, visibility, cloud height and present weather. From now on, until the end of this thesis; the term "case company" is used to describe the production factory and related support functions of this specific division in which the analysis is conducted.

6.1.1 Delivery process

Figure 21 introduces the structure of the case company's delivery process. Delivery process can be considered as a logistical process which comprises activities regarding purchasing, manufacturing and finally delivering finished products to the customers.

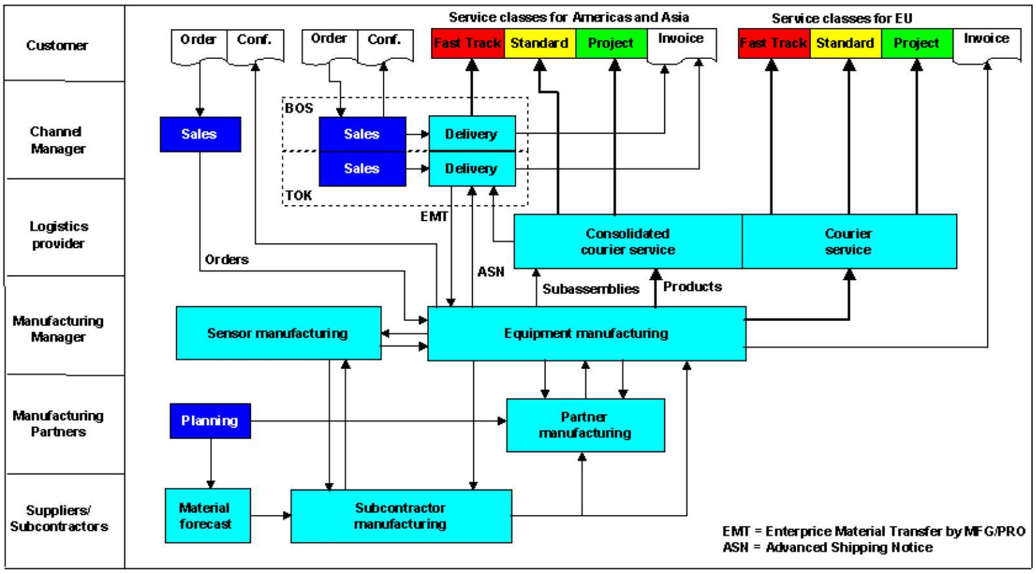


Figure 21. Description of case company's delivery process.

As the figure 21 shows, the case company has two factories, a sensor factory and an equipment factory. This analysis concentrates on quality failures which take place in the equipment manufacturing, introduced in the figure 22. In order to have a more thorough understanding of the manufacturing process it can be divided into three main sections: pre-assembly, testing and calibration and final assembly. Supplier related actions are in the minor part of this study; however their importance is remarkable due to the fact that more and more of materials are acquired from suppliers.

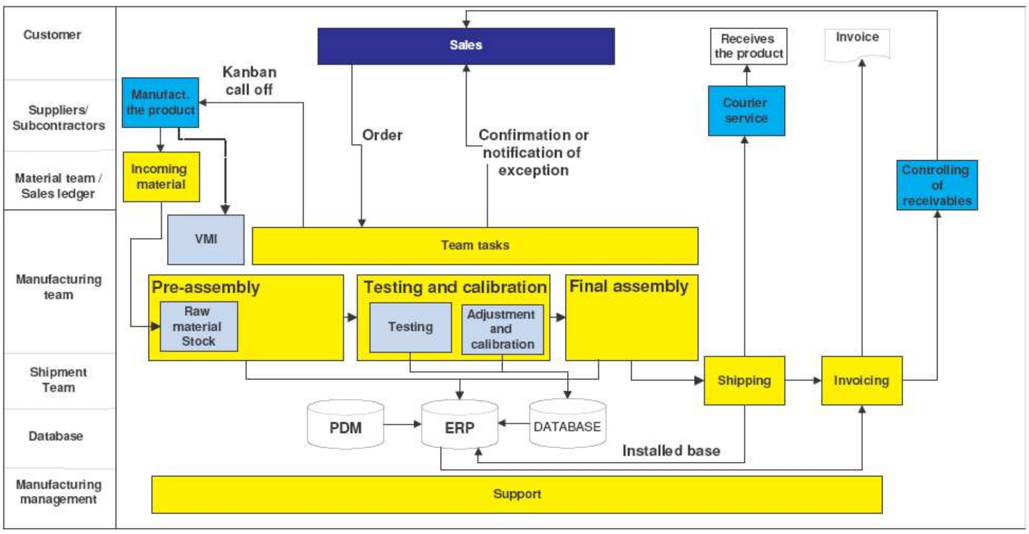


Figure 22. Equipment manufacturing process.

Equipment manufacturing is executed in four manufacturing teams, with approximately 10-15 persons per team. Depending on the team, they manufacture products for 1 to 3 product lines, which mean that the number of product families also varies a lot. Manufacturing teams differ from each other mainly in production volumes. This is due to characteristics and complexity of manufactured products. Figure 23 summarizes team volumes and their share of total sales.

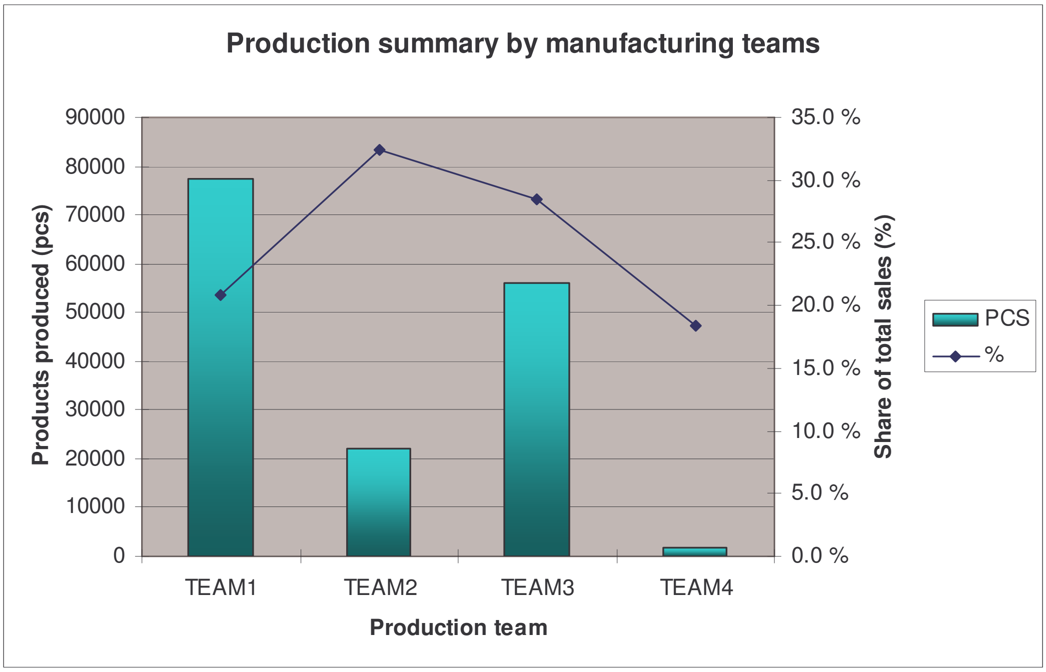


Figure 23. Summary of production output rates in 2007.

Depending on the product the number of operators involved in assembly process varies. Within some products one operator executes only a certain phase of assembly e.g. testing and calibration or replenishment of buffer stocks and within some products the same operator takes care of all manufacturing tasks. In many cases the same operator also receives the work order from the company's ERP system and also release finished products for the shipping team. This requires that operators must be multi-skilled and motivated to avoid errors in complex and various tasks.

In Make-to-Order (MTO) environment manufacturing process starts when a customer order is received. According to configuration, products are assembled from usually tested sub-assemblies, modules and components which are produced to buffer stocks. Depending on the product, manufacturing lead time varies from few minutes to few days, mainly due to long calibration and testing times but also due to complexity of products.

6.1.2 Mass customization in the case company

Many companies nowadays are executing a strategy of mass customization - the low cost production of high variety and individually customized goods and services. This is due to today's competitive environment which is changing dramatically all the time. Customers demand products with lower prices, higher quality and faster delivery customized to match their unique needs (Zerenler & Özilhan, 2007). In mass customization economies of scale are gained through the components rather than the products. In addition, economies of scope are gained by using the modular components over and over again in different products (Pine, 1993).

The concept of mass customization is widely used in the case company. In general, mass customization is executed through platforms and configurable product structures. Same platforms can be used across several product lines and platform thinking is executed through the use of the same electronic/ electromechanical modules, mechanical parts, component boards and same software. From the customer aspect, mass customization is visible through products' configuration possibility. Depending on the customer's application, customer can select the needed options among the provided features of products. Example of configuration structure is presented in figure 24.

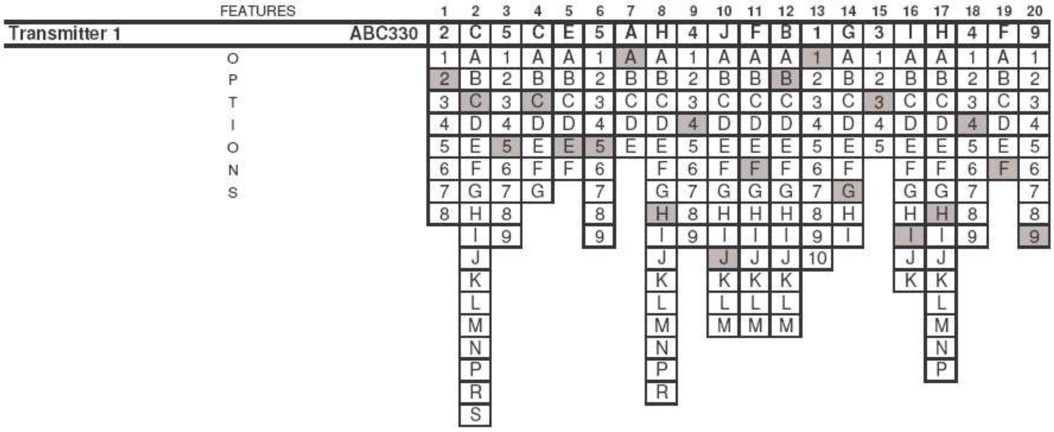


Figure 24. An example of the configuration structure.

The share of configurable product families of all product families in the case company is approximately 50-60 % (discussion with case company's product lifecycle management manager 2008), while the rest of the products can be considered as standard products.

6.2 Analysis of quality failures in delivery process

In order to clarify how principles of poka-yoke methodology and problem solving processes could be effectively utilized in case company, the aim of this analysis is to provide an extensive overview of quality failures. In this context we consider "quality failure" as all kind of non-conformance to a product specification or any deviation to planned and faultless delivery.

As mentioned earlier, analysis concentrates on quality failures which take place in delivery process and especially in equipment manufacturing; quality non-conformances of purchased items are not in the scope of this analysis. The main objective is to provide information about:

- fault types and categories
- fault distribution by products

- fault distribution by manufacturing teams
- origins of faults in manufacturing process

Data used to conduct these analyses is gathered from the case company's HelpDesk-system and from internal inspection reports. HelpDesk-data comprises all the filtered customer complaint cases between Q1/2007 and Q3/2007 considering delivery process. Data of internal inspection stands for the reports of 100 % final inspection process for selected products. Final inspection process was started in the spring of 2007 and the number of products taken to final inspection has gradually increased.

6.2.1 Pareto analysis of quality defects by category

Case company delivers approximately 180 000 products per year (data from 2007 sales). However, when manufacturing mass customized products this means that the batch size of similar products is very small; most of the product configurations can be considered as one-of-a-kind.

Quality failures in this context comprise all the quality non-conformances, for example any deviations of specifications and customer needs, which occur in the delivery process. In order to have an overall view of quality failures, figure 25 illustrates the distribution of defects according to the defect type (this defect type categorization has been used in the case company for a long time and the category for the specific case is defined by the performer of the customer complaint when receiving the case).

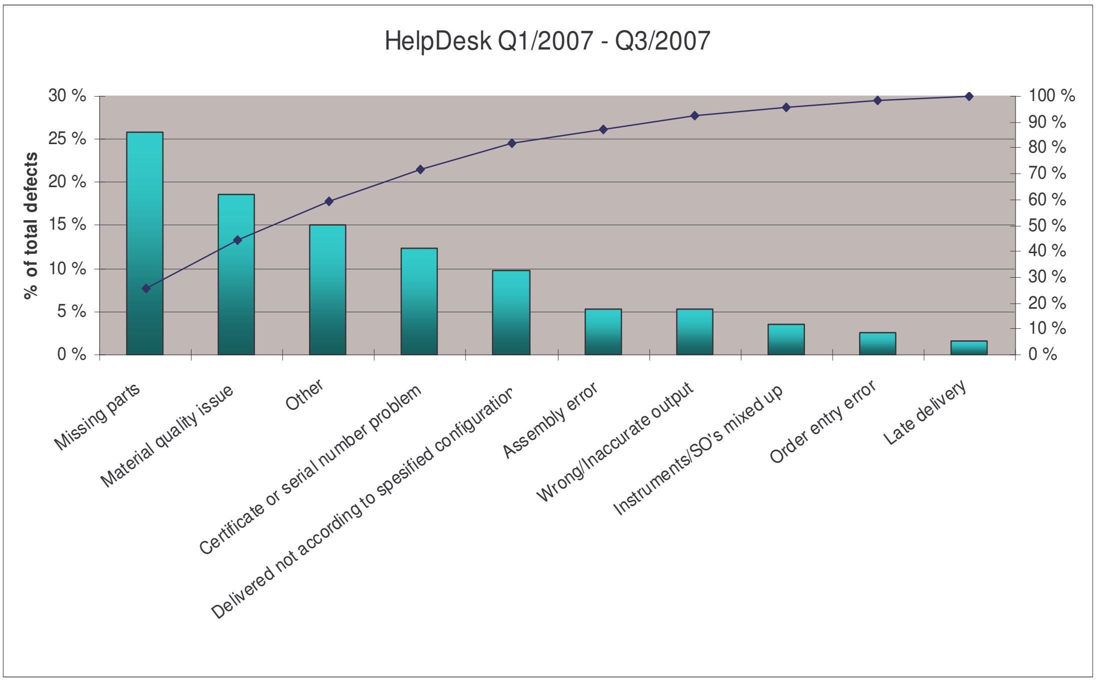


Figure 25. Customer complaints by fault category.

As this pareto analysis shows there are three major categories which cover almost 60 % of all the customer complaint cases. The biggest category, missing part(s), comprises almost 30 % of the total. This is not a surprising result because of the large configurability of products and the large number of items operators have to handle manually. Typical characteristics regarding this category are that missing parts are usually additional "parts" that need to be added to sales package according to the customer's choice. Parts are usually picked and added to sales package in the final assembly. Different kind of accessories, installation kits and manuals (wrong language) are most common types of missing parts.

The second largest category among the customer complaints comprises material quality issues which cover almost 20 % of all cases. Wide range of cases can be explained by the diversity of manufactured products and their characteristics. Compared to missing parts category the major difference is in the place where the mistakes occur. Most of the material quality issue cases occur in the pre- assembly or a material can be already defective when incoming from the supplier. Typical defects in the assembly are scratches and dents in mechanical parts, defective solders, cable damages, dirt in clean surfaces and incorrect wirings which naturally are not according to quality requirements.

The category “other” includes cases which are not in the scope of this thesis; they are mainly R&D cases which only have little interface to the delivery process and are thus excluded of this study. However, this also signals that there is a need for more specific classification of categories to obtain relevant data.

Certificate and serial number problem category was the fourth biggest category of customer complaints during the study period. Typical cases of complaints can be summarized as following:

- calibration certificate missing from the sales package
- product’s serial number is different in labels and in certificates
- wrong year codes in serial or in lot number
- duplicated serial numbers to the same customer (when ordered more than one product)

Most of the cases can be considered to be caused by human errors, simply due to carelessness or misidentification. Among the customers this usually causes some confusion even if it has no effects on product’s functionality. However, when a company markets its products as premium value products, these kinds of errors might have effect on company’s image and reliability and are thus very embarrassing ones.

The next three categories, “delivered not according to specified configuration”, “assembly error” and “wrong / inaccurate output” can be treated as a one big group. In these categories the product is not assembled as the customer has wanted. Instruments could have been assembled with wrong modules or incorrect cables, with wrong bushings or the instrument has wrong software settings. These kinds of errors can occur due to many causes and they have to be analyzed at a detailed level case by case. Sometimes it may also happen that the sales order and instruments mix up and thus wrong instruments end up to wrong customers.

6.2.2 Pareto analysis of quality defects by products

As illustrated in figure 26 below, there are only a handful of products which covers almost half of the all complaint cases. Due to case company's Helpdesk maintenance methods, the actual number of defected products is not available. Thus, one complaint case can refer to one or more defected products. However, research data can be valued quite relevant for this purpose, while the average number of shipped products per sales order is low.

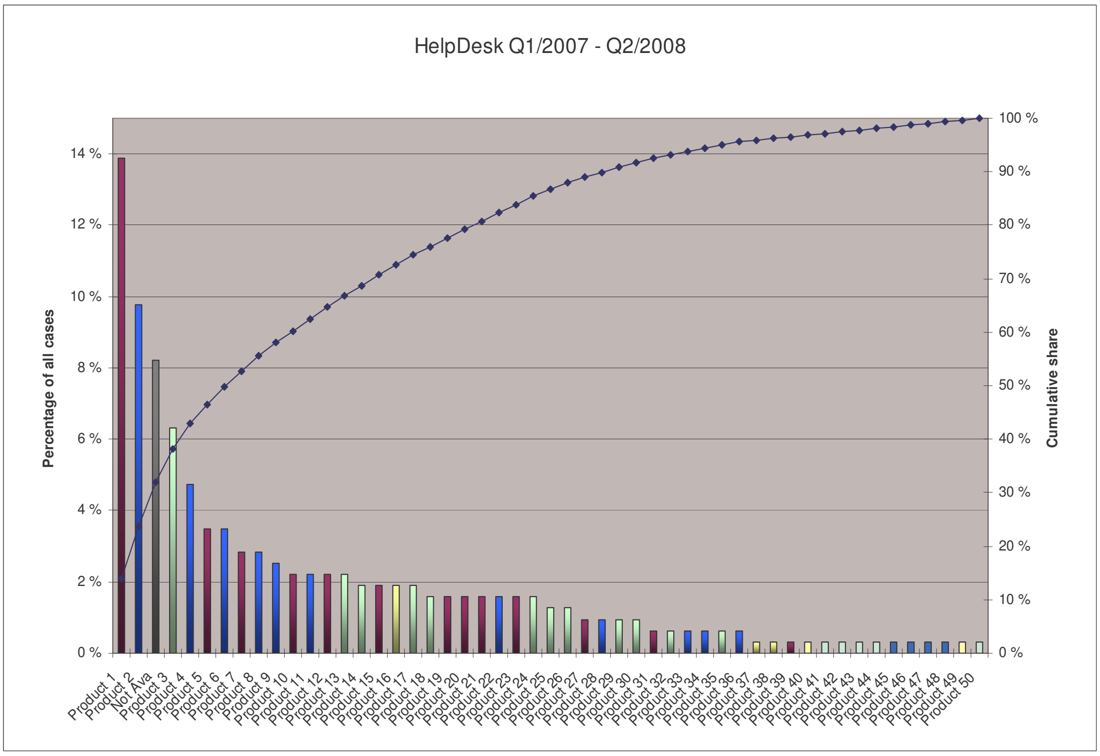


Figure 26. Customer complaints by products.

When analyzing the top 5 products further, a few very reasonable explanations why these products are on the top of the list can be found. Products 1 and 2 are firstly among the most sold products in volumes and secondly they also have the most configurable product structures. Compared to two previous products, product 3 instead, is a quite new one with low volumes and has only a few features which can be configured. In addition only one operator executes the whole assembly process himself, which might be one reason for the high rate of defects. However, product 4 is not a configurable product and thus makes an exemption compared to previous ones. "Not Ava" stands for the information not available or otherwise cannot be allocated easily to a specific product.

Trying to identify some similarities between defects and products, analysis of customer complaints by products indicates that every product has own product specific defect types and the causes behind the defects can vary a lot. This analysis reveals, not surprisingly, that most complaints are directed to products with high volumes and most configurable products, where the possibility of making a mistake is highest. The connection of how products' maturity and the number of operators executing an assembly task affects to error rate is not in the major role. Products with complex structure and long lead-time in production seem to have relatively small number of complaints based on the data of this study. This indicates that assembly processes with these products can't proceed if certain steps are not executed correctly.

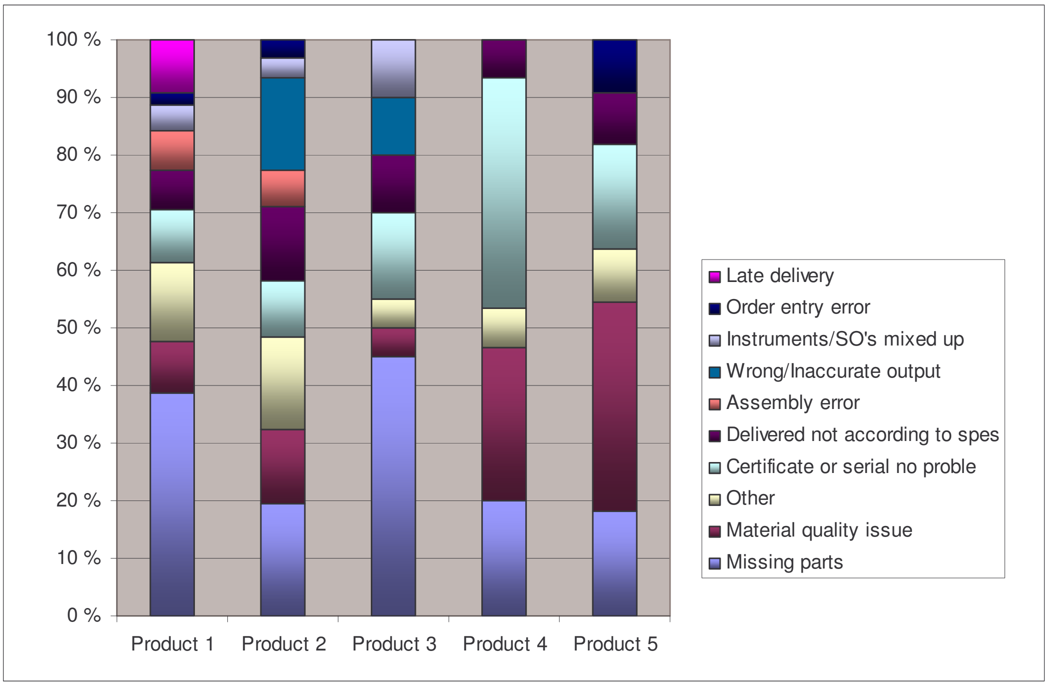


Figure 27. Defect type distribution in top 5 products.

A claim that every product has some product specific defect types is proved according to the examination in figure 27. Within every product one or two major categories can be found which comprise a great share of all defects to one product. Products 1 and 3 faces the major problems concerning missing parts, instead of product 4 has major problems with certificate and serial number problems and with material quality issues. The most problematic issue, however, is that even products 1 and 3 have both “missing parts” as the largest defect category; the reasons behind the problems can vary a lot. Thus, finding a universal solution to decrease the defect rate in this category may be a challenging task.

6.2.3 Manufacturing team comparison

Manufacturing teams differs remarkably from each other by the volumes of manufactured products and complexity of the products. One aspect to define possible problem areas in manufacturing environment is to take a look at how defects are divided between manufacturing teams. Defect distribution by teams is introduced in figure 28.

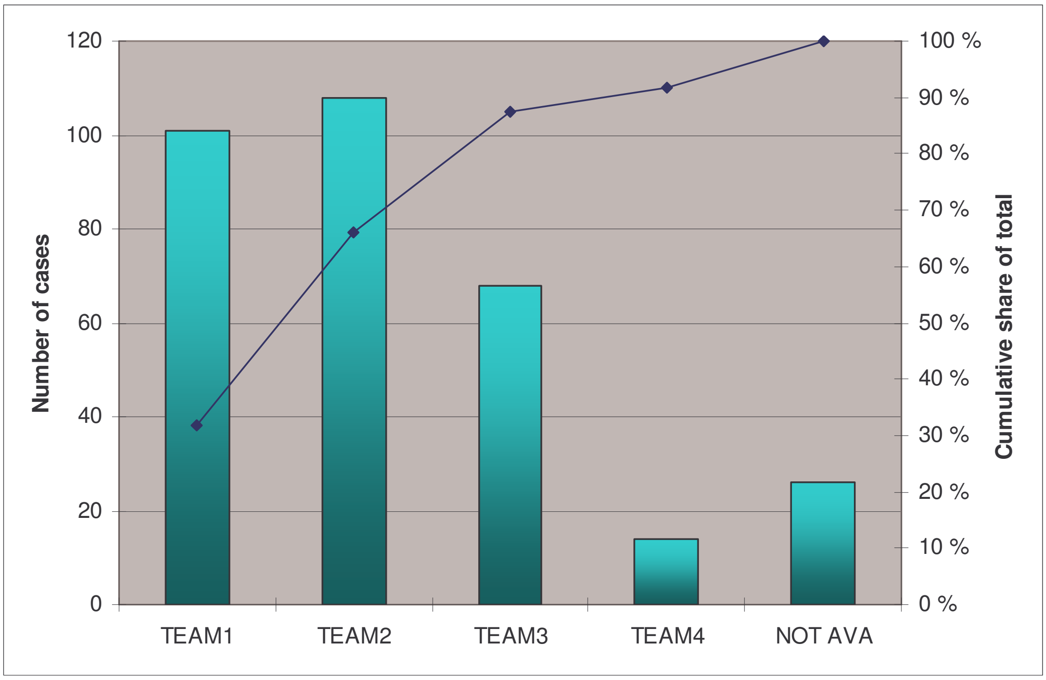


Figure 28. HelpDesk-case distribution by teams.

Manufacturing teams 1 and 2 comprises together almost 70 % per cent of all the complaint cases. The result of this comparison is not surprising; team 1 manufactures most of the volumes and team 2 has the most configurable products, which explains the distribution of cases. However, it is a bit surprising that team 3 has over 30 % less cases even though its volumes are second highest, products have more complex structures than team 1 and team represents and manufactures products for three product lines. This result can thus be considered remarkable good in team 3.

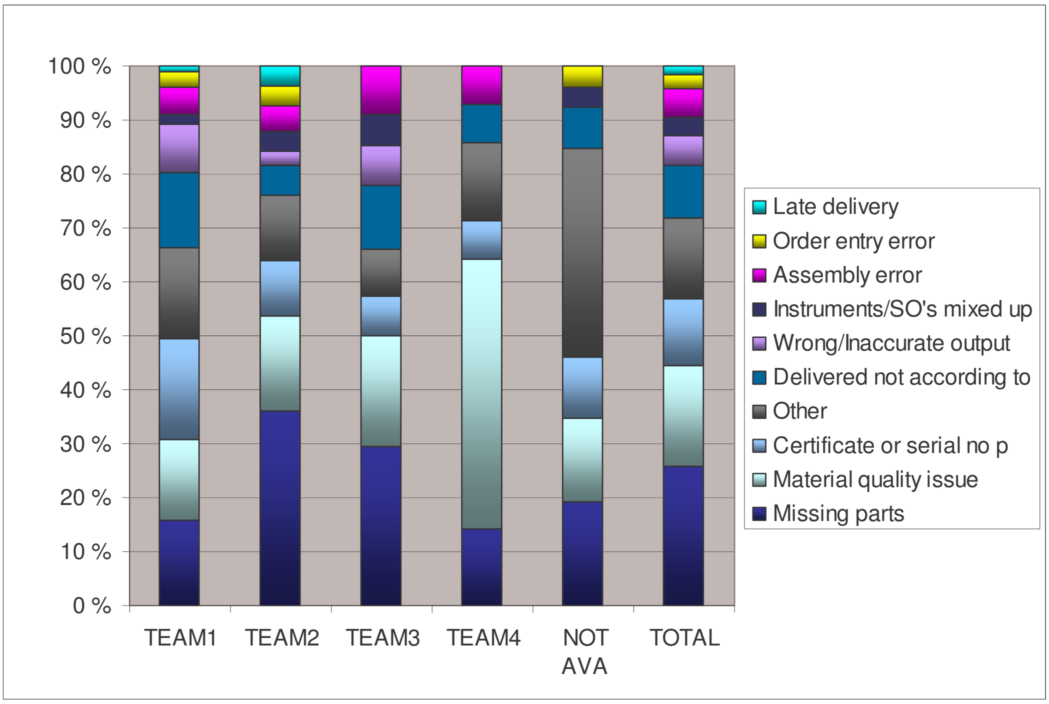


Figure 29. Defect type distribution by teams.

Figure 29 illustrates defect category distribution in manufacturing teams. As this comparison points out variation between teams exists. Manufacturing team 2 and team 3 have almost the same kind of distribution in category comparison while team 1 differs quite a lot from these two teams. Team 1 doesn't have any dominant defect category, however, certificate and serial number problem-category can be considered to be relatively big compared to teams 2 and 3, where most of the problems were faced with missing parts. The results of team 4 cannot be compared to other teams while the number of manufactured products is noticeably smaller.

6.2.4 Pareto analysis of internal inspection process

In addition to customer complaints another source to obtain useful information of quality failures has been used. As already mentioned, case company executes final inspections for finished products (complete sales packages) before the final shipping. Inspection is carried out to all products sold to one specific geographic area and for the top 3 products presented in the figure 26. In this inspection, sales packages are opened by inspectors and contents of packages are checked at the accuracy of every feature of the sales order. However, equipments are not electrically tested in this inspection process which decreases the reliability of this inspection method a bit.

During this study, actions towards developing the internal inspection system further in order to obtain more specific information of faults were executed. Another objective has been to develop the feedback and monitoring system of quality failures.

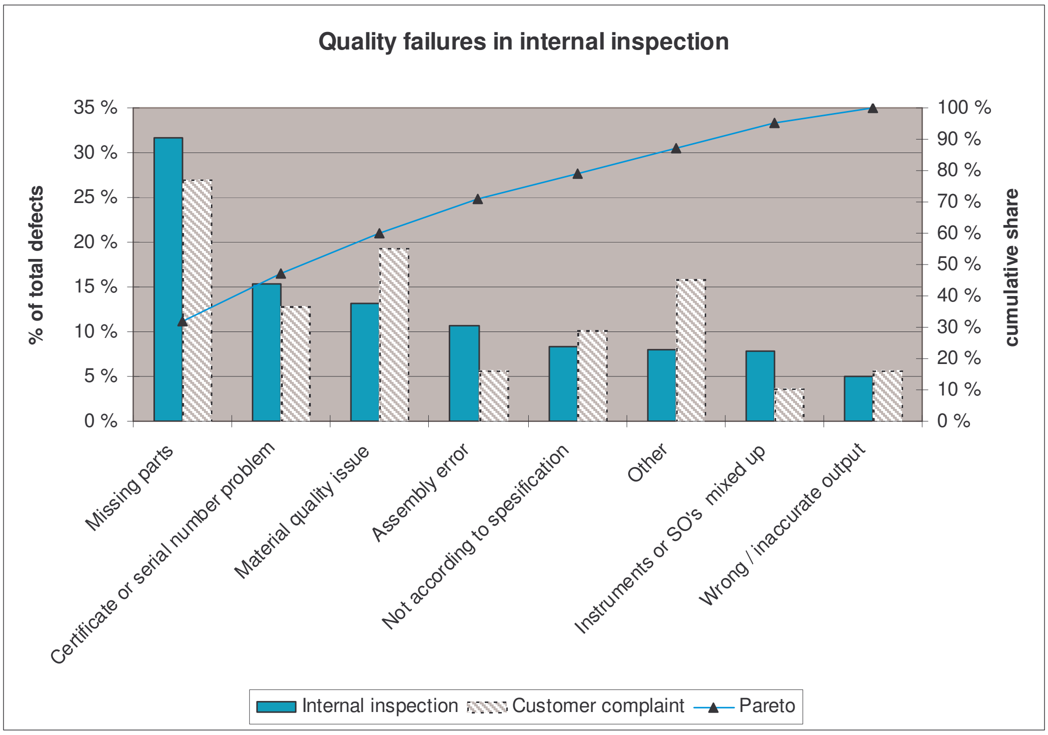


Figure 30. Final inspection pareto analysis and HelpDesk comparison.

As the results of internal inspection pareto analysis shows, similar trend to customer complaint pareto exists. Missing parts and certificate and serial number problems are the major categories.

Due to data has been gathered afterwards and final inspection process has been at full scale use since late Q3/2007, the correlation of how the inspection process and the corrective actions based on it has effected on the number of customer complaints and defect distribution can’t be stated yet.

6.2.5 Origin of fault in manufacturing process

Targeting development actions to right phases of the manufacturing process it is reasonable to clarify in which part of the process most defects occur. In this examination manufacturing process is divided in three parts; assembly, testing and calibration and final assembly. In addition there is a group "supplier" which stands for the cases where the origin of fault can be traced back to supplier actions.

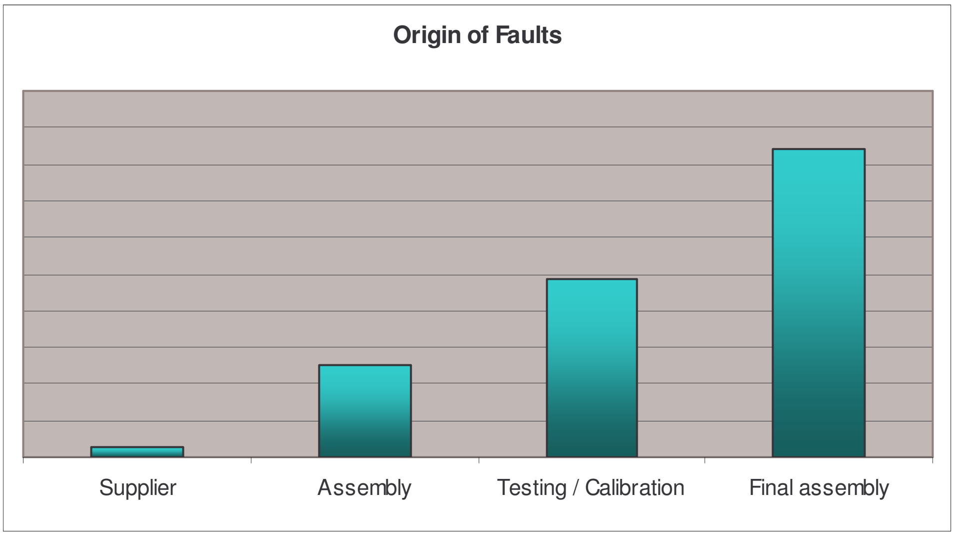


Figure 31. Origin of faults in manufacturing process.

The results introduced in figure 31 show that the majority of faults have taken place in the final assembly. In this stage the product itself is complete and fully functional, waiting for additional parts and accessories to be added into sales package according to configuration.

Analysis supports also the insight that assembling basic structures of products are executed quite correctly and the mistakes are controlled pretty well. In pre-assembly, products are assembled to a stage where all the main components are included and products are electrically functional. Defects occurred in pre-assembly are mainly reported in material quality issue-category, e.g. incorrect wirings or other visually detectable failures.

Typical defect types which take place in testing and calibration phase are related to wrong outputs, e.g. operator enters temperature unit F instead of C. Also some certificate and serial number problems have its origin in here, while the certificates and labels are printed straight from the test station.

6.3 Summary of quality failure analysis

As the results of analyses have shown, a great majority of quality problems were derived from only a handful of products. The largest category of defects according to both data sources was missing parts. Certificate and serial number problems can be considered to be as a second largest independent category, because the categories other and material quality issues cover such a great variety of different type of cases. The aim of this part was to provide data of quality failures from many different aspects and point out which areas should be improved and further developed.

In the production environment where the manufactured products are largely configurable, the number of different kind of defects can be very high. This is a major challenge for utilizing poka-yoke methods effectively, while the root causes of the problems varies a lot. However, utilizing poka-yoke method is useful and advisable approach for controlling these quality failures, due its nature on eliminating human errors effectively.

The analysis revealed also some weaknesses and the areas which need improvement regarding existing quality reporting methods. For example categorization of defect types and reporting methods should be evaluated thoroughly. Also the meaning of the final inspection should be evaluated according to the framework of poka-yoke theory, which suggests that judgment inspection process (as final inspection process can be compared in this context) is the lowest form of inspection and only helps to detect mistakes, not to reduce or prevent them effectively. However, at this stage the benefits of this inspection process can be appraised to be very remarkable due to vital information it provides.

7 CASE STUDY: ROOT CAUSE ANALYSES OF TWO QUALITY FAILURE CASES

This chapter presents a profound examination of two typical quality failure cases in the case company. The main purpose is to define possible root causes for the problems and according to the results identify and consider how and what poka-yoke methods could be utilized to presented quality issues. Cause-and-effect diagram added with 4M principles has been used as a tool for root cause analysis.

7.1 Case 1: Missing or wrong parts

As presented in the chapter six, the category missing parts is the largest defect group in both pareto analyses. A closer look to cases reveals that products with large configurability are on the top of this defect category. Another issue concerning this category is that errors usually occur in the final assembly. The following case represents both of these characteristics.

Problem description

Customer has received a measurement unit UNIT 1 with a wrong installation kit inside the sales package. Instead of needed KIT 1 there was KIT 2 in place. Customer took contact to the company and required replacement. Company's representative shipped the right assembly kit to the customer as a corrective action immediately.

The description above represents a typical example of the mistake in the final assembly related to picking of correct items. The following cause-and-effect diagram summarizes possible root causes for the problem.

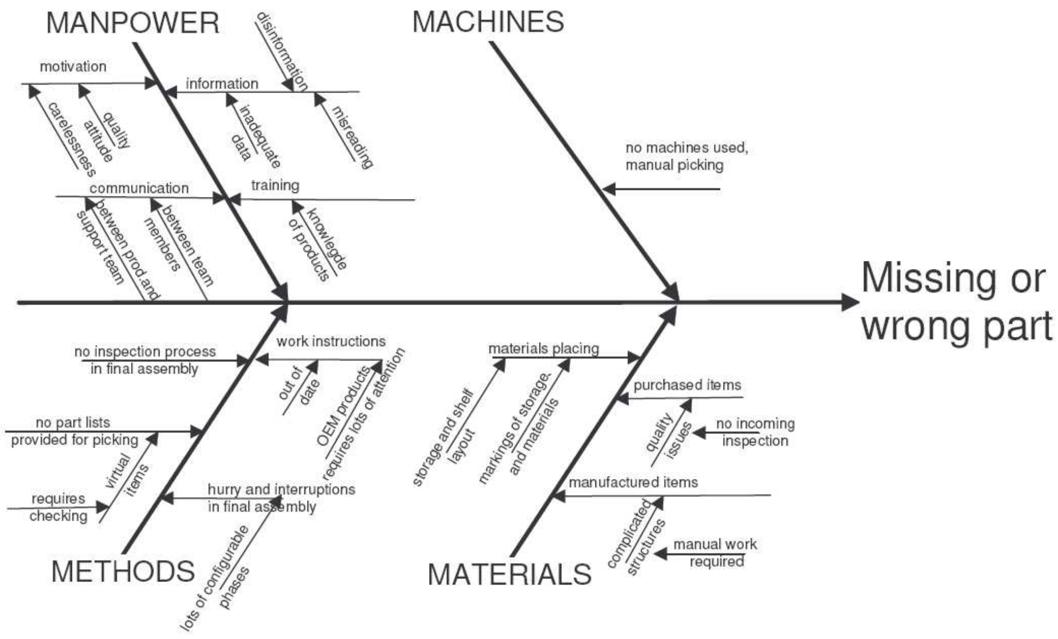


Figure 32. Cause-and-effect diagram of missing or wrong parts.

As the cause-and-effect diagram shows there are various causes behind this kind of error which makes the finding of preventive solutions very challenging. However, the most profound causes derive from working methods and materials.

Regarding working methods a few critical issues can be found. In the picking phase, only a list of features is provided for the operator instead of providing an overall list which covers all the items that need to be picked for the specific sales order. Due this, there can occur misreading in the specific mark of the configuration code which cause the error to happen. As in this case all the accessories and assembly kits are picked just before the packing phase and releasing the product to the shipping team. It is just operator's responsibility to check that all the needed items are picked correctly because there is no separate inspection process after the picking phase. Sometimes out-of-date product documentations and instructions may be a cause for the shipment with wrong or missing parts.

Some causes for missing and wrong parts can be derived from the materials related aspect. In the final assembly picked items can be both purchased items and manufactured items. In this specific case KIT 1 is purchased but KIT 2 is manufactured in house by adding some items into the KIT 1. In addition, part lists for checking the right structure of items are not always easily available. All the materials needed in the packing phase have no shelf storages in the packing area. The operator must move around the factory floor to collect the items needed. This interrupts the packing operation and cause that some parts may unintentionally be left out from the sales package.

When analyzing the case in the framework of poka-yoke inspection methods and control function, several notifications can be found. Taking a closer look to the picking phase shows that there are no “inspections” in this process which confirm that the right items are added into sales package. While the operator is responsible for the correct execution of picking and picking phase is usually carried out by one person the suggested level of poka-yoke solution would be informative self-check. It should either warn about the mistake occurred or control and support the picking of right items.

However, finding a general solution to missing part problem can be regarded very challenging. As the cause-and-effect diagram illustrates there are various causes behind this phenomenon. In some cases implementing preventive actions would require only small changes in the process to obtain remarkable results, while in some cases the whole process should be totally reorganised. Due to products’ diversity, solutions to one product might not be easily applicable into another.

Derived from the problem description and from the cause-and-effect analysis some suggestions can be made as possible solutions to missing part problems:

- generating picking lists
- pre-moulded packages which indicates visually if some items are missing (especially in standard products)
- improving the layout of packing area

- improving material storage layout more supportive for picking materials according to configuration (see proposal in appendix 1)
- the use of reader devices to control picking of correct items (bar codes, RFIDs)

7.2 Case 2: Certificate or serial number problem

Quality issues concerning certificate and serial number problems comprise a large share of reported quality failures. Even though these mistakes don't have any effect on equipment's functionality, they are still considered to be very embarrassing quality failures. Usually, they only cause some confusion at the customer site and correct certificates and labels are delivered soon to the customer. However, in some cases it may play an important role if, for example, the equipment is named as reference equipment for the specific application and the mix up is noticed after official documentation and verifying. Despite the situation, this kind of quality issues always refer to carelessness and of course, in some extend it may have an effect on company's imago and credibility if same problems continue to occur.

Problem description

Customer has received a measurement unit UNIT 2. The unit has a serial number B2720017 on its product label and in its card box. However, in attached calibration certificate has the serial number B2720016. S/n B2720017 is confirmed as the correct ID of this specific unit.

This is a very typical example of quality issue faced with product labels and certificates. In a normal situation, the customer is satisfied by delivering afterwards correct certificates or correct product labels, depending on the case. The following diagram clarifies the root causes behind this problem area.

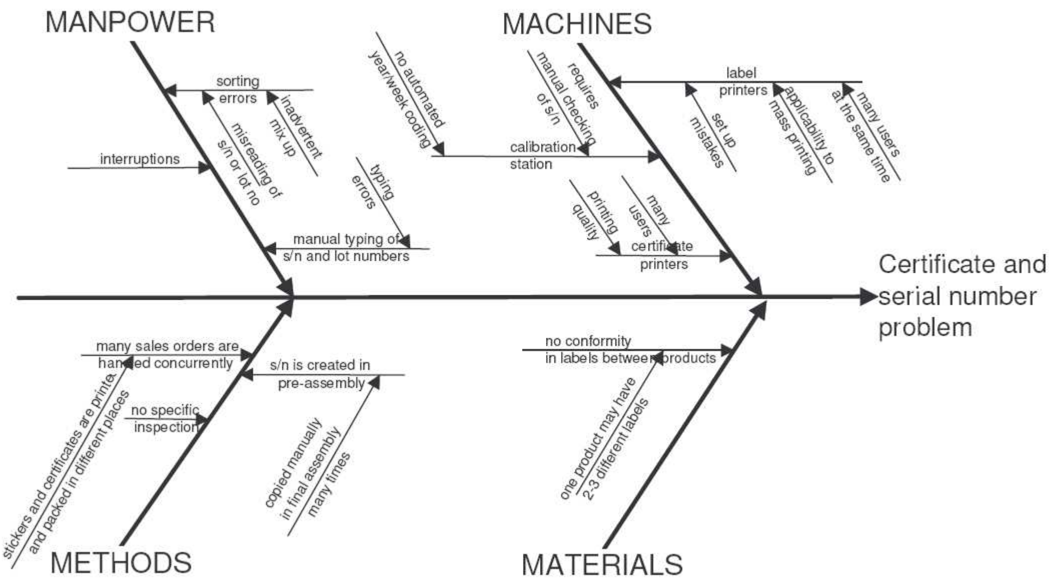


Figure 33. Cause-and-effect diagram of certificate and serial number problems.

As mentioned earlier this type of errors has no effects on products functionality but can cause confusion among the customers. As in the case 1, as likely most of the certificate and serial number problems occur due to human errors. However, cause-and-effect diagram expands the outlook for the problem.

In this problem area the finding of unambiguous root causes is very challenging as the cause-and-effect diagram shows. The following conclusions concerning the root causes can be drawn out:

Methods

Printing of product labels and certificates to one product can be done in worst case in three different places. Due this, the possibility of mixing them is regarded high while they need to be moved around. Another major issue within working methods is that s/n is created as a first task in pre-assembly. After this s/n is manually copied many times in the following operations, which raises the possibility of making mistake. Within some products the level of automation has been increased to avoid copying errors.

Manpower

In a manpower examination, human errors take place due to interruptions in operations and inadvertent errors in sorting the labels or certificates (because the number of printed items simultaneously is high). Also typing errors with serial numbers are common because they normally include 8 marks that need to be typed manually. Within some products hundreds of serial numbers are handled within one working day by one operator and thus it is not a surprise that these kind human errors may happen, especially in a hurry.

Machines

Quality problems caused by machines are mainly related to printing quality in both certificates and labels. Also selected label printing techniques and print materials are not fully suitable for this magnitude of printing. However, technical requirements for label materials forces to the use of selected printing techniques and materials. Problems faced especially with sticker printers are due to inadequate number of them and the insufficient level of automation.

Materials

Regarding the material aspect the most important issues concern the number of different labels needed to one product. One product may have at least three different kinds of label stickers, which need to be manufactured with different machines. It would be recommendable that labels could be printed with just one printer. Also the creation of some principles and rules for the designing of new label blankets would be advisable, while almost every product has its own specific design in labels. This makes the controlling of them very challenging.

As in the case 1, there are no any kinds of inspections or checks to cover this kind of quality non-conformances. The feasible poka-yoke solution should provide a procedure which decreases the risk of human error concerning e.g. the manual typing of serial numbers or sorting of labels and certificates. If contrasting these issues to lean environment, all of the activities mentioned can be considered as some sort of waste.

Due to attaching labels and certificates to products and sales packages is done in the very end of the production process the biggest challenge is faced with designing mistake-proofing method. It requires that poka-yoke solution informs immediately about the mistake and prevents its flow into the next phase. The following aspects should be taken into consideration when defining poka-yoke implementations:

- minimizing the manual typing of serial and lot numbers (data should be electronically readable, e.g. bar codes and RFIDs)
- printing of labels and certificates just before the packing phase (unnecessary movement will be avoided and thus the risk of mix up is minimized)
- decreasing the need for sorting out labels from each other due to mass printing (in a batch size of one the risk of mix up is minimized)
- defining visual requirements for the printing quality of labels and certificates

8 UTILIZATION OF MISTAKE-PROOFING METHODS: ANALYSIS AND RECOMMENDATIONS

In the empirical part of this study so far, extensive analyses of quality problems and more detailed descriptions of two case examples have been introduced. The aim of this chapter, instead of defining poka-yoke solutions to individual cases, is to generate overall procedure of what steps need to be taken into consideration when utilizing and implementing poka-yoke methods. Analyses and case examples act as a background for the definition of this procedure. In addition, the current problem solving methods in the case company are examined and some recommendations are given on the grounds of this examination. For this purpose, a specific evaluation and development matrix tool has been created.

In addition, the following topics will be discussed thoroughly later in this chapter:

- prioritization of development areas in the case company
- proposals and recommendations for correcting existing quality failures
- recommendations for developing quality reporting systems and monitoring
- company-wide mistake-proofing efforts
- challenges faced with the mistake-proofing implementation

8.1 Defining the evaluation and development matrix

A matrix introduced in figure 34 will act as a framework for an analysis and development tool. The matrix has two dimensions; the first dimension consists of current and ideal states and the second dimension covers corrective and preventive action approaches in problem solving. Dimensions have been chosen according to the theoretical examination discussed in chapter 3, including perspectives of Toyota’s problem solving methodology (short-term and long-term aspect) as well as control cycle perspective (see figure 4) presented by Shigeo Shingo.

This matrix can be used, like now, to provide an overall analysis of problem solving methods but also as a development tool for individual quality improvement cases. The aim of this matrix is to help at collecting information and examining cases from different aspects.

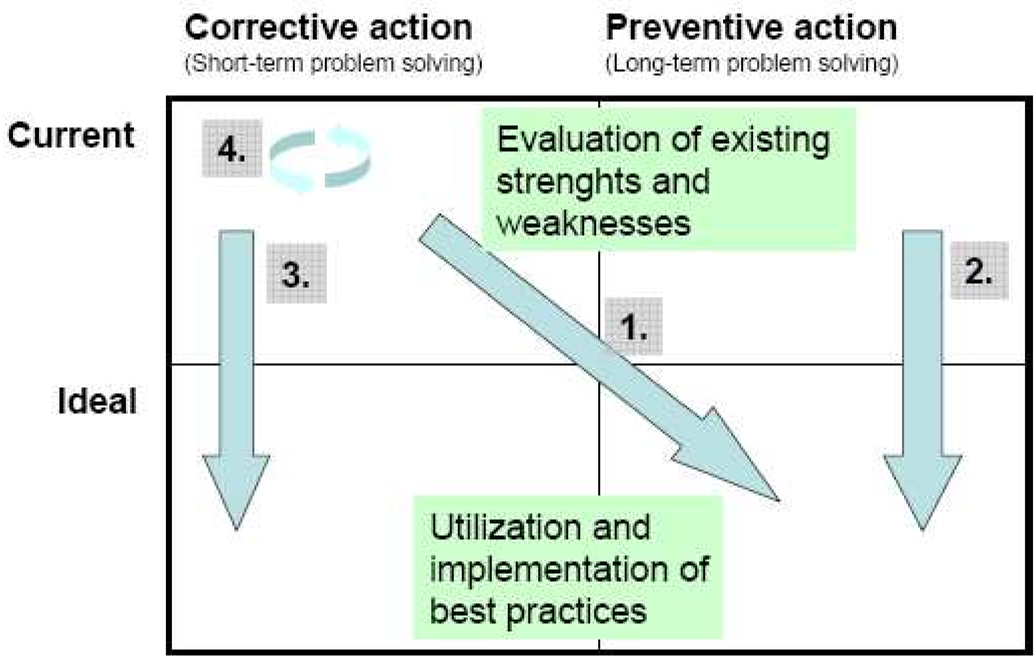


Figure 34. Framework for evaluation and development matrix.

The presented framework includes four possible states of movement. The numbers beside the arrows describes how remarkable the changes are from the initial state to the new state and are as follows:

1. Designed solution model for specific problem is effective and can be considered as permanent and preventive for similar cases. This is the most preferable movement.
2. At this state preventive solution model for a problem exist, but is not efficient enough. With some improvement efforts it is possible to make method more stable and reliable.
3. There are some problems which cannot be eliminated totally, or the benefits achieved through the total elimination are minor. Thus, the main emphasis should be paid on mitigating the effects of the problem.

4. No movement to any direction. Problems are so rare or cannot be controlled otherwise.

In the current state section existing problem solving methods in case company are analyzed. The main interest is on how mistakes are detected, what are the root causes behind occurring problems and what actions take place immediately and how preventive actions are handled. The results of these build a basis for developing the ideal state and its related actions. In the background of proposals concerning the ideal state the theory of poka-yoke and efficient problem solving methods will be utilized.

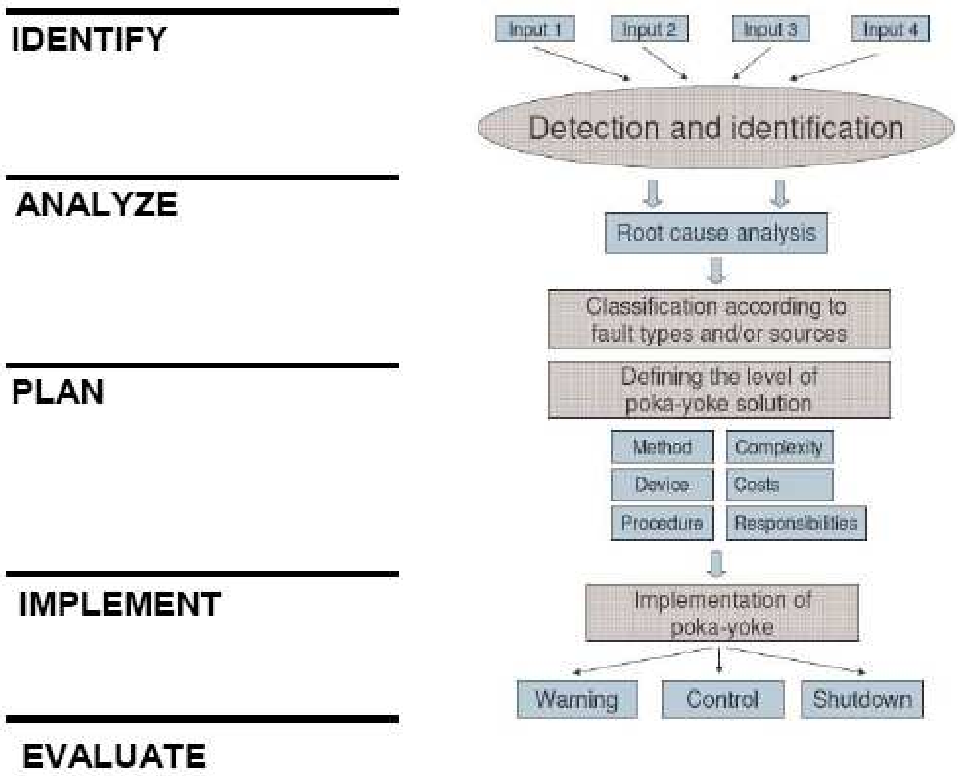


Figure 35. Poka-yoke implementation process.

Within every section of the matrix there are a few suggestive steps which should be taken into consideration when implementing and utilizing poka-yoke methodology. Steps introduced in figure 35 concentrates on the following aspects:

- *Identification*: definition of detection methods; how certain type of defect can be detected with existing or future methods
- *Analysis*: clarification of root causes and common characteristics of defects
- *Planning*: defining, analyzing and comparing possible mistake-proofing methods
- *Implementation*: executing the implementation, advising the operators
- *Evaluation*: evaluation of implemented method, approval or re-implementation

In the following sections 8.1.1-8.1.4 descriptions of case company's existing problem solving methods and suggestions regarding the ideal state are provided.

8.1.1 Current state and corrective actions

Detection and identification

At the current state, most of the occurred quality failures were not detected in the manufacturing process itself but through the final inspection process and customer complaints. This indicates clearly that in existing manufacturing processes the level of mistake-proofing is not sufficient, especially in the final assembly where the majority of mistakes take place. Referring to figure 31, however, mistakes do seldom pass the testing and calibration process easily, which indicates that mistake-proofing methods in pre-assembly and testing and calibration process can be considered to be a satisfactory level.

Detection of an occurred defect as early as possible is of great importance. Referring to the case examples presented on the chapter 7 that kind of mistakes are usually detected by the customer. Due to long feedback loop, there are no evidences available anymore of which particular reasons were behind the mistake. If quality failure is detected in final inspection process this prevents that the faulty unit won't be sent to a customer until it has been repaired. At this time the circumstances are traceable and the possibility to control the upstream processes still exist.

Problem solving and corrective actions

All customer complaints concerning the delivery process are handled by a responsible person. As an immediate corrective action a replacement is normally sent to the customer or to the sales representative or in some cases, the product is pulled back from the customer for the repair. In many cases this is the first time when the operator gets the information of fault execution and together with the responsible person they check the situation and try to clarify possible causes behind the problem. If the mistake is detected in the final inspection, the person inspecting corrects the fault him/herself or returns the product back to production. As soon as the defect is detected it is important to inform all relevant interest groups and especially the operator. However, sometimes it may be hard to identify who has manufactured the specific product. Very often the main emphasis of corrective action is only to correct the specific product; efforts should be more paid on finding the causes from the process. This conclusion can be made because similar problems arise again and again after a while of previous corrections.

Weaknesses regarding current state of mistake-proofing

Following aspects of mistake-proofing can be identified in the current state:

- Lack of quality checks in final assembly (majority of reported quality failures occurs in this part of assembly).
- Corrective actions are primarily targeted on product aspect, no changes or corrections in the process which causes that mistakes continue to occur.
- Corrective actions are usually type of “warning”. Teams are informed and told to pay more attention next time or e.g. new instructions are created. However, after a while same mistakes might continue to occur.
- Due to long delay of detection of a mistake, original circumstances of the occurrence remain unknown and thus correcting the problem is challenging.

- Low utilization rate of already handled Helpdesk-cases, even the same mistakes are recurrent. No common database for corrective action reports.
- In some cases root cause analyses are not conducted thoroughly.

As the notes above points out, some weaknesses regarding mistake-proofing and problem solving can be found. A more thorough study of customer complaint cases reveals that the majority of the faults happen due to human error; this indicates that a need for mistake-proofing processes is important. It is very typical aspect for this kind of high-technology product manufacturing that most efforts of development are targeted to products' technical functionality and faultlessness. This statement applies as well to case company. Manufactured equipments have usually no problems with technical performance but the chain of "making-of-quality" ends when sales package need to be covered with customer's required options. Everything goes well all the way to the final testing and the calibration stage of manufacturing process, but after that the problems begin. Also in many cases the level of technical mistake-proofing is on the very satisfactory level before final assembly.

8.1.2 Current state and preventive actions

The aim of preventive actions is to generate long-term solutions which prevent the reoccurrence of similar defects. Normally, preventive solutions are conducted and implemented as a result of detailed and thorough examination and study of mistakes and their root causes.

Long-term and preventive action process has two approaches. The first aspect is to generate long-term solutions to quality issues of already known quality failures (existing problems, which are usually corrected at some level, but the solution is only temporary in-kind). The second aspect regarding preventive actions is to utilize mistake-proofing methods before a mistake has even occurred. In this situation possible error states are known at some level.

On the grounds of the empirical study some observations about the case company's problem solving methods can be made. As the results of quality failure analyses reveal, preventive solutions for quality issues have not been efficient enough. This conclusion can be made on the basis of that the same mistakes are occurring regularly. Especially in cases of missing parts and certificate and serial number problems this phenomenon is most obvious.

The following weaknesses can be found concerning preventive action methods in the case company:

- The mentality of using "human error" as a root cause for a specific problem is too dominant.
- Lack of systematic utilization of problem solving tools or methods.
- Preventive solutions are usually "weakly" preventative, such as telling a team to pay more attention to execution, making of instructions or adding the product under the final inspection. Any of these, however, do not fill the requirements of preventive problem solving.
- Long-term solutions implemented have actually only made "judgment inspections" more effective.
- Lack of organized problem solving teams and clear responsibilities.
- Existing data of delivery quality failures has not been analyzed at sufficient level to utilize it into the preventive actions.

Due to ramp-up processes for taking a new product into full-scale production are quite fast, the possibility of pre-studying mistake-proofing methods is low. During ramp-up processes the main effort is to analyze methods from technical aspects of manufacturing. At this point, only small effort is put on picking and packing phase of production while they are held as secondary issues. However, this usually causes that the real problems becomes visible when the full-scale production is already running. Changing of working methods at this point can be laborious and might even cause delays in production.

8.1.3 Ideal state and corrective actions

Even though it is almost impossible to eliminate some mistakes totally the greatest effort should be paid on mitigating the effects mistakes may cause. A starting point in ideal state is almost the same as in the current state: detection of defects happens through customer complaints and final inspection process but most importantly, more and more in added checkpoints in manufacturing processes.

There are a few issues which are of utmost importance on this stage. Firstly, corrective actions for controlling problems should be started immediately and secondly, to initiate actions for problem solving procedure. When a defect is detected first time, it should be confirmed that no more faulty products are delivered to customers or the flow of faulty units should be stopped in in-house processes. The operator should be also informed immediately. After containment of the problem, the emphasis should be targeted on starting to clarify possible root causes and initiate problem solving process for preventing same mistakes from occurring. Key concern is to find out possibilities how to detect defects earlier and prevent them from reaching the customer.

Compared to current state situation in the ideal state the main difference is that the corrective action can be executed faster, e.g. by utilizing the data obtained from similar cases. And as stated earlier, some defects are so rare that their total elimination is unreasonable, so the aim of corrective actions is to mitigate the effects of them as much as possible.

In the ideal state possible problem statement is done thoroughly in the first place which helps later the processing of the problem and narrows the group of possible solution models. The aim of is stage is also to provide supporting data for finding the preventive solution for the problem in the next phase.

Compared to current state situation:

- People are more aware of the existing quality problems and are able to react to the problem faster.
- Problem solving process does not end when a case is closed to a customer.
- A common database for quality failures and corrective action reports exists.
- Customer complaints are not the primary inputs to start corrective actions in the manufacturing process.
- Inspections and/or checkpoints are added to manufacturing processes for controlling mistakes better.
- Judgment inspections have been replaced by informative inspections.
- Warning mechanisms are replaced by control or shutdown mechanisms.

8.1.4 Ideal state and preventive actions

This is the most desired stage of the matrix. On this stage the true aim of quality improvement efforts is in the prevention of mistakes especially in manufacturing processes. Processes and their defect states are well-known and the major interest is on possible causes ("inputs" in figure 35) of defects. The "inputs" are usually conducted from the root cause analyses. With the information about possible defect sources, it is possible to set up inspections and quality checks to right phases of the processes.

Poka-yoke implementation process should start when a new input is detected. The input is the target of “poka-yokeing”. The mentality of preventive actions should be “what kind of poka-yoke do we need to detect the causes and prevent them from turning into a defect”. When implementing poka-yokes to specific problems following issues should be taken into consideration:

- Defining the level of inspection technique: judgment, informative or source. Source inspection is always the most preferable technique.
- Assessing possible solution models between method, device and procedure.

- Comparing solution's complexity and implementing costs to the benefits obtainable (e.g. are the massive changes regarding IT-systems or lay-outs worth of execution).
- Defining clear responsibilities for the implementation and monitoring (including operators, support functions and management).

If we contrast case company to the ideal state the major changes are required in the raising the level of "inspections". In the current state most of the preventive actions have just raised the intensity of judgment inspections but to develop and improve preventive action methods further it requires that informative inspections and source inspections are implemented. In practice this means that stages of manufacturing are split into smaller phases and they are controlled by poka-yokes.

Steps towards more preventive mode in the case company:

- systematic utilization of problem solving methods
- problem solving actions should be mainly targeted for improvement of the processes
- increasing the level of work supportive methods
- increasing the importance of correct execution in the final assembly already at the ramp-up phase
- defining clear responsibilities concerning problem solving
- continuous monitoring of quality failure cases (helps at prioritize development efforts)

8.2 Recommendations for main quality failure types

As the nature of this study is, the main emphasis is paid on identification of existing quality problems. Due to short period of time only minor poka-yoke implementations were executed. Thus, the main effort is to provide recommendations and proposals for possible poka-yoke solutions.

According to pareto analysis in the figure 30, majority of quality problems are faced with the categories of "missing parts" and "certificate and serial number". Together these two groups comprise nearly half of all mistakes reported in HelpDesk and in internal final inspection process. The following section provides some detailed suggestions of methods to decrease the occurrence of these mistakes by utilizing poka-yoke methodology.

8.2.1 Poka-yokes in missing part category

Reducing the number of missing part - cases, main efforts of mistake-proofing should be targeted on the products with high level of configurability and on final assembly in manufacturing process.

Final assembly is normally executed manually and the operator is responsible for the correct execution. In addition, this phase of manufacturing process includes many configurative steps and at the moment there are no “poka-yoke" methods which assure that for example picking phase is executed correctly and the possibility of human error is eliminated.

Applying inspection and poka-yoke methods to this area of quality failures the following proposals can be made for the case company:

Missing manuals or wrong language manuals

- use of multi-language manuals, especially in manuals with only a few pages
- providing manuals only through the internet or e.g. the use of USB-stick (all languages provided in one source)
- weighting methods (however, does not apply to wrong language, but may detect a missing manual)

Screws and cables

- design of products so that correct assembly requires certain screws are inserted (R&D), or making missing screws easily visually detectable
- additional testing in test stations, which checks that the specific cable corresponds the same as the configuration code requires
- inspection process and/or poka-yokes should be installed in pre-assembly because the parts are collected at this stage

Missing or wrong installation kits and other accessories

- poka-yoke method should be type of control or shut down because items are picked in the final assembly and if they pass on this stage; customer is more likely to receive a faulty unit
- rationalizing of options of features; existing options can be both purchased or manufactured in-house and the difference in their structure is only minimal
- use of pre-moulded packages, which works as a visual indicator for missing item
- material storage layout (all picked items should be stored in one place)
- controlled picking of materials

8.2.2 Poka-yokes in certificate and serial number problem category

According to analyses certificate and serial number problems comprise a large share of existing quality problems. During this study, new printers for both certificates and labels have been bought and taken into use. However, this doesn't have much effect on reducing defect rates while the possibility of human error still exists in mixing up certificates and labels.

As pointed out in the cause-and-effect diagram earlier, different products have different kind of labels and stickers and they are printed in different phases of production. Only within few products there are utilized the system where the right lot or serial number is read electronically and transferred to printer. However, at the moment, the serials are copied many times manually which increases the possibility of misreading or misinterpreting.

Considering the possible poka-yoke methods the same challenges are faced like in the case of missing parts: this part of assembly is done in the very end and thus the time to react a problem is minimal. Below are presented some issues that should be taken into consideration:

- minimizing the manual typing of s/n and lot markings
- handling of only small number of labels, stickers and certificates at a time
- organizing the printing of labels and certificates into the one place
- creation and printing of the serial number in the final assembly
- the use of label sheets which include all necessary labels for one product, see example in appendix 2.
- more extensive use of reader devices e.g. bar codes and RFIDs

8.3 Supportive systems for mistake-proofing

Improving the level of mistake-proofing can be also achieved through the effective utilization and improvement of many supportive systems and tools already used in the case company. These efforts may even have a greater overall effect on decreasing the number of faulty deliveries due their effects on working methods. From the case company's point of view discussion concentrates firstly on quality reporting and monitoring systems and secondly, quality of data and information used in everyday operations in manufacturing.

8.3.1 Quality reporting systems in delivery process

As a kick-off for this study was that the number of customer complaints referring to origin of delivery process had increased. The internal inspection process was started on spring 2007 and the number of products taken under the final inspection process has been gradually increased. Before the study the only information of the quality issues concerning the delivery process was reported quarterly and only in the level of fault category distribution (see figure 25 as a starting level). The possibility of drilling down to product level or team level did not exist or it required excessive amount of work. Also the utilization of quality data was at the low level. Only people involved with a specific product or product line had a comprehensive and specific knowledge of existing quality problems. As with these statements the following conclusion can be drawn: reporting methods of quality issues needs rationalization and the level of informative data needs to be increased.

Continuous quality failure reporting is very critical at this point of implementing poka-yoke methods. With the help of accurate information available, it is easier to put focus on correct places and issues, but in addition, evaluation and measurement of implementations is even more vital.

In order to have been able to conduct these analyses in this study, it has required lots of manual work to be done. This indicates that the existing reporting methods are not the kind that supports the utilization of it. During the study many development areas concerning quality data collection methods have been identified. The primary source for external quality failures, case company's HelpDesk system, needs the following requirements to be fulfilled to gain the sufficient level needed in the future:

- improvement of data "drill down"- possibilities
    - adding new compulsory fields; e.g. the product name, number of faulty items
- fault category rationalization
    - classification of fault types
    - depending on the performer of the case the fault category varies; categories are not unambiguous
- shortening the reporting period of HelpDesk (at the moment 3 months)

During this study some of the suggestions above have been tested in the final inspection reporting and the results have been very promising. Especially, the possibility to get easily an overall view of the quality failures, as well as the drill down possibility is considered to be very useful and important aspect.

However, when defining the development areas of quality reporting methods, a few crucial issues remain open: who will be responsible of delivery quality issues in the future and what will be the needs of quality organization in the case company? From this point of view, major changes in quality reporting system have not been made. The purpose of this study has been to point out the areas which need improvement and to increase the utilization level and usability of quality reporting systems.

8.3.2 Quality of data and information

As described in chapter 2, there are many types of human errors which may cause a mistake to happen. Some of them are closely related to the quality of data and information handled in daily operations. In this context “quality of data” is considered as all data related to materials, instructions and methods used in the delivery process. Referring to table 1, most of the human errors in the case company can be imagined to fall into categories of forgetfulness, errors due misunderstanding and errors due to lack of standards. In many cases "quality of data" can be seen as a partial cause to these errors. Next there will be taken a short review of data quality issues from the selected areas which have the most effect on daily operations.

Work order

As mentioned earlier the case company executes Make-to-Order manufacturing. When a new sales order is entered to MFGPro (ERP-system in the case company), operator receives it and places it into a job queue of the team. Next the operator changes the status of order to WIP (work-in-progress) and prints the paper version of the work order. Printed work orders move with the products through the manufacturing process all the way to shipping point.

Work order includes e.g. a configuration code, list of selected options of features and detailed shipping information. Primarily, work order should act as a summary of needed information to be able to manufacture the right product and ship it to right customer. However, in many cases work order is tailored to act also as some kind of narrow picking list for needed items. At the moment, there are not provided any other kind extensive picking lists.

Due to work order prints are tailored differently depending on the product and its configuration structure, the outlook of them varies. This causes that when the operator takes a new product (from different product family than previous) under work, he/she has to learn how to read the work order right. For example, the same option character can stand for "normal mounting kit" or "wall mounting kit" depending on the product. This kind of variation requires that operator must pay extensive attention to this kind of non-value performance. In addition, even if there aren't any problems with interpreting the right option, in case of any frequently used option; the operator must confirm the right items that need to be picked up from separate BOM, bill-of-materials, documents. Obtaining this information can be very time-consuming and it easily interrupts normal processing. In some cases operator may have difficulties in finding the right source for the information. According to interviews during the study period, the idea of printable picking lists was held very promising according to the personnel in manufacturing. However, other methods, such like providing the same information via computer screens, should be also assessed carefully.

Work instructions

Quality of data is an important issue concerning work instructions. Due to high pace of changes in product structures this creates pressure to keep work instructions up to date. The admirable state of work instructions should be on the level where the assembly operation can be correctly executed unambiguously according to instructions.

Work instructions are normally available near work place in product maps (as paper versions) and, of course, electrically available in the company's PDM system. Up to the present, production people have preferred paper versions of work instructions. Product maps include usually detailed assembly information with text and photos, BOMs and any other relevant information e.g. regarding OEM-products. However, the level of instructions varies a lot by products.

Typical problems faced with work instructions are that the information is out-of-date or the information is useless for the purpose regarding especially paper versions of instructions. Errors due to out-of-date information are totally inadvertent errors from the operator's point of view. In some cases the information obtained from product maps is totally insufficient for correct operation execution; e.g. there are no photos at all or job phases are not explained detailed enough.

Based on the interviews and meetings with production teams, we have identified which work instructions and product maps need urgent updating. There are three major issues which raises the importance of the quality of data of work instructions. Firstly, instructions should be unambiguous and easily available in every work place. Secondly, in the case of new worker's training, good instructions work as an enormous support for the worker. Thirdly, documented instructions are always much more reliable than information obtained first time from another person verbally.

PDM system and Engineer-Change-Orders

Case company uses Aton software as a Product Data Management system. Operators in assembly do not, however, use this master data source much since they find it too complicated to use. Also finding the specific information is sometimes found difficult, mostly due to the lack of routine of using the Aton software. This is slightly conflicting issue because PDM system includes master data and updated instructions. Updating changes into product maps is very laborious updating should be done immediately when changes take place.

Gaps in the flow of the information may happen when a new engineering change order (ECO) is released. If the operator is not aware of changes in product structures, he / she will execute assembly process inadvertently wrong. Due to this, new methods of how to inform production teams about changes and to confirm that a new procedure is adopted by all should be defined.

8.4 Mistake-proofing in the organization

It would be useful that the utilization of mistake-proofing methods would stay as a continuous process in the organization rather than only a one-shot effort during this study. The best way to confirm the continuance is to spread responsibility for enhancing the use of this methodology widely over the organization. As this study has already shown there are many interest groups whose actions and decisions are directly or indirectly in connection to quality issues. This doesn't mean that mistake-proofing is the only and absolute way to improve overall quality; it is preferably a method which should be taken into consideration behind all quality related activities.

To spread mistake-proofing efforts across the relevant interest groups in the case company the following figure 36 summarizes the roles and responsibilities that are recommendable. Chart comprises three states of product's lifecycle from product development phase to full-scale production and recommendations about general tasks of different interest groups from the mistake-proofing aspect.

	R&D	PRODUCT LIFECYCLE MANAGEMENT-TEAM	PRODUCT LINE (as a sales representative)	TESTING / CALIBRATION	PRODUCTION	QUALITY DEPARTMENT
Product development	Using of poka-yoke design principles	Manufacturability issue feedback		Defining critical technical parameters		Informing R&D of known problem areas
	Built-in poka-yokes in products		Configuration structure	Defining of additional features that can be tested		
	DFM	Planning of supportive tools and methods for production process				
Ramp-up / Pre-production		Process flow / layout planning and development			Immediate feedback of "bad" practices during ramp-up	Participation and auditing
		Importance of final assembly / picking			Defining possible inspection methods	
		Defining possible inspection methods				
Production					Inspections/checks carried out by poka-yoke devices	Quality control
						Responsibility for immediate corrective and preventive action launch
	Poka-yoke method planning	Poka-yoke method planning		Poka-yoke method planning	Poka-yoke method planning	Poka-yoke method planning
						Evaluation and feedback

Figure 36. Generic mistake-proofing tasks within interest groups.

8.4.1. Mistake-proofing in Research and Development unit

To gain the "preventive"-mode in mistake-proofing, mistake-proofing efforts can't wait until mistakes are discovered in production. The control of mistakes should start at the earliest stage of product design, in this case in R&D phase of new product process.

In the beginning of the new product process and product development phase and latest in the ramp up phase, manufacturability issues should be taken under tight investigation. Primary tasks should be, at first, to identify the mistakes that are most likely to occur and then implement different techniques to minimize or eliminate them. Typical aspects in product development would be, for example, that parts are designed so that they can be only assembled in the correct location and orientation. Also designing parts and products so that assembly can't proceed if parts are missing is preferable. As these examples shows, in mistake-proofing even negligible changes can have an important influence on eliminating mistakes.

8.4.2 Product lifecycle management (PLM)

It is because PLM-team takes care of products' ramp-up processes and related issues to manufacturability, this team has many ways to affect improving the level of mistake-proofing. During the product process, PLM should examine very critically all the manufacturability issues. Also supportive methods and tools should be planned at this stage. When a product is ready for the ramp-up and the first series of products are manufactured, the emphasis should be paid on the smoothness and practicality of the process flow e.g. lay-out issues. As mentioned earlier, final assembly should be one of the key areas in addition to pre-assembly. During the ramp-up process possible forms of poka-yoke methods should be defined and implemented.

8.4.3 Product line

Product line is responsible for products' customization and through that the creation of configuration structure. Product line defines what features and options are provided to customers. However, more emphasis should be paid on developing configuration structures in the future. As the results of these analyses have pointed out, complex configuration structures can be regarded as one of the reasons in the background of many quality issues. When starting to define configuration structure for the new product, all possible "killer" combinations should be carefully analyzed. If some of these cannot be totally avoided then relevant mistake-proofing methods should be implemented in the first place. It would be recommendable that co-operation with R&D and PLM is made.

8.4.4 Testing and calibration process

In testing and calibration process the main emphasis is naturally on technical characteristics of the product. However, if possible and without having too much extra load on testing capacity, it would recommendable to define what features could be easily tested alongside with the technical features. This point of view should be taken into consideration already as on early stage as possible. With this procedure 100 % inspection is possible and it can be executed automatically.

Poka-yokes in this stage detect mistakes made in the pre-assembly. In case of majority of products, e.g. the right outputs for the device are set by reading the configuration code electrically. This eliminates the possibility of misreading compared to situation where parameters are manually set. Other applications could be e.g. that electronic testing detect if the equipment is equipped with or without display and compares it to configuration code's requirements.

8.4.5 Manufacturing and quality department

Mistakes and quality failures take place in manufacturing processes. In this context poka-yoke devices and methods are targeted to detect or inform about any deviations occurring in manufacturing processes. This study has already provided many ways of how poka-yokes can be utilized in the operations. Manufacturing teams and quality team are in the major role of reducing the number of quality failures. People in manufacturing teams are the best experts regarding the execution of various tasks in the processes. It is of utmost importance to utilize their knowledge in the development of possible poka-yoke solutions concerning bad practices.

Quality department (includes both sourcing function's responsibility of incoming material quality and all production quality responsibles) should have an overall responsibility of controlling the utilization of mistake-proofing methods in all the stages from product design to full-scale production. Quality department is responsible for continuous monitoring and controlling of quality failures and depending on the situation also responsible for immediate launches of corrective and preventive actions. However, it must be kept in mind that quality department is just one party among other interest groups in the making of quality.

8.5 Challenges in poka-yoke implementation in the case company

Implementing poka-yokes in the case company can be very challenging due to the large number of unique type of mistakes. To provide poka-yoke solution into every single problem requires a lot of resources and work but in many cases this is the only way to correct the problem. In this situation it is important to define beforehand what benefits can be achieved through the implementation so that scarce resources won't be thrown away. Finally, a short discussion of quality cost aspects in the case company is provided.

Interpreting the true nature of mistake-proofing, Hinkcley (2006) states in his book "Make no Mistake!" that the effective mistake-proofing techniques share the following attributes, regardless of the target of the implementation:

- they are like checklists that verify correct procedure or conditions
- they are based on 100 % inspection, since mistakes cannot be detected by any other means
- inspection methods must be reliable
- inspections are autonomous
- to control rare events, devices must be inexpensive to design, implement and operate
- inspected process should be completely known

If we contrast these attributes in practice in the case company the most profound question arises with the 100 % inspection: how to arrange 100 % inspections smoothly in the different places in the assembly flow? This is the most critical step to get rid of 100 % final inspection which only helps to sort out faulty products of non-faulty products.

To find the correct places where to add inspections might also be a difficult issue. Due to the nature of faults, many of the existing quality failures take place in the final assembly where the lead time of the process step is very short. Thus, suggested poka-yoke solutions should not make operators' work more complex and they should not lengthen the lead time. However, in some places total rearrangement of process flow and layout may be the only way to correct the problem.

Due to products' large configurability, most of defects can be considered to be very unique-in-kind and as the average batch size of manufactured products is low, manufacturing processes may vary a lot and are not stable all the time. Also due to the technical complexity of electronic devices or components, they have to be processed every unit differently. Even if the visible problems are exactly the same; root causes behind them can vary a lot which increases the challenges regarding implementation.

Since there are many types of mistakes, mistake-proofing devices must generally be customized for each specific condition. Thus, in this context, mistake-proofing should be viewed as an approach for providing generic methods for understanding and controlling mistakes rather than a strictly defined procedure.

Quality cost thinking in the case company

The reported quality costs in the case company are approximately somewhere between 1-2 % of direct costs. Due to the nature of quality costs (as presented in chapter 4) and according to my experiences obtained during the study, the true costs of quality related can be considered to be higher.

In the case company, existing quality-based costs can be assessed to be more type of avoidable cost of quality than necessary costs of quality. This stands for the estimation that more money is spent to fix the quality failures already happened than used to prevent them to happen. So called external failure costs (costs to correct mistakes detected by a customer) are thus very dominant.

To be able to decrease the costs of poor quality, there are some obvious issues that should be taken into consideration in the case company. Firstly, totally new in-process inspections should be added and secondly while the amount of purchased goods is remarkable, incoming inspection process for critical components should be re-considered. In addition, not enough resources are allocated to preventive work at a sufficient level. One way to add workers interest in quality costs is to make all scrap and defected products visible. This helps them to pay more attention on the quality of correct execution of their work.

As it is criticized that 100 per cent inspections are totally waste of money, this claim can, however, be disproved by the utilization of poka-yoke methods. To make this approach cost efficient also in the case company, existing 100 % final inspection process for selected products should be replaced with new in-process inspections. Here the benefits would be much higher, while mistakes could be corrected almost immediate (minimizing the need for rework) and the feedback of the failure to the previous process is faster.

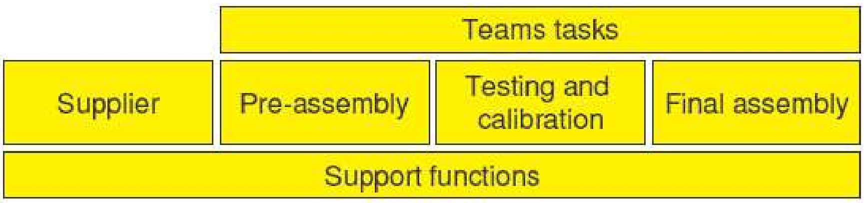
9 CONCLUSIONS

How can all defects in complex manufacturing as well as in everyday living activities be prevented when the most of them are, at some level, caused by human errors? This question has been in the major role during this study. Case company produces mass customized products, which causes that the number of different kind of end-products is very high. The objective of mass customization is to maximize the service level of the manufacturer and keep lead times at very competitive level. However, due to large configurability of products, it requires that lots of emphasis is paid on the correct execution of assembly tasks to avoid mistakes from occurring, especially in the production environment where the level of automation is considerably low.

One of the main objectives of this study was to define ways and methods how to tackle against continuous and increasing number of quality failures. For this purpose the poka-yoke methodology was chosen. As the theoretical part has already shown, the use of poka-yoke methodology can be justified with two absolute arguments: firstly, it is an effective method for eliminating human errors and secondly, because of its true nature at aiming ambitiously towards preventive mode of mistake-proofing.

The analyses conducted in this study were mainly quantitative. Suitability for the purposes of this study and for further use in the case company the information analyses provided can be regarded remarkable valuable. This was the first time case company was able to have such a detailed information about overall quality failures, defect distribution by products and production teams, and origin of faults, just to name a few. With the help of this information it is now possible to prioritize development actions effectively. However, if continuing to utilize the results of the analyses in the future, reporting systems regarding quality failure monitoring needs urgent updating or the work done during this study remains untapped. Issues related to these actions are discussed more thoroughly in section 8.3.

The effectiveness of poka-yoke methods is based on inspection techniques (discussed in chapter 2). In the ideal state they are sort of invisible checks, executed by operator or some automated system, which verify the correct execution of process step and the quality of product. If contrasting the principles of poka-yoke methodology with results of quality analyses we can find clear connections between them. These connections are summarized in the following figure.



	Supplier	Pre-assembly	Testing and calibration	Final assembly
Existing level of quality failure detection	Moderate	Moderate	High	Low
Main issues regarding mistake-proofing	•Quality assurance of incoming material •Development of visual inspection process	•Paying attention on manufacturability issues, including tools, instructions etc.	•Mistake-proofing already at good level •Possible to increase additional tests e.g. for detecting wrong parts in assemblies •Main emphasis on electronical functionality → last check for this purpose •Should not restrict testing capacity or increase the lead time	•Most of the quality failures takes place in this section •Lack of sufficient supportive methods for detecting mistakes •Operators responsibility of correct execution is high •The utilization level of IT and automation should be increased
Need for utilization of mistake-proofing methods	Not urgent	Not urgent	Not urgent	Urgent

Figure 37. Summary of mistake-proofing efforts in the case company.

As the summary obviously shows, the main area for quality improvement efforts can be found from the final assembly where most of the quality failures take place. This stage lacks most of the methods for detecting mistakes and operator's responsibility for the correct execution is high. However, testing and calibration processes utilize mistake-proofing methods already very well at some level. In the future the importance of this stage should be increased even further. Most importantly, the efforts on final assembly and supplier related issues should be raised into the new level. As more and more parts and assemblies are acquired from outside, it is important to detect possible quality non-conformances before they are taken into manufacturing processes in-house. The choice for specific mistake-proofing method for individual cases depends on the application and the stage of the manufacturing process. However, in the end of the manufacturing process poka-yokes should be more in type of control or shut down instead of warning, to prevent faulty units proceeding to customer.

In the organizational point of view raising mistake-proofing efforts as a common concept in the case company is of utmost importance. It is not only a method for production and quality departments but also for other interest groups to start thinking in a preventive mode in quality related issues.

Even though this study concentrates only on examining the suitability of poka-yoke methodology to the quality issues faced in the case company, we can't forget the fact, that the chosen methodology is just one among many others quality control techniques. Best results in quality improvement activities can be achieved by combining best practices from different methods and applying them into the needs of the case company.

It is predictable that in the future the markets become more and more competitive and due to this the importance of quality will have a major role in this game. It will be those companies, who can satisfy the customer needs by high-quality and non-faulty products and services and whose internal processes are effective and fault-free, to survive best. It remains to be seen whether the statistical quality control methods continue to strengthen its position in the field of quality control techniques or will the poka-yoke concept start to gain more ground.

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