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QUALITY 4.0 ENABLING COST OF POOR QUALITY MEASUREMENT

Examiners:

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ABSTRACT

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Cost of quality and cost of poor quality as part of it have been much researched in the literature since their inception in the 1950s. The value of using a cost of quality system has been more pronounced in the literature than the usage in companies. Quality 4.0 is an emergent topic in the literature, describing the how application of Industry 4.0 technology changes quality management. This thesis aimed to understand how Quality 4.0 can enable the measurement of CoPQ and how the case company should form its CoPQ system for a part of the company.

The thesis started with reviewing the literature of Cost of Quality and Quality 4.0 to understand the development, current state, and challenges with the topics. The results from the literary review were then used to synthesize the two topics and formulate what Cost of Quality measurement could change by applying Quality 4.0. Then the case company's current model and challenges were described based on documentation and expertise at the company and proposals for a suitable cost of poor-quality model for the company were made.

The results indicate that Quality 4.0 has the potential to greatly improve the accuracy, coverage, and usage of cost of quality with lower cost. The advance in capability favors the usage of process cost models or Activity-based costing, which have previously been too laborious and costly to develop and maintain. These types of quality costing have the most benefit in also providing understanding at the root cause level and can be developed further to simulate systems of work. The case company is recommended to widen its scope of quality costing from Cost of Poor Quality to Cost of Quality to gain the full benefits available with the combination of Quality 4.0 and Cost of Quality.

TIIVISTELMÄ

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Laatumuutoksia ja huonon laadun kustannuksia on tutkittu paljon kirjallisuudessa 1950-luvulta asti. Laatumuutosten käsittelyn hyödyt on painottuneet enemmän kirjallisuudessa kuin yritysten toteutuksissa. Laatu 4.0 on nouseva aihe kirjallisuudessa, joka kuvaa miten Teollisuus 4.0 teknologia muuttaa laatujohtamista. Tämä työ pyrkii ymmärtämään miten Laatu 4.0 mahdollistaa laatumuutosten mittaamista ja miten kohdeyrityksen tulisi muodostaa huononlaadun kustannuksien mittaussysteemi yhteen osaan yritystä.

Työ alkaa kirjallisuuskatsauksella, jolla pyritään ymmärtämään laatumuutosten ja laatu 4.0 kehitys, nykytila ja haasteet. Tuloksia käytetään luomaan synteesi kahden aiheen välillä ja esittämään miten laatumuutosten mittaaminen voi muuttua laatu 4.0 sovelluksien kautta. Tämän jälkeen kohdeyrityksen nykytila laatumuutosten käyttöön ja sen haasteen kuvataan, perustuen yrityksen dokumentaatioon ja työkokemukseen yrityksessä, ja luodaan ehdotukset sopivasta mallista laatumuutosten käyttöön.

Tulokset viittaavat siihen, että Laatu 4.0 mahdollistaa laatumuutosten käytön tarkkuuden ja laajuuden ja käytön merkittävän parannuksen ja kustannuksien pienentämisen. Parantunut kyvykyys suosii prosessikustannusmalleja ja aktiviteettiperusteiseen kustannuslaskentaan perustuvia malleja, joiden käyttö ja ylläpito on aikaisemmin ollut liian työlästä ja kallista. Näillä laatumuutosten hallinnan tyypeillä on suurin etu myös juurisyiden ymmärtämisessä ja niitä voidaan jatkokehittää työsystemien simulaatioiksi. Kohdeyritystä suositellaan laajentamaan laatumuutosten hallintaa huonon laadun kustannuksista laatumuutuksiin kokonaisuudessaan, jolloin täysi hyöty Laatu 4.0 ja laatumuutosten yhdistämisestä voidaan saavuttaa.

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TABLE OF CONTENTS

1	Introduction.....	5
1.1	Background.....	5
1.2	Research objectives and scope.....	5
1.3	Methodology.....	6
1.4	Structure of the thesis.....	7
2	Development of Cost of poor-quality thinking.....	8
2.1	Definition of Quality.....	8
2.2	Quality Costs.....	10
2.3	Quality cost models and categorization.....	11
2.3.1	PAF-models.....	16
2.3.2	Crosby’s model and Process cost models.....	17
2.3.3	Opportunity models and intangible costs.....	19
2.3.4	Activity-Based Costing.....	19
2.3.5	Taguchi Loss Function.....	22
2.4	Activities of quality costing.....	23
2.5	Accuracy of cost of quality cost measurement.....	24
2.6	Value of Cost of Poor Quality.....	24
2.7	Limitations of Quality Costing.....	27
3	Quality 4.0.....	29
3.1	Definition of Quality 4.0.....	29
3.2	Linkage to Industry 4.0.....	30
3.3	Models of Quality 4.0.....	31
3.4	Value Propositions of Quality 4.0.....	34
3.5	Implementation of Quality 4.0.....	34

3.6	Technologies and tools	36
4	Cost of poor quality through quality 4.0.....	40
4.1	Changes to quality performance and costs.....	40
4.2	Value propositions linkage of Cost of Quality and Quality 4.0.....	41
4.3	Application of CoQ through Quality 4.0	42
5	Cost of poor quality at case company	44
5.1	Current Cost of Poor Quality system	44
5.2	Problems of current system.....	46
6	Proposed model for case company	48
6.1	Top down approach.....	48
6.2	Bottom-up approach.....	48
6.3	Comparing the approaches (Avaataulukko, jatka jos aikaa).....	49
6.4	How should the CoPQ model for frontlines be.....	51
6.5	Where can Quality 4.0 technologies aid CoPQ estimation at case company?.....	51
6.6	How Cost of Quality supports Quality 4.0 adoption and implementation.....	52
7	Conclusions.....	54
	References	57

1 INTRODUCTION

This chapter presents the background of the thesis to understand the context of the work. Then the research objectives, scope, methodology and structure of the thesis are presented.

1.1 Background

There are generally two ways a company can improve its profit margin. It can increase revenue or decrease costs. Quality costing has been around since the 1950s and the research has quite strongly suggested that using the approach is beneficial for companies aiming to reduce costs due to both bad and good quality. Still, in a 2009 survey by Chartered Institute of Management Accountants, less than 10% of firms were said to analyse quality costs.(Wood, 2013, i) From the companies using it, the cost of poor quality is estimated to be in the range from 5% to 30% of service and manufacturing companies gross sales. (Metricstream, 2014)

Quality 4.0 is an emergent topic in the literature which from technological viewpoint applies Industry 4.0 technologies to quality activities. It also describes the shift in mindset and competencies needed from the quality community to reflect the current needs of organisations. The applications of Quality 4.0 to cost of quality has not been studied much so far, at least explicitly in the English literature.

The case company issued this thesis to improve the current usage and system of quality costing, which currently includes only Cost of Poor Quality. The usage of the topic has waned over the years and is now also relevant as a means to support new quality management initiatives.

1.2 Research objectives and scope

The purpose of this thesis is to discover how Cost of Poor Quality calculation can be enhanced by using Quality 4.0 technologies and methods and how the case company can implement this in practise.

This is done through the two research questions:

1. How can Quality 4.0 enable better Cost of Poor-Quality measurement?
2. How should the case company develop its CoPQ-system in the frontlines?

The thesis will only look at the operations of the case company, including selling, installing and maintaining the products and services of the company and exclude the supply line operations such as sourcing and manufacturing. Even though the case company uses the term Cost of Poor Quality, the thesis will look at the wider term of cost of quality, which includes Cost of Poor Quality, as most of the literature focuses on the whole and some authors use the terms interchangeably.

1.3 Methodology

The method used in the thesis can be categorized into philosophical conceptualization (Meredith, 1993), a type of theory building that uses reflective approach, integrating literature on Cost of Poor Quality and Quality 4.0, summarizing the commonalities, contrasting differences and bridging the existing theory on the topics (Gilson & Goldberg, 2015). The research streams on Cost of Poor Quality and Quality 4.0 are synthesized and adapted to answer the first research question and then the findings and understanding gained is used to answer the more empirical second research question. In the empirical part of the case company, information was gathered from different quality documents and personal experience of working in the company.

1.4 Structure of the thesis

Chapters two and three describe the relevant theory of Cost of Quality and Quality 4.0. Chapter four attempts to answer the first questions through combining the theory from Cost of Poor Quality and Quality 4.0. Chapter 5 describes the current state and challenges of the case company with regards to Cost of Poor Quality, whereas chapter six looks at the possible solutions for the case company. Chapter seven concludes the thesis. The logic of the thesis is presented in figure 1.

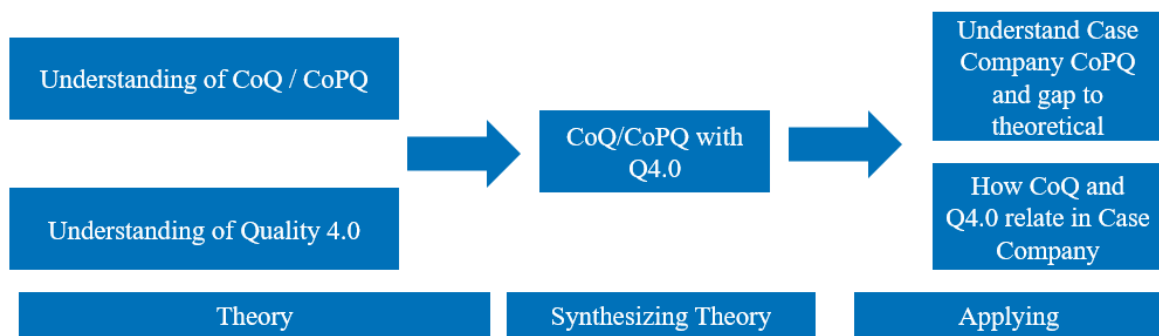


Figure 1. Logic of the thesis.

2 DEVELOPMENT OF COST OF POOR-QUALITY THINKING

This chapter presents the relevant literature behind the development of the Cost of Poor-Quality concept and categorises different models and point of views. First it needs to be defined what we mean with quality, then understand cost of quality and cost of poor quality as part of that.

2.1 Definition of Quality

Quality is very multifaceted as a concept and used commonly in different meanings. In everyday situations, quality means the subjective evaluation of goodness of a certain thing. Commonly customers make this type of judgement of well a certain product or service meets their expectations. (Montgomery 2006, pp. 4-5)

Over the years many “gurus” of quality have given their own definitions of quality along with their other contribution. Juran & Gryna (1988) defined quality as fitness for use, focusing on how well the features of a product or service fulfil the purpose of the customer activity. Crosby (1979) used more of an engineering perspective, defining quality as conformance to requirements. In his view, quality was either present or not, dismissing the concept of quality levels. Deming (1986, p. 169) did not define a single phrase for quality but insisted that quality can only be defined by the customer. In his writings he emphasized that quality products have a predictable degree of variance, lower cost and better suitability for the market (Lowe and Mazzeo, 1986).

Garvin (1984) has identified different definitions taking five approaches to quality:

1. Transcendent
2. Product-based
3. User-based
4. Manufacturing-based
5. Value-based

These approaches exemplify the variety of viewpoints quality can be looked at from, not only the customer viewpoint and help to operationalize quality, when the final customer may be far away in the value-chain.

Garvin later (1987) also proposed eight dimensions that can serve as framework for strategic analysis relating to quality:

1. Performance
2. Features
3. Reliability
4. Conformance
5. Durability
6. Serviceability
7. Aesthetics
8. Perceived Quality.

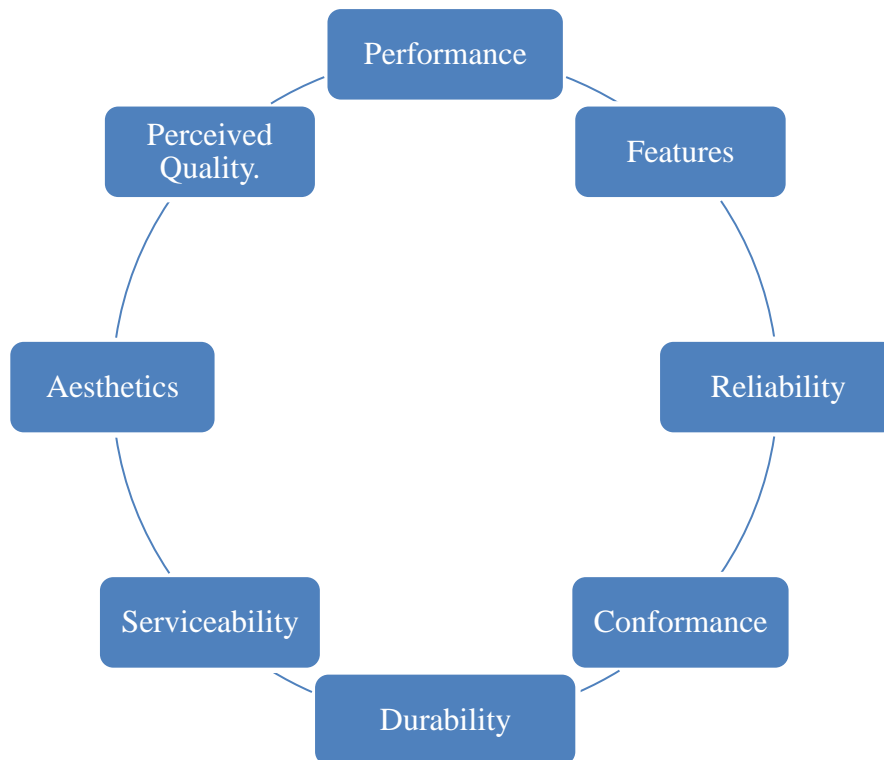


Figure 2. Dimensions as a framework for strategic quality analysis (Garvin 1987)

These dimensions can be used to compare products, services, and offerings and also to differentiate.

The different definitions, approaches and dimensions show the exhaustiveness and difficulty in giving a single definition for quality. Watson (2020) proposes a transcendental definition for

quality: “Quality is the relentless pursuit of goodness coupled tightly with the persistent avoidance of badness.” This comprehensive definition then needs to be operationalized to fit the commercial environment, by decomposing it to relevant parts of product, service or process quality, like the dimensions by Garvin.

2.2 Quality Costs

Quality costs are defined as “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, product failure, or manufacturing defects.” (Wood, 2013)

Major historic steps in the development of Quality cost thinking found in the literature include:

- Feigenbaum (1943): First quality costing analysis – dollar-based reporting system
- Juran (1951) concept of quality costing, the economics of quality and the graphical form of the CoQ model.
- Feigenbaum (1956) proposed the quality cost categorization of prevention, appraisal and failure (internal and external) costs which is still accepted widely.
- American Society for Quality Control (ASQC) Quality Costs Committee established in 1961 aiming to promote usage of quality costing and further develop the techniques
- US Department of Defense require contractors to measure their quality costs in 1963 (Acosta, 2015).
- Crosby’s model of Cost of Conformance and Cost of Non-conformance (1979) and contrary to Juran proposes that “Quality is Free” – no trade-off between quality and cost
- Fine represents dynamic model of Quality Costs (Fine, 1984)
- Kooper and Kaplan (1988) Activity-based costing developed

Even though Feigenbaum with his team developed the first quality costing analysis, the thinking on Cost of Poor Quality can be said to have started with one of the earliest writings on Cost of Quality by Juran in his 1951 *Quality Control Handbook*. Juran used the famous analogy of “gold in the mine” to describe the potential for quality improvement. Juran & Gryna (1988) describes how this arose from the need to “sell” quality related activities to managers and use their main language: money.

Feigenbaum is recognised by American Society of Quality (ASQ) as an innovator in quality cost management. He was the first to characterize quality costs as the costs of prevention, appraisal, and internal and external failure, which became known as the PAF-model. According to Juran (1998) this traditional model has had a remarkable longevity. Watson (2005) attributes Feigenbaum with incorporating the financial thinking into quality by conceptualizing the cost of poor quality.

Feigenbaums work established important tenets of cost of poor quality:

1. “Quality and cost are a sum, not a difference.”
2. Quality is the most cost effective, least capital-intensive route to productivity
3. Cost based analysis methods to identify process performance improvement opportunities. (Watson, 2005)

What is prevalent in the literature, also noted by Juran & Godfrey (1999, p 8.2.), is that the term quality costs are sometimes equated with the term cost of poor quality, referring only to internal and external failure costs. Others take the term to mean all the costs related to running the quality department and the activities it performs.

Further thinking is presented in the next chapter with proposed models of Cost of Quality.

2.3 Quality cost models and categorization

Schiffauerova & Thomson (2006) summarize the main idea of Cost of Quality analysis, being to link improvement activities with associated costs and customer expectations, regardless of which quality cost model is used. This allows targeted action for quality cost reduction and increasing quality improvement benefits.

There are three notable studies that review the current state and literature of Cost of Quality, Dale & Plunket (1987), Hwang & Aspinwall (1996) and Schiffauerova & Thomson (2006). The models presented in the studies are presented in Table 1.

Author	Plunkett & Dale (1987)	Hwang and Aspinwall (1996)	Schiffauerova (2006)
PAF	X	X	X
Crosby's model			X
Opportunity Model			X
Process Cost Models		X	X
ABC Models			X
Cost-Benefit		X	
Taguchi loss function		X	

Table 1. Categorization of different Cost of Quality Models in notable reviews of literature on Cost of Quality

Dale & Plunket (1987) note the almost unanimous acceptance of the PAF-model, found in research and guides published in English by their time. Most ambiguity is found in what is categorized in external failure costs. They summarize the use of Quality related costs into three broad categories: Promoting quality as a business parameter, quality costs giving rise to performance parameters, and enabling the planning and controlling of future quality costs.

Hwang & Aspinwall (1996) propose using Cost of Quality models at two levels: Macro and Micro. Macro to relate quality costs to top management's strategic planning and to determine problem areas at organisational level. The Micro to explain the causes of quality problems, by applying a process cost model to selected problem areas. The authors define four broad categories of Cost of Quality Models, as seen in Table 1.

Schiffauerova & Thompson (2006) divide the review CoQ models in to five categories: PAF-models, Crosby's model, Opportunity or intangible cost models, Process Cost models, and ABC models. The models in the groups can differ between each other but the categorization is based

on the underlying principles. They also note that PAF-model is the most used in companies. While the published examples of companies using CoQ have been able to reduce CoQ and improve quality for the customer, their review suggests that only a minority of companies use a formal quality costing method.

Most of the Cost of Quality models are based on the static view of quality costs, presented in figure 3. This was developed based on the labor-intensive process of using inspectors for quality control, which results to the costs of quality control going up as quality conformance increases and loss due to defects decreases. The model concurrently proposes an optimum level for Quality of Conformance, where the for the Total Quality cost is minimized. (Schiffauerova & Thomson, 2006)

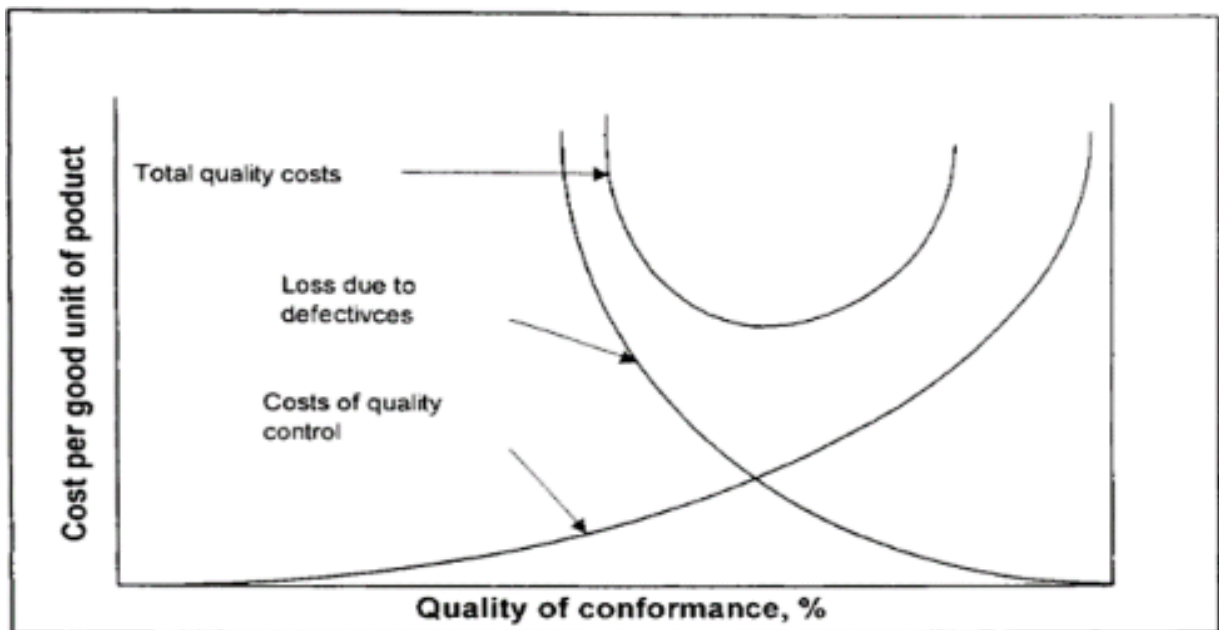


Figure 3. Model for Optimal Quality Costs (Juran, 1951, p.8)

Since the start of the two opposing views, many authors have developed and advocated for a dynamic view of Cost of Quality, which is mainly based on taking into account technological progress and learning over time (Fine, 1986; Ittner, 1996, Freiesleben, 2004; Schiffauerova 2006b). Also, an important omission in the old model is the intangible benefits of customer

goodwill that result from prevention activities (Angel & Chandra, 2001) This modern view of Cost of Quality is represented in figure 4. In the new model costs of prevention and appraisal are done in a way, with technological solutions, that the cost curve for those isn't as strongly linked to total quality costs. The total cost curve is also negatively sloped, the optimum approaching the perfect quality level. This represents Deming's (1986) viewpoint that "Quality is Free", as the cost of delivering defective products to the customer is so high that optimal quality cost is reached at zero defects, 100% conformance.

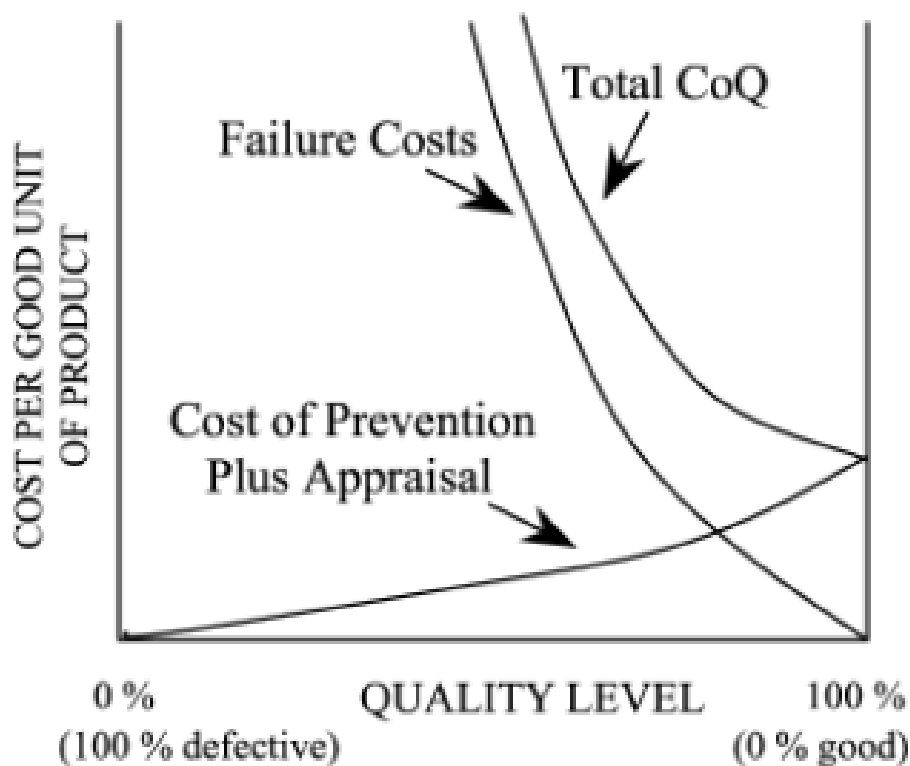


Figure 4. Modern view of Cost of Quality (Schiffauerova & Thomson, 2006)

The modern view also has been susceptible to criticism. Freiesleben (2014) points out that both the new and old model neglect a variety of hidden costs, which will be discussed more in the chapter about Opportunity model. As the amount of hidden costs changes the shapes of the curves, a better illustration would be to take into account the current quality level of the company. Figure 5. shows the development of the cost per unit of good product over time, which the author proposes to be a more suitable illustration, where C is the costs of achieving good quality and q is the current quality level.

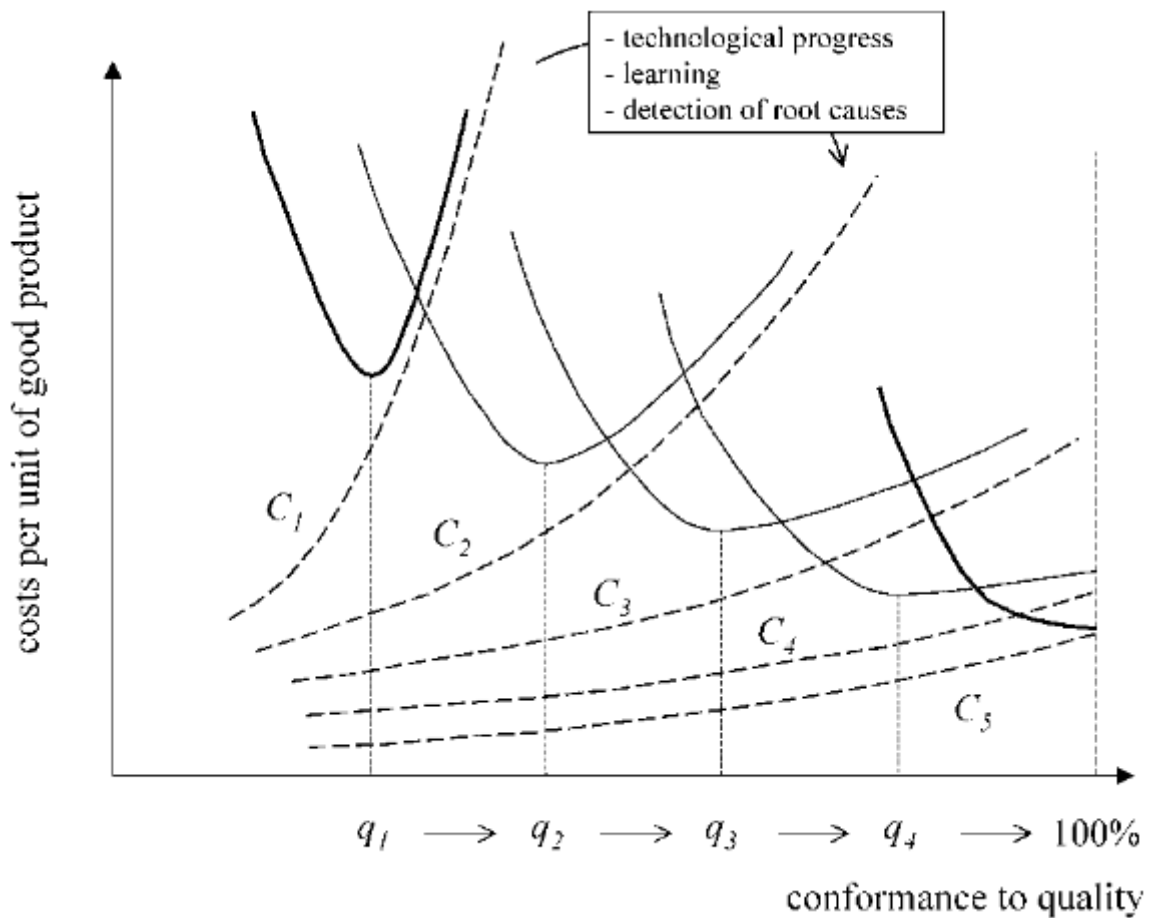


Figure 5. Dynamic view of Cost of good product

The figure starts with the old model of Cost of Quality, where the cost of removing all root causes for quality problems is initially too high. As the company learns to detect further root causes and improves the technology, quality will be improved to a new level. Over successive periods the total cost curve will reach that of the new CoQ model, and approximated quality perfection. The changes in different levels from C1 to C5 reflect the improved return on prevention. (Freiesleben, 2004)

In summary, it is important to relinquish the idea of cost-quality trade-off in organisations and focus instead on the elements that drive quality level and reduce costs: root cause analysis, learning and retention of knowledge and effective technology introduction. Five major models of categorizing quality costs are presented in the following subchapters.

2.3.1 PAF-models

The oldest model for quality costs was developed by Feigenbaum (1956) which has according to many (Williams, 1999; Schiffaurova & Thomson 2006; Woods, 2013;) become the most common model for cost of quality, and it is adopted by majority of companies practising quality costing and prominent quality associations such as ASQ and British Standards Institute (Sturm et al., 2019).

Feigenbaums original categorization was between costs of control and costs of failure of control, which further divide into what is now referred to as the PAF-model. In this model the costs are categorized into Prevention costs (P), Appraisal costs (A) and Failure costs (F). (Sturm et al., 2019) Feigenbaums model is seen in figure 6.

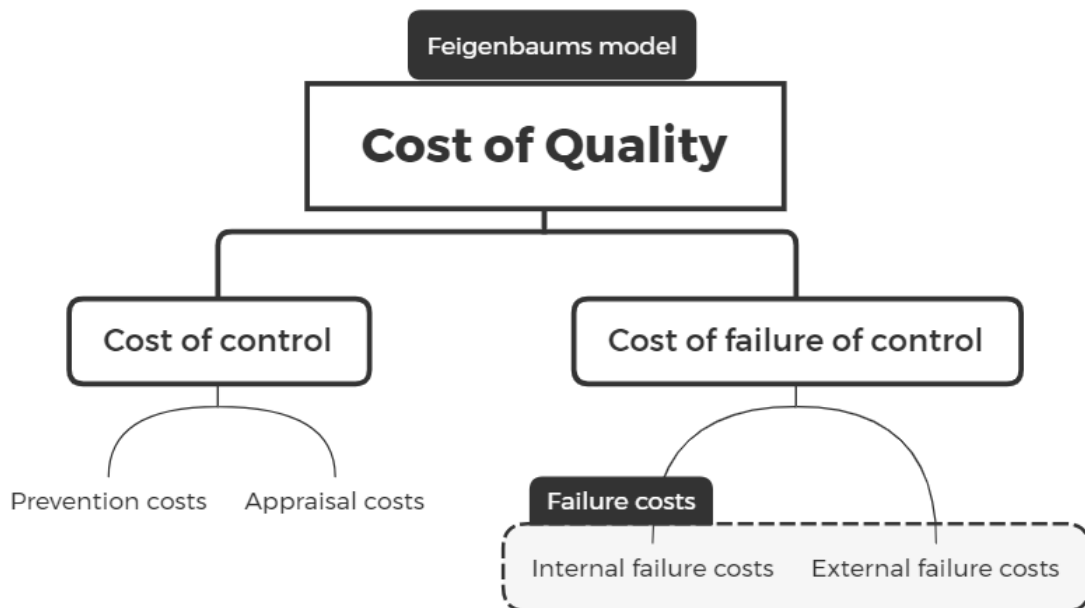


Figure 6. Feigenbaums PAF-model (Adapted from Feigenbaum (1956))

The phrase “Prevention is better than the cure”, which is attributed to Dutch philosopher Desiderius Erasmus Roterdamus (1466-1536) (Genuis, 2007), has become a tenet of quality. It is generally cheaper to prevent the error or find the error before the error reaches the customer

(Feigenbaum 1987, Wood 2013). Prevention includes practical activities such as quality engineering, training, maintenance of patterns, tools and creation of quality instruction (Hwang & Aspinwall, 1996), and more general systematic activities as process control and design, product and service design and supplier relations, audit and screening (Kim & Nakhai, 2008).

Appraisal costs are related to measuring the current quality level of a process (Schiffaeurove & Thompson, 2006b), implementation and maintenance of an appraisal system which detects non-conformances. The main costs come usually from inspection, testing, and auditing (Hwang & Aspinwall, 1996)

Failure costs are costs incurred in dealing with failures. These are usually split to internal, meaning before the delivery of a product or service to the customer, or external, after the delivery to the customer. (Schiffaeurova & Thompson, 2006)

2.3.2 Crosby's model and Process cost models

Process cost model was developed by Crosby in his influential book *Quality is Free* (1979), where cost of quality is determined as the sum of the price of conformance (POC) and the price of non-conformance (PONC). (Crosby, 1984, pp. 85-86)

Price of non-conformance is the price of all the expenses involved in doing things wrong and price of conformance is the price necessary to spend on getting the outcomes right. (Crosby, 1984, pp. 85-86) Each of the cost elements in a process is categorised as either COC or PONC and this is done for each process. This requires understanding the process in questions sufficiently but also leads to identifying quality problems and their causes more quickly than with the PAF-model. (Hwang & Aspenwall, 1996)

The process cost model also allows to identify, where PONC is high and possible prevention activities are needed, or where POC is high and process redesign might be needed (Porter & Rayner, 1992). The authors insist that to meet customer requirements both process design and how to process is operated need to be addressed. Process design is directly linked to POC, what

kind of prevention and appraisal activities we designed and PONC is linked to how well we operate the process.

The process can be mapped simply with a flowchart and identifying process owners and key process stages and the calculating or estimating the quality costs needed at each stage of the process (Porter & Rayner, 1992). Example of the process cost model can be seen in figure 6. A more demanding and time-consuming approach is to use the IDEF (the computer-aided manufacturing integrated program definition methodology), applied mainly by experts in systems modelling (Shiffauerova, 2006).

Process cost model structure

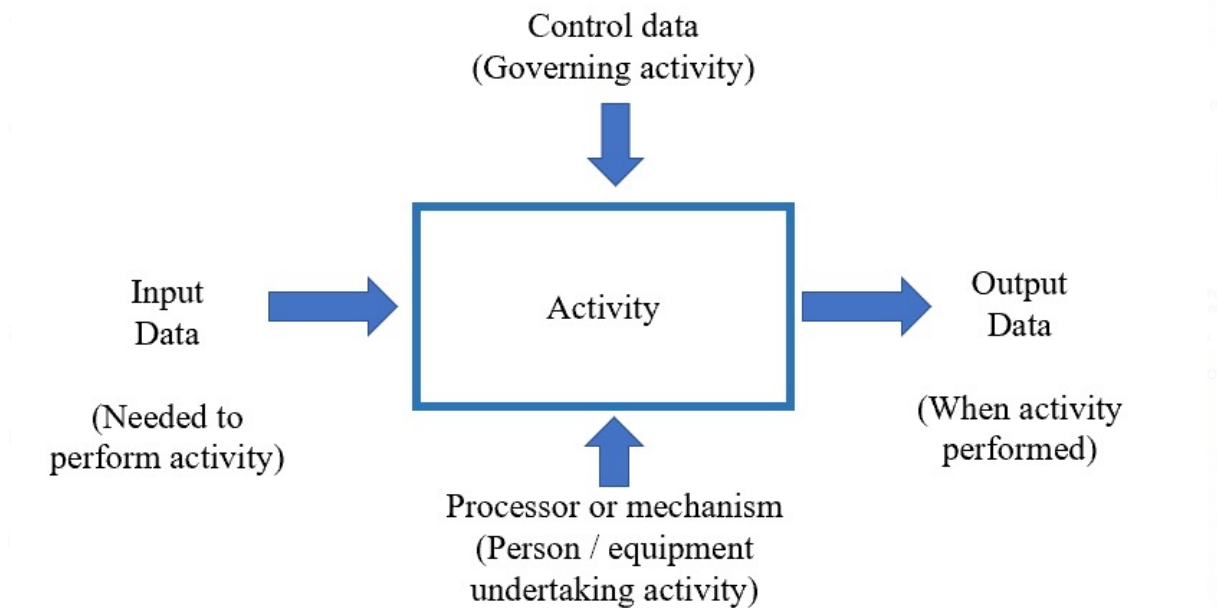


Figure 7. Process cost model structure. (Adapted from Hwang & Aspinwall, 1996)

Proponents of the process cost model prefer it because it takes a more integrated approach to quality and promotes process thinking and ownership (Porter & Rayner, 1992). It also emphasises cost of each process, instead arbitrary definitions of COQ (Goulden & Rawlins, 1995). The emphasis on process allows to better find hidden cost components, which are not produced by the traditional accounting system (Sailaja, 2015).

2.3.3 Opportunity models and intangible costs

Some CoQ models attempt to incorporate opportunity costs and intangible costs to CoQ. For example, Sandoval-Chavez and Beruvides (1998) use three categories of opportunity costs: underutilization of installed capacity, poor delivery of service, and inadequate material handling. Intangible costs – for example loss of customer goodwill, delays in productive work due to stoppages and rework and loss of morale, are usually seen as profits not earned due to non-conformance. (Shiffauerova & Thomson, 2006) The issue with these is that they don't show up explicitly in the standard cost accounting systems and are consequently always up for debate as estimates.

2.3.4 Activity-Based Costing

Traditional cost accounting lumps many cost of quality items to overheads and then allocates those to cost centers. This does not provide the information needed for cost of quality but is used for the purposes of external financial reporting in income determination and inventory valuation. (Tsai, 1998; Yang, 2008) This has been recognised as a problem by for example Oakland (1993, p. 210) who states: “quality related costs should be collected and reported separately and not absorbed into a variety of overheads”, since majority of Cost of Quality methods are process/activity oriented (Tsai, 1998).

Activity-based Costing was developed by Cooper and Kaplan (1988) to improve the accounting of product costs, where the traditional cost accounting tended to overcost products of high volume and undercost products of low volume, mostly due to the allocation of overhead. In the first ABC-systems, overhead cost is divided into cost pools, cost pools contain the cost of a group of related activities, which are consumed by products. A unique factor which approximate the consumption of cost is used to distribute each cost pool to products. In traditional cost accounting the factor would be called allocation basis, while on ABC the factor could be volume related or volume unrelated. (Raffish & Turney, 1991, pp 77-80). ABC is described in short by Tummala et al. (2002): “it measures the total cost of each significant activity performed and identifies the cost driver of the activity”.

Turney (1992) presents a two-dimensional ABC-system. The first view of ABC where focused on the resource, or cost assignment view had in short three parts: Cost objects, activities and resources. Cost objects, which create the need for activities, and activities create the need for resources. (Tsai, 1998) The cost assignment view of ABC is shown in figure 8.

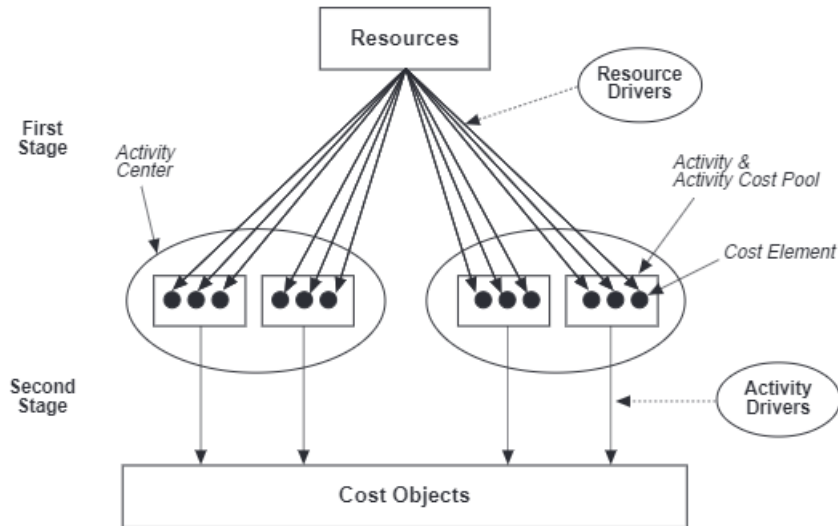


Figure 8. Cost assignment view of ABC (Tsai, 1991)

The process of assignment resources of cost objects is two-staged. First, resources drivers are used to connect resources costs to activities. Resources driver is a specific factor, used to estimate the consumption of a resource by an activity. A resource mapped to an activity becomes a cost element of an activity cost pool and the activity cost pool represents all the costs linked to an activity. Activity centre comprises of related activities, form example a process or a function. In the second stage, activity drivers are used to distribute cost pools to cost objects. (Tsai, 1998)

The second view is the process view is the process view, which consists of three parts: activities, costs drivers and performance measures. The cost drivers provide information on why the activities are done, and the performance drivers on how well the activities are performed. Cost drivers are factors that cause the cost of an activity to change (Raffish and Turney, 1991), usually determining the workload and effort required to execute an activity. (Turney, 1991, p. 87). The complete two-dimensional model of ABC is presented in figure 9.

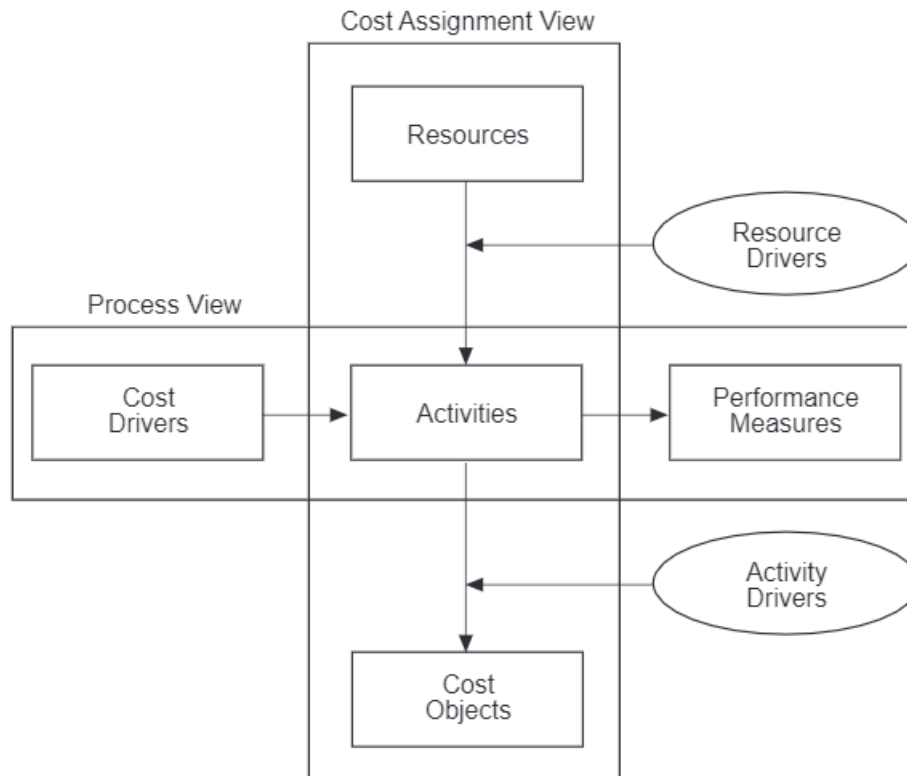


Figure 9. Two-dimensional model of ABC (Tsai, 1998)

In ABC, activities can be sorted into Value adding (VA) and nonvalue adding (NVA) (Özkan & Karaibrahimoğlu, 2013), which is why it can be used as a supportive accounting method to COQ initiatives (Schiffauerova, 2006). Tsai (1998) presented a framework for Cost of Quality Measurement under activity-based cost accounting, which can overcome the major deficiencies of the COQ systems presented before by:

- Being able to allocate overhead costs to COQ elements
- Being able to track quality costs to their sources; and
- Provide information about how indirect workers spend their time on different activities.

According to the author, to facilitate this the COQ and ABC systems should share a common database for the costs and nonfinancial information. The difference of ABC and the traditional accounting system is transitioning from a system designed for cost control to a system to make better decision overall. (Ness & Cucuzza, 1997) The standard accounting system has been

argued to be not designed for this, their main use being in external reporting to shareholders (Makhanay et al., 2018)

2.3.5 Taguchi Loss Function

Dr. Genichi Taguchi defined quality as : “the loss imparted to society from the time the product is shipped.” He disagreed with the goal post mentality of Conforming or Non-conforming and instead focused on removal of variation to a minimum, around target values, without adding cost. (Woods, 2013) He developed what became known as the Taguchi Loss Function to illustrate this, seen in figure 10, in with the quality characteristic nominal is best.

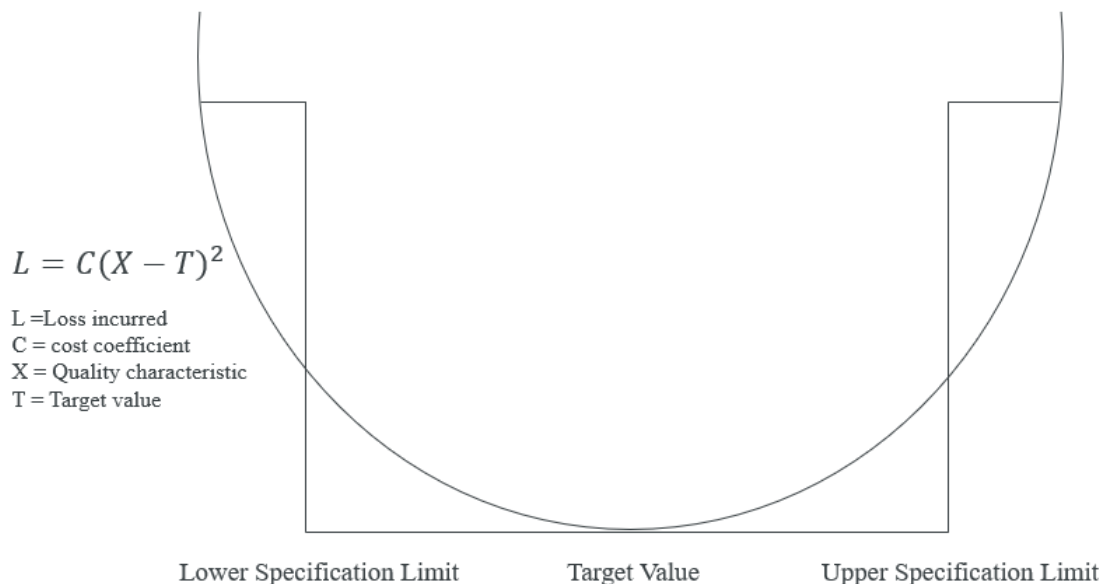


Figure 10. Taguchi Loss function (abridged from Albright & Roth, 1992)

The idea of Taguchi is to make products and services robust, so that the quality characteristic used in the quality function is not easily moved from the target value as external conditions change. (Antony & Kay, 2000) The function only considers the impact of the finished product, not including avoidable cost or prevention and appraisal. Also, the use can be difficult in cases where the quality characteristic is not easily measurable, and the related function is hard to identify.

2.4 Activities of quality costing

Sörqvist (1998) categorizes two general approaches for Cost of (Poor) Quality measurement, building a measuring system or performing an assessment. The former can be difficult to use successfully, since considerable changes are required, and the time required can be measured in years, whereas the latter can be carried out in a few weeks with a team.

The general activities and best practises of quality costing were reviewed by Luther and Sartawi (2010) to be the selection, collection, measurement, classification, analysis, reporting, and use of quality cost data.

Selection has to do with what financial quality metrics are used in the company and what is the scope of them and how are they presented. Collection and measurement are about how, how often, and who is involved in the collection of data. Classifying is about what kind of model for categorizing the costs are used, for example PAF-model. (Luther & Sartawi, 2010) Different sources of quality costs include budget and expense sources from accounting, additions and subtractions from accounts, salary amounts and headcounts. Operational data can be from event counts and cost per event, yield losses and special credits. (Wood, 2007, p. 52-53)

Analysing the costs can be done across different dimensions, such as product line, process and department. They can also be divided into higher or lower level of detail components. Reporting is about the frequency of reports, what kind of comparisons, for example two past time period or budget is used (Luther & Sartawi, 2010). Common bases used for reporting are presented by Wood (2013, pp. 38-39), which are usually based on percentages to sales, production or service costs, material costs.

Usage of the cost of quality data can be in addition to operational metrics to provide a financial view of the quality. These can be linked the objectives of the quality improvement efforts to provide a clear assessment of goals and progress. A widely used practise is to use the quality metrics to attract the attention of top management to quality issues and to obtain resources for the work of quality. (Luther & Sartawi, 2010).

2.5 Accuracy of cost of quality cost measurement

Measurement of costs of quality is hardly straightforward, because of the lack of general agreement on a specific broad definition of quality costs. (Schiffauerove & Thomson, 2006) This makes comparability between companies especially difficult. Effort has mostly been put into estimating direct quality costs, since indirect costs are harder to measure (Lari & Asllani, 2013). Love and Irani (2003) acknowledge that only some components of quality costs can be measured with a certain degree of accuracy and objectivity.

The general agreement on the topic is that the real, partly hidden, cost values are much greater than the estimated costs (Sailaja, 2015; Prester, 2016). Crosby proposes that getting the first 75-80% is quick and could be put together in few days. These numbers are in most cases alarming enough, that the rest can be left to reveal itself later while expanding and adjusting as needed. (Crosby, 1984, pp.56-57)

2.6 Value of Cost of Poor Quality

Dale & Plunkett (1987) categorize the variety of uses of quality costs into 3 main categories. The first is to use quality as a business parameter to garner top management attention. The second is to use it to generate performance measures, using ratios or indexes to sales or other business costs. The third, is to enable the planning and controlling the future quality costs.

Also, in more recent literature, Yang (2008) concluded that quality cost have many potential benefits. Key ones include focusing on the poor performance areas that need improvement, supporting the overall control of quality, and improving the organisations competitive advantage through higher quality and lower costs.

A strategy for the planning and controlling the future quality costs and achieving the benefits is presented by Wood (2013) in four premises:

1. Directly minimize failure cost
2. Invest in the “best” prevention activities to generate improvement
3. Decrease appraisal costs as improvement is reached

4. Continually review and redirect prevention targets to accumulate further improvement. The strategy of Wood is based on the logic that each failure has a root cause, causes can be prevented and, in line with Feigenbaums thinking about quality being cost-effective, prevention is always cheaper.

Variety of other noted use cases in literature for cost of quality are categorized in Table 2.

Use of Cost of Poor Quality	Category of use	Originator
Cost based analysis methods to identify process performance improvement opportunities.	Finding focus areas for improvement	Feigenbaum (1956)
Selling quality to managers	Quality as a business partner	Feigenbaum (1956)
Estimate potential benefits following from quality improvement initiatives	Planning of future quality costs	Porter & Rayner, (1992)
Helps in identifying where problems exist and quality costs occur	Finding focus areas for improvement	Johnson, (1995)
Evaluate success of quality programme	Evaluate work of quality	Johnson, (1995)
Lever to top management commitment for improvement projects	Quality as a business partner	Hwang & Aspinwall (1996)
Emphasis on origin of failures and related costs, bringing awareness and accountability to those responsible	Support culture of quality	(Johnson, 1995; Plunkett & Dale, 1998)
Prevent non-conformance occurrence by providing corrective action	Planning of future quality costs	Johnson, 1995; Love & Li, 2000; Aieong et al., 2002)
Highlight improvement areas and allocate resources accordingly	Finding focus areas for improvement	Hwang & Aspinwall (1996), Chopra & Garg (2011)
Share lessons learned to other functions	Support culture of quality	(Love & Li, 2000)
Signals related to the potential impact of poor quality on the financial performance of a company	Quality as a business partner	Aieong et al, (2002)
Aid management to identify the kinds of activities that are more favourable in reducing costs of quality	Finding focus areas for improvement	Aieong et al, (2002)

When an organizations quality system matures, external failure cost decreases as percentage of total quality cost (Cost of Quality)	Evaluate work of quality	Sower et. Al (2007)
Evaluate strengths and weaknesses of quality system	Evaluate work of quality	Sirvastava, 2008
Cost of (Poor) Quality is a key metric for Quality Maturity	Evaluate work of quality	DeFeo, 2018
Project monetary benefits and effects of changes proposed by quality improvement	Planning of future quality costs	Sirvastava, 2008
After quality cost implementation failure cost decreases even while sales increases	Planning of future quality costs	Uyar (2008)
Works in focusing on the performance areas in need of improvement	Finding focus areas for improvement	(Yang, 2008)
Determine and radicate activities in the organisation that neither provide or enchanche quality	Evaluate work of quality	(Abdelsalam & Gad, 2009, Tye et al., 2011)
Support in reducing rework and resulting claims	Planning of future quality costs	(Hoonakker et al., 2010)
Decrease in failure costs while increase in sales.	Planning of future quality costs	Tye et al. (2011)
Motivate employees to pursue quality goals	Support culture of quality	(Tye et al, 2010)
Companies with cost of quality system have smaller failure costs and invest more in prevention and appraisal than companies without formal system.	Quality as a business partner	Kerfai et al. (2016)
Higher quality paired with lower cost, depending on effectiveness of quality improvement programs	Quality as a business partner	Kim and Nakhai (2008)
Higher cost is not necessary for increase in quality level	Evaluate work of quality	Li & Rajagopalan (1998), Ayati and Schiffauerova (2014),
Decrease in failure costs can be obtained with minimal or no increase in conformace cost in long run.	Planning of future quality costs	Omar and Murgan (2014)
Long term horizon of a quality improvement program	Planning of future quality costs	Duarte et al. (2016)
Long-run empirical evidence of cost of quality behaviour	Planning of future quality costs	Ittner 2001

Using quality costs as a performance measure for operational processes.	Quality as a business partner	Lari & Asslani 2013
Using CoQ as part of management support system for better decisionmaking	Quality as a business partner	Lari & Asslani 2013

Table 2. Uses of cost of quality

2.7 Limitations of Quality Costing

Sower et al. (2002) revealed two major reasons for not tracking cost of quality:

1. Lack of management interest and support – value not worth the effort
2. Lack of adequate accounting and computer systems.

Wood (2013, pp. 2-3) opposes both by proposing that quality cost analysis is the way to elevate quality to a strategic issue and that in the age of current data processing tools, the technical feasibility is an excuse. The state of cost of quality seems to be that academic interest has been much wider and theoretic in nature than implementation in companies.

Freiesleben (2004) find the idea of an optimum quality level linked with a minimum cost point to be the main limitation of all CoQ models. Since maximizing profits is the prime objective of most companies, cost curves and minimizing costs are irrelevant in isolation. Maximizing profits using total costs can only be reached by assuming that revenues are constant. This is not the case in competitive markets, it is widely considered since the publishing of the PIMS-study (Profit Impact on Marketing Strategy) that revenues will increase along with increasing quality levels. (Freiesleben, 2004; Szymanski et al., 1993) Sörnqvist (1998) doesn't consider prevention as cost, rather an investment in quality. In his view, measuring prevention cost is trivial since the available information is never sufficient for meaningful optimization

Some firms end up reporting failure cost elements, which are already covered by the accounting system, such as internal failure and appraisal cost (Atkinson et al., 1994). To counter this, wide collaboration, and support between functions in the company is needed (Luther & Sartawi, 2011).

Sub-optimization may occur when some parts of cost of poor quality are easier and have been shown successful to be measured. For example, this has led to improvement work concentrating

on production. (Sörnqvist, 1998) Also most of the research comes from the manufacturing environment.

Rassfeld et al. (2015) surveyed over 200 companies in Germany about their usage of quality costs. About two thirds of the companies systematically captured quality related costs. The main reasons for not capturing quality related costs were:

1. Price of data collection is too high
2. Problems in separating costs
3. No expected advantage
4. Lack of transparency of processes.

Pires's (2013) study of 154 Portuguese companies' usage of quality related costs similarly showed that the reasons for not implementing were the lack of advantage gained or that they didn't know which benefits could be obtained.

It can be argued that the limitation of quality costing has been the discrepancy between the theoretic literature and the actual, persistent implementations in companies. Although many case studies with real companies show benefits, many companies are more eager to take the approach of Deming who saw no need to measure or control quality related costs.

3 QUALITY 4.0

This chapter will describe the proposed definitions for the emerging concept of Quality 4.0, models for Quality 4.0 looking at different perspectives and finally the Value Propositions stemming from Quality 4.0 implementation.

3.1 Definition of Quality 4.0

Dan Jacop of LNS Research (2017) coined the term Quality 4.0 to describe the impact of digitalization on quality technology, processes and people. The definition being: “aligning quality management with Industry 4.0 to enable enterprise efficiencies, performance, innovation and business models.

Boston Consulting Group (BCG) (Küpper et al., 2019) defines Quality 4.0 as the application of Industry 4.0’s digital technologies to quality management, which is basically the same as the LNS definition but without explicitly defining the goal of Quality 4.0.

The American Society for Quality (ASQ, 2020) defines Quality 4.0 as: “bringing together Industry 4.0’s advanced digital technologies with quality excellence to drive substantial performance and effectiveness improvements.”. This definition is similar to LNS definition but mentioned goal does not extend from performance and effectiveness to innovation and business models, as with LNS

Sony et al (2020a) describe Quality 4.0 from quality functions point of view as: “Digitalization of quality of design, quality of conformance and quality of performance using modern technologies”, such as cloud computing, IoT and CPS (Sony et al., 2020b).

Watson (2019) describes Quality 4.0 as “the application of digital technologies to productive systems to gain profound knowledge of their operations so that their real-time performance change be optimized”. Watsons definition is wider in scope, all digital technologies, not limiting to Quality 4.0. He also motivates Quality 4.0 by acknowledging it as a response to an emerging customer requirement to expand its digital industrial applications.

Radziwill (2020, p. 2) describes Quality 4.0 as improving connectedness, intelligence, and automation to enhance performance and promote organizational excellence. Those technologies arise in great deal from the smart-factory aspects of Industry 4.0. (Radziwill, 2020, xxiii), but this definition doesn't specifically mention Industry 4.0 but more qualities.

Zonnenshain and Kennet (2020) describe their take of the emerging Body of Knowledge of Quality 4.0 mainly concerning:

1. Quality as a data-driven discipline
2. Application of modeling and simulation for evidence-based quality engineering
3. Health monitoring and prognostics of quality
4. Integrated quality management
5. Maturity levels with respect to Industry 4.0
6. Integrating innovation with quality and managing for innovation
7. Quality 4.0 and data science
8. Integrating reliability engineering with quality engineering
9. Information Quality.

3.2 Linkage to Industry 4.0

Industry 4.0 comprises of Cyber-Physical systems, Internet of Things (IoT) and Internet of Services (IoS) (Sartal, 2019). On a more general note it describes the application of computer technologies to industrial systems and digitizing work, using new technologies (Watson, 2019). As we have four industrial revolutions as concepts, authors have also proposed four quality revolutions (Radziwill, 2018)

As the first industrial revolution speeded production with steam powered engines and mechanization, in Quality 1.0, emphasis was placed on volume and level of production instead of quality of each item. Quality was assured by inspection and measuring and consequently removing bad items. (Radziwill, 2018)

The second industrial revolution introduced assembly lines and mass production, powered by electricity. Quality 2.0 can be summarized as Quality by Design (Radziwill, 2018), with

statistical measures acceptable quality levels were set as standards to be adhered to. Also, a financial measure of quality begins to form as scrap and rework are calculated of the output that is non-conforming. (Watson, 2019)

The third industrial revolution introduced computing and Information and Communication technology, leading reduction of human participation in manual labor as a result of gains in productivity. (Watson, 2019) Quality 3.0 came saw a rise in quality empowerment with holistic approaches as Total Quality Management (TQM) and Six Sigma. (Radziwill, 2018) With each step-change in industrial technology quality has also had to evolve, leading us to Industry Q4.0

3.3 Models of Quality 4.0

The first model of Quality 4.0 came from LNS (2017) where technology advances were related to the 11 aspects that build on “traditional quality”. The 11 aspects are suggested to be used for assessing the current state and prioritizing investments. The author also emphasizes first building the quality foundations on the 11 aspects, to ensure the organization can leverage the new technologies. The LNS model can be seen in figure 11.

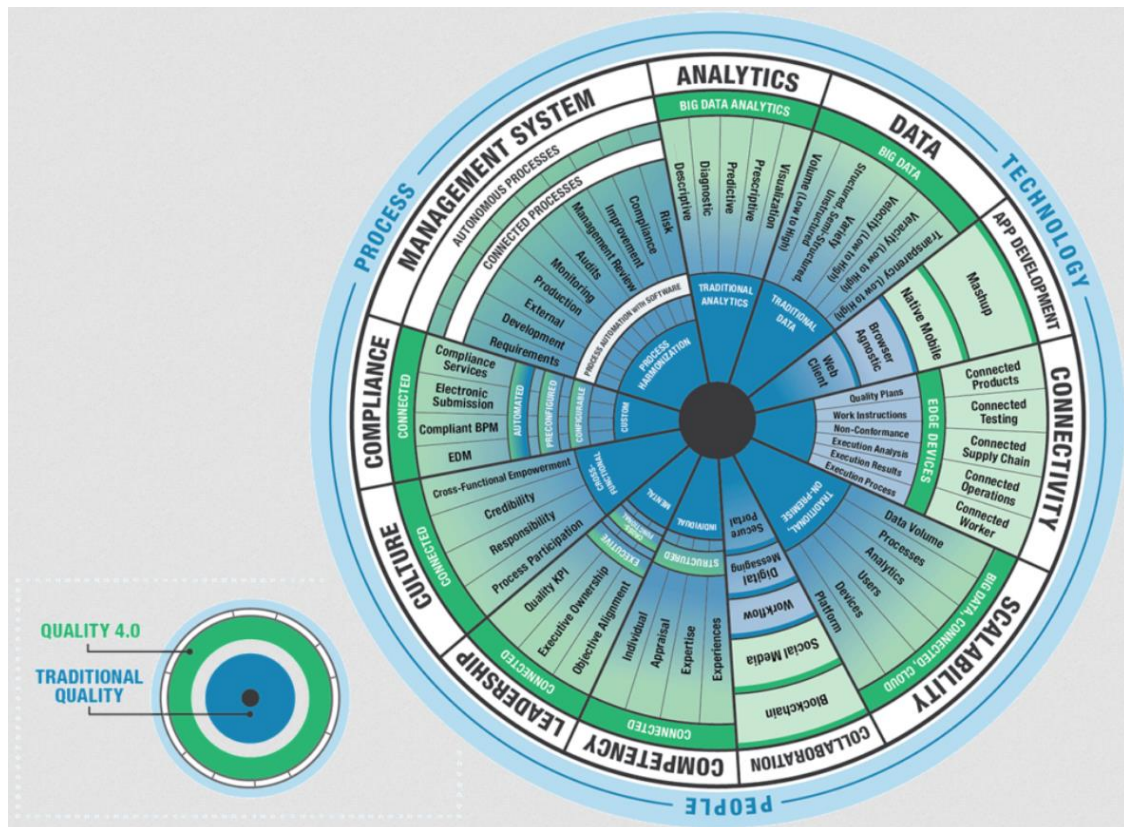


Figure 11. 11 aspects of Quality 4.0 (LNS, 2017)

Padhi and Illa (2019) did not use the term Quality 4.0, but a similarly talked of “smart quality” in the context of smart factories. Smart factories have the properties of seamless system architecture, largely automated data processing, largely autonomous quality processes, and applying predictive analytics. The authors define 5 dimensions of quality management in a smart factory based on these:

1. Defect analysis and resolution is changed using big data and advanced analytics and collaboration requiring human interference is facilitated online.
2. Statistical Process Control (SPC) applications are integrated with other systems and equipment, enabling easier data collection, detection of out-of-control states and the systems can take actions, such as shutting down a machine or notifying personnel, or even performing Out of Control Action Plans (OCAP) automatically.
3. Defect prevention and continuous improvement are aided with Big Data analytics of data from IoT, predictive analytics, automated corrective actions through machine learning and real-time dashboards to manage quality and highlight potential problem areas.

4. End-to-End traceability should be achieved from raw materials, suppliers, stages of the manufacturing process, test results, and storage locations, using one platform where all the data is pulled from multiple sources, combined by a serial number for the product.
5. Predictive quality can be attained to predict number of defects and scrap. This can be achieved by extracting large scale data from multiple systems along the production process and performing complex what-if analysis on it.

Watson (2020b) takes a less mystifying approach, which focuses more on the applications than new technologies, with presenting a Quality 4.0 applications taxonomy. In his view, Quality 4.0 strives for evidence-based decision-making and rule-based actions. He presents the components that support this as:

1. Detection and Data Capture

The cost of sensory technology has come down, which allows large amount of data being generated in the cyber-physical systems (Lee et al, 2013). This data can further be used by quality management systems (Sony et al, 2020a).

2. Data Transmission

Technologies in data Transmission have progressed in speed, reliability, and coverage. These include wireless networks, mobile devices, data streaming and 5G networks.

3. Data Recording and Storage

Memory technology has been progressing along with speed of computer processing. Digital electronic recorders, data loggers, databases and cloud storage have become widely available and quick to implement.

4. Data Sorting and Processing

Data can be sorted and processed efficiently and intelligently in previously too effortful ways with for example, big data analytics, machine learning and automated process mapping.

5. Data Modeling

Realtime representations of digital twins can be used to experiment before changes in the real-world environment with modeling and simulation, enabled by data science and probability theory applications with sufficient computer processing power available.

6. Data Application

Application of the data is available to a wide range of individuals through virtual collaboration tools. Systems can be automated, and closed loop diagnostic and remediation systems created

(Watson, 2020b). This type of applications approach is more approachable for someone who hasn't heard of Quality 4.0 and the technologies, and products currently involved with, but rather points to the advances to the processes most organizations already have relating to data.

3.4 Value Propositions of Quality 4.0

Sony et al (2020b) studied the motivations of companies mainly in the US to adopt Quality 4.0. The top motivation was "Reliable information", meaning reliable data from sensors, used for quality management. The second top motivation is highly linked to the first; Big Data applications where several flows of data from different facets of the organization and from the customers can be combined. Improved customer satisfaction, the third ranked motivation, can be achieved through more detailed "Voice of Customer" leading to better suited products and services, which can be achieved through analyzing the streams of data about the customer with big data analytics. The fourth and fifth ranked top motivations were productivity improvements, and cost and time savings, which can be achieved through more optimized work and reduced failure costs as quality level increases with Quality 4.0 methods and technologies.

Radziwill (2018) describes six categories of value propositions for Quality 4.0 initiatives according to significant:

1. Augment or improve upon human intelligence.
2. Increase the speed and quality of decision-making.
3. Improve transparency, traceability, and auditability.
4. Anticipate changes, reveal biases, and adapt to new circumstances and knowledge.
5. Evolve relationships, organizational boundaries and concept of trust to reveal opportunities for continuous improvement and new business models
6. Learn how to learn by cultivating self-awareness and other-awareness skills.

These are more complicated than the motivations of the respondents but align with the purpose of the top motivations in Sony's study, reliable information enables many of these when also received at the right time.

3.5 Implementation of Quality 4.0

According to Boston Consulting Group (BCG) study, with ASQ and Deutsche Gesellschaft für

Qualität (DGQ, “German association for Quality”), on Quality 4.0 in manufacturing sector in the US and Germany, only 16% of organization had implemented Quality 4.0 initiatives. From the remainder, 63% had not started planning and only 20% were in the planning phase. (BCG, 2019)

In the study, quality cost transparency and centralization of quality data were selected as one of the top cross-functional use cases in a value chain. This means combining data sets from multiple functions in order to generate insights and address critical pain points across the company. Other Quality 4.0 use cases they found are presented in Table 3.

R&D	Procurement	Manufacturing	Logistics and sales	Service and after-sales	Cross functional
Agile product development	Supplier performance management	Predictive Quality	Pick by Light	Warranty management enhanced	Centralization of Quality Data
Usage pattern data	Integration of supplier quality data and analytics	Machine vision quality control	Glove equipped with barcode reader	with IoT and analytics Remote quality diagnosis for customer support	End-To End quality management system
Advanced analytics to support decision making		Digital SOPs on touchscreen for manual assembly			Quality cost transparency

Table 3. Use cases of Quality 4.0. Adapted from BCG (2019)

Chiarini (2020) used a systematic literary review to understand the relevant topics and issues related to Quality 4.0. The four key topics were: creating value inside the company through quality data, analytics and AI, developing the needed skills and culture for Quality 4.0 with the quality people, co-creation of customer value, and the use of cyber-physical systems and ERP for quality assurance and control.

Sony et al (2020a) studied the key ingredients of effective Quality 4.0 implementation based on literature. The first two ingredients, handling of big data and improving prescriptive analytics align with the first topic of Chiarini (2020). Big data will come from the variety of sensors, data capture systems and communications systems as part of the Quality 4.0 technological ecosystem. Prescriptive analytics algorithms based on the data can operate as a decision support system or take automated decisions in as issues are detected.

The second two are effective horizontal, vertical, and end-to-end integration and Quality 4.0 as a strategic advantage. The author emphasizes the need for the three types of integration to be able to strategically extract, analyze and decide on data. This is seen as key for an effective and efficient Quality 4.0 programme. A competitive advantage can be gained from better quality of products and services as a results of Quality 4.0 programme but also the ability of the smart connected products to create a better understanding of customer preferences. Smart, connected products also serve as a platform for offering new value-added services.

The last four ingredients can be described as the “soft” side of Quality 4.0, namely leadership, training, organizational culture, and top management commitment. Requirements for leadership are both in change management but also in the exemplifying and fostering a style of innovation and learning. Training will need to be orchestrated in a strategic manner for employees to be able to use the tools of Quality in their work. On top of operating, another level of technical proficiency is needed to develop and install the new systems. Quality 4.0 technology can also aid by using new methods of training, such as Smart glasses, gloves, AR, and VR. Organizational culture needs to be open and encouraging for the use of new ways of working with Quality 4.0 solutions. Top management commitment is crucial, as with correct understanding of the effects and benefits of the change, management can allocate resources and motivate employees to use Quality 4.0 solutions. (Sony et al, 2020b)

3.6 Technologies and tools

In this chapter some of the main technologies of Quality 4.0 and their use cases are presented.

Cyber-physical systems link objects in the physical world to data sources, people and other objects and communicate via global and local networks. (Radziwill, 2020, p 3.) They are mechanism, which are monitored or controlled by computer-based algorithms, integrating computation, networking and physical processes (Sartal, 2020, pp 12-13).

Internet of Things (IoT) can be defined generally as a network connecting a multitude of smart objects, embedded with sensors (Cicirelli et al., 2019) From capability perspective, Martinelli (2019) defines it entailing devices connected through a standard communication protocol with capabilities to self-identify, localize, diagnose states, acquire data, and process data.

Artificial intelligence encompasses the techniques and knowledge created to make “intelligent” machines, meaning to be able to function with foresight to fulfill their expected task in their area of application. Industrial AI technologies that can be used to create smart production systems, intelligent sensors, and edge computing. (Martinelli, 2019) Common use cases of machine learning are chatbots, computer vision, language processing, making complex decision, navigation, personal assistants, and robotics. (Radziwil, 2018).

Machine Learning refers to the automated detection of meaningful patterns in data (Shalev et al, 2014, xv-xiv) ML learning algorithms can be used, for example to identify anomalies in the data to indicate out of control performance or extensive variation. Examples of this found were detecting over- and underconsumption of energy in facilities (Faltinski, 2012) and detecting intruders in networks (Vidyapeetham, 2012).

Two generally used approaches of this are unsupervised learning and supervised learning. **Unsupervised learning** is the application of unlabeled data to find relationships between observations. Examples of this is Grieco et al (2017) extracted patterns from Engineering Change Requests by using k-means clustering. The clustering revealed themes, that the companies could use to improve efficiency of the work. Unsupervised learning can also be for process mapping, by generating it from event log (Khodabandelou et al, 2014) and to recognize objects from video (Shin et al, 2012). **Supervised learning** is training a model based on labeled data. For example, Huang et al (2018) used a supervised learning to create a model for detecting

bursts in pipes of water utilities, which had low false positive rates even in a real distributions network.

Neural networks are a method of supervised machine learning than can be used for classification and prediction task. A neural network consists of an input layer with one or more input nodes, a hidden layer with nodes, and an output layer with one or more nodes. The hidden layer performs some transformation to the signal coming from the input nodes and the signal ends up in the output node. For the network to work as intended, it must be trained with many prior observations. (Radziwill 2020, pp 362-363). For example Sa et al., (2016) used a deep neural network to detect different types of fruits, while Pandey et al (2013) use image processing and machine learning to grade fruits automatically.

Data reduction techniques can be utilized automatically to find key predictors for process performance and to enable model building. Reducing the variables makes the computation less intensive and avoids overfitting the data. Techniques that can be used are Principal Component Analysis, Linear Discriminant Analysis, and autoencoder-type neural networks. (Radziwill, 2020)

Radziwill (2018) recognized the potential of **blockchain technology** to improve both quality of data and transactions. Blockchain is a digital ledger containing transaction data, which is shared. The transactions are mapped in chronologic order forming a “chain” forming a data structure that is immutable once the newest record in the chain has been verified and logged. As common use case is tracking events, for example time, information, money, or a supply chain. (Radziwill, 2020)

Big Data can have many practical definitions but a general one is that it’s an amount of data that your current capabilities to and tools can’t deal with. It needs parallel processing or can’t be stored at one place. Demchenko et al. (2013), figure 12, presents the characteristics of big data with 5 Vs:

1. Volume – there’s much of it
2. Velocity – coming fast, event real time streaming
3. Value – some data is useful for different purposes, some not at all

4. Veracity – data quality varies as sources can be multiple
5. Variety – comes in multiple different forms

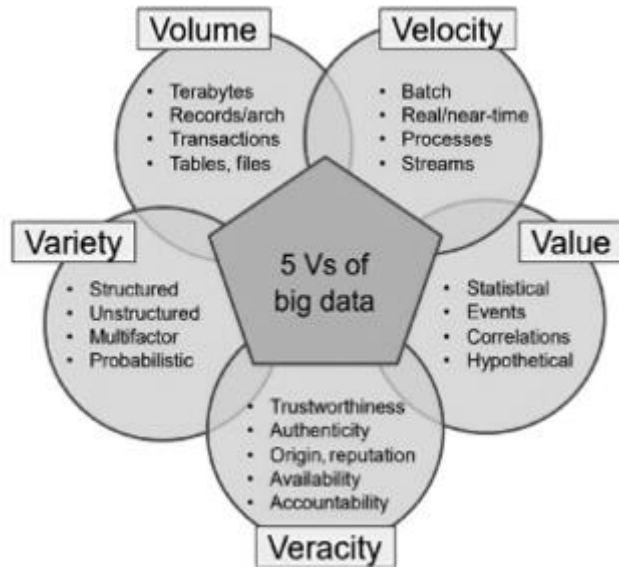


Figure 12. Five characteristics of big data (Demchenko et al., 2013)

4 COST OF POOR QUALITY THROUGH QUALITY 4.0

This chapter aims to synthesize the literature on CoQ and Quality 4.0 and propose areas where the two concepts conjoin.

4.1 Changes to quality performance and costs

Quality 4.0 does not change the goals of quality and performance improvement but makes achievement of them faster and more complete. This happens through increasing amount of data and cheaper and more powerful technologies. (Radziwill, 2019, pp 321-33) The same can be said of the cost of quality but the weight of different categories of Cost of Quality will likely change.

The true cost of quality has been argued to be unknown and unknowable. (Deming, 1986) That will probably remain to be true in the widest scope of the term, but Quality 4.0 enables as to take a considerable step chain towards reaching for that perfection.

Quality 4.0 enables a new level of quality maturity where prevention costs become the main component in CoQ. This will happen as automated prevention activities will replace the need for appraisal and reduce the failure costs. The dynamic cost of quality model presented by Freiesleben (2004) becomes more prevalent as technology progress drives new possibilities for root cause removal and the return on prevention increases.

Significant initial investment is required to reach the benefits of Quality 4.0 (Sony et al, 2020a). Freiesleben (2008) presented a simple measure that can help with deciding which quality improvements of technological nature, investments from an economic point of view to make. The measure uses the prevented cost of poor quality, C , summed over periods of n , where the improvement is effective, and the investment amount I as follows:

$$\frac{n \times C}{I} > 1$$

The investment should be conducted when the prevented costs of quality are greater than the investment in the chosen time period. This kind of calculation supposes that we have reasonably

accurate estimates of costs of poor quality, at least more certain than trying to estimate revenue increases, after we have found out a root cause of an issue.

4.2 Value propositions linkage of Cost of Quality and Quality 4.0

From the six categories of value propositions for Quality 4.0 initiatives by Radziwill (2018) presented before, two directly relate to Cost of Quality. The first one is the increase in the speed and quality of decision making and the second is the improvement of transparency, traceability, and auditability. Both also have to do with the top motivation factor for the adoption of Quality 4.0, reliable information (Sony et. al, 2020b). The study did not ask what reliable information respondents wanted, but clearly the flow of money, understood in better detail through process cost models or Activity-based costing than with the standard accounting system, is important for managers.

The speed of decision making based on cost of quality data, can be improved as the delay in reporting is decreased to near real-time in advanced cases. Data can be continuously captured, recorded, stored, processed and modeled to be used by applications. The applications can also have better predictive and prescriptive capabilities than before when only singular failures cases were given attention in ad-hoc manner. Better and more timely data also improves the quality of decision making.

The second one concerns mostly how the accuracy and coverage of Cost of Quality measurement is vastly improved. When more cost data is gathered through better and cheaper technologies, performance of analytics is enhanced, and the infrastructure for sharing the data and information formed from it is in place, the organization can become more transparent also in the Cost of Quality point of view.

Improved traceability increases the coverage of CoQ calculation in a process, service or products lifecycle. Currently in delivery projects, the measurement of CoQ is much better in the upstream factory environment and the measurement performance degrades when the parts are shipped out of the factory. This is because the environment of the factory has much less

variation and the scale has allowed even the use of expensive sensors. When the technology becomes cheap enough to start use in individual equipment, workers and sites, traceability of cost be greatly improved.

4.3 Application of CoQ through Quality 4.0

End-to-end traceability can be achieved through increased connectedness enabling a new level of Cost of Quality detection and data capture. More cost information can be collected and with better granularity as more and more process steps across the value chain have the ability to detect, transmit, and record data. These advances relate to the selection, collection, and measurement steps of Quality Costing, as seen in figure 13.

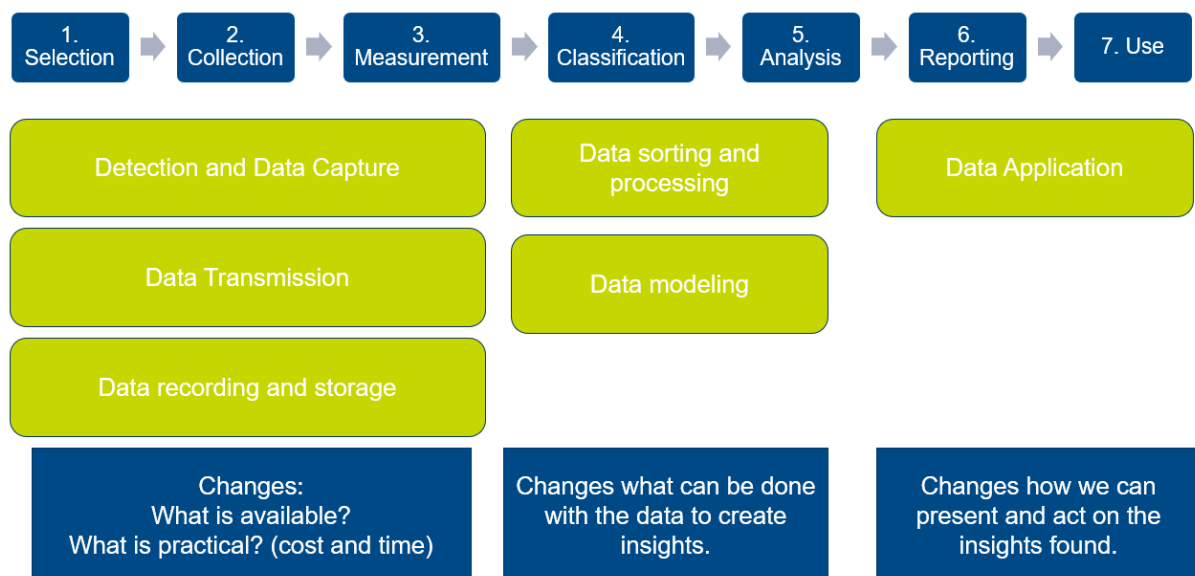


Figure 13. How quality costing activities link to Quality 4.0 applications taxonomy

Enhanced capabilities in Data sorting and processing and data modelling make the more detailed/complex models of cost of quality, instead of arbitrary categories like PAF, easier and less costly to implement and maintain. For example, Activity based costing and process cost models classify costs to activities and processes, which are meaningful for understanding the work. Dynamic process cost models can be created from automated process mapping to modeling all the way to creating a digital twin of the process. Cost data can be categorized with natural language processing, machine learning and automated classification.

With Quality 4.0 technology it is possible to use Activity Based Costing more widely, not only in manufacturing as it is mostly used currently and to implement it with significantly reduced cost and effort. Also, digital and so called “office work” can be measured more accurately and allocated accordingly. One of the barriers to accepting to take on an ABC-initiative has been the cost of replacing or sustaining another system on top of the traditional cost accounting system. The cost of this can be said to have significantly come down as technologies in general and the Q4.0 technologies have evolved to be less expensive and more reliable. Adopting ABC would still require a major change management initiative but can be argued to also be easier than before since more of the work is automated. These aspects still don't solve the main objection to ABC as noted by Quin et al. (2017) in Irish firms at least, which is that management is still satisfied with their current, traditional cost accounting system.

In the reporting and usage steps, Cost of quality can be calculated in real-time, so far at least in manufacturing operations as presented by Zaeh (2014), using real-time data from operations and cost data from process databases and ERP-system. Artificial neural networks can be used to predict expected cost of quality, as for example Tawfek et al. (2012) did for construction projects.

Cost information in the form of activity/process costing can be used by decision making algorithms to for example prioritize issues coming from noticed field failures. This could look at accrued cost so far at the time of failure and cost estimate of different actions based on planned costs and other dependencies.

Blockchain technology can improve the quality of data and the quality of transactions relating to quality costs, for example having a reliable chain of activities which can be followed to determine where to place responsibility. This could be done inside the company also but might be more suitable with suppliers and outsourced work.

5 COST OF POOR QUALITY AT CASE COMPANY

This chapter briefly describes the current practice of quality costing at the case company, which means Cost of Poor Quality in the organization. Also the current issues are addressed. This chapter is based on the documentation of the system and issues observed while the author was working there.

5.1 Current Cost of Poor Quality system

This work is done for the Front Line (FL) operations of the case company, the subsidiary companies selling products, installing, and maintaining them. They buy the products and materials from the Supply Line (SL). The activities starting from Selling the products to it being installed and moved into service are termed Delivery. The work is also limited to the viewpoint of two main geographical areas in the company.

The case company defines CoPQ as describing the impacts of inefficiencies and wastes in the business. The purposes of CoPQ is to:

- Measure inefficiencies in processes
- Identify biggest opportunities for improvement
- Increase visibility of hidden costs
- Measure waste via “out of pocket” money
- Support better and faster decision making (full-chain cost understanding)
- Eliminate manual, de-centralized reporting, keep reporting methods and formulas simple and manageable. (Case Company, QD-02702, 2015)

The company has a legacy Cost of Poor-Quality calculation guideline which notes many different aspects but is laborious to use and mainly relies on estimations. The company doesn't have an explicitly stated model for cost of quality but basically all the costs are failure costs. Price of Non-Conformance (PONC) is used in four phases of the Delivery: Dismantling, Rigging and Hoisting and Commissioning to describe the cost of lost time. It is also used as a cost category in warranty costs but otherwise it is limited in usage.

PONC hours are back reported by employees, for each the four phases of the Delivery, in four different reason categories:

1. Material
2. Site condition
3. Waiting time
4. Customer cause

Material PONC hours are hours wasted when for example material is not delivered on time, or it is broken so that it cannot be installed. Site condition category means time lost due to site not being ready when planned work is supposed to start and needs to be fixed before starting the value-adding work. Waiting time is for example waiting within the work phase, due to electric outage or other work needed to be done that interferes with planned work of the employee. Customer cause is for example when access to the site is obstructed or a contractual issue causing extra time.

Most of what the company currently categorizes into CoPQ is the cost of unexpected maintenance jobs, when the installed equipment develops a fault that the customer or computer system judges as needing immediate attention. This excludes normal, planned maintenance for the equipment.

During the delivery of the equipment, most of the currently measured CoPQ is from the extra time spent on installation on top of planned, some of this categorized as PONC and the second main part from warranty claims noticed in the materials that have been shipped from Supply units. The company applies a chargeback system between Supply Line units and Frontline units to allocate the cost of issues and warranty to the responsible party. Considerable resources are needed in performing the chargeback system, but the costs related to it are not part of CoPQ.

The approach taken is mostly top down from global quality, even though some FLs might have their own approach. In this approach the categories for CoPQ are defined from the top and each is using the same categories and measures. This has led to inaccuracies because FLs report their time and cost differently and not all those differences are reflected in the measurement.

5.2 Problems of current system

There are four notable problems with the current CoPQ system used for Frontlines. First is the lack of consistency in design of the system. The only designed aspect of Cost of Poor Quality for FLs in the case company seems to be the concept of PONC (Price of Non-Conformance) in delivery projects. Otherwise the categories seem to have been taken from available data that has been generated by other business needs and reporting needs more organically. This is likely quite common since companies don't generally want to develop parallel systems for cost reporting, sticking to standard cost accounting. Data is also spread in different dashboards and files, from multiple ERP systems, making the calculation laborious.

The second notable issue is the differences in reporting from frontlines leading to inaccuracies in cost of poor-quality reporting. There have been different practices in reporting time and cost, which has led to inaccuracies in reporting specific aspects of CoPQ coming from certain FLs. This has been improving in recent years with harmonization programs unrelated to CoPQ but will still need to continue and results reflected in the CoPQ reporting practices.

The third notable issue based on the literature is the apparent lack of minimum limit in chargeback system between FLs and SLs. Woods (2008, p.66) states having a minimum limit in a chargeback system as one of the ground rules. Otherwise the system has a tendency to overgrow and redirect resources use. In the case company the chargeback system has no minimum value and disputes about responsibility take up considerable time. This decision nonetheless supports filing each error in the process, which is a good thing, but perhaps disputing or changing responsibility of the initial chargeback request should be limited to a certain amount.

The last issues is that the system is limited in scope which also limits the possible benefits available from the system. There is no clear view of how much countries spend on price of conformance or appraisal and prevention, only failure costs are frequently collected. Walsh (2005) argues that without the measurement of prevention and "inspection" (appraisal), CoPQ is not a complete measure since it lacks relevant attributes to define quality performance. In the current state the cases company can only evaluate the outcome, failure costs, but can't see how

much resources were spent on achieving that outcome (expect at the traditional income statement level) and what type of variation exists between units. In the current state benchmarking can be done only for the outcomes, not to the processes that lead to it.

CoPQ is also limited to parts of operations, not looking at the whole value chain. The most advanced Cost of Quality is in manufacturing, but end-to-end visibility is missing that would enable to identify for example the CoPQ by product through the value chain, from design choices to final customer usage. This issue is not in the scope of solutions in this thesis but still a relevant point.

6 PROPOSED MODEL FOR CASE COMPANY

The case company could widen its application of cost of poor quality to the direction cost of quality, to be able reap more of the benefits found in the literature. This could be done in a continuum of two approaches or a combination of the two: Top-down and bottom-up.

6.1 Top down approach

This is in my view what the case company has largely done with FL Cost of Poor Quality. Looking at data that is available from most countries and choosing the cost categories and items based on amount of costs, measured with current capability of reporting accuracy, mainly using budgets and expense sources as basis. This can be categorized into the Macro level usage of Cost of Quality, as proposed by Hwang and Aspinwall (1996)

Using this approach would entail continuing with the current categories used and improving the coverage and accuracy of the current categories. The use of the current categories will likely still bring value, since the visualization of the data and “one set of numbers” has been developed in QlikSense software platform. The work on harmonizing the reporting some of the current cost categories is also still ongoing.

6.2 Bottom-up approach

The bottom-up approach, originating from processes in FLs, could be done through activity-based costing or process cost models. This could be done as part of the DMAIC projects, used for process improvement in the company, as part of the current state analysis in the Measure phase. Usage of this kind would be the micro level usage of Cost of Quality (Hwang & Aspinwall), enabling to tap into further benefits by helping to explain causes of quality problems.

Activity-based process cost models bring enough detail to the process to be useful for root-cause analysis. They also facilitate culture of process orientation. Process mapping is done anyway in DMAIC projects, so mapping also the financial flow can be done at the same time with relative ease. The benefits of Activity-based costing are in better allocation of overhead

costs, tracking of costs to sources (Tsai, 1998) and better decision making (Ness & Cucuzza, 1997).

Activity-based costing has been not popular after the first waves of implementation, due to the workload and cost of running the system and having a second cost accounting system. These challenges could be argued to now have overcome with better technology in data capture, transmission, storage, modeling, and application. Many of the manual tasks can now be automatized. ABC is designed to support decision making, whereas standard cost accounting is needed, as a necessary evil, for financial reporting purposes. The downside of this solution is that it requires bigger changes in the company finance processes and mindsets.

If the organization is not ready yet for ABC, process cost models could be used as a first step to that direction. Process cost models can be used more in an isolated fashion in the beginning and require less effort and collaboration to implement in the beginning. This approach is also closer to what the organization is already doing with DMAIC projects so it would not require a culture change, as changing or introducing a new accounting system would.

6.3 Comparing the approaches (Avaataulukko, jatka jos aikaa)

Comparison of the approaches is presented in Table 4., contracting the solutions to the key features that the CoQ system should have. What can be observed is that both approaches have different strengths

CoQ feature	Top-Down	Bottom-up
Systematic quantification of the financial impact	Can be more systematic, since application across FLs is similar	Less systematic at global level, can be systematic within FLs. Needs sound design principles
Creating a sense of urgency	More within global operations.	More within FLs, less in global if aggregation is not efficient
Understanding the needs of the organisation	Satisfy global and management	Better satisfy FL needs
Eliminates root causes of waste	Possibly company wide, systemic changes	Better suited for projects in FLs
Focuses organization on the greatest opportunities for improvement	Yes in global viewpoint, less for FLs	Focuses on processes, where the value is created
Comparability between FLs	Yes, but subject to inaccuracy	Likely not
Emphasis	Aggregates of outputs, lagging measure or progress	Understanding process factors and inputs
Implementation effort required	Small, improving current reporting	Significant, process model work in Frontlines and implementing ABC

Table 4. Comparison of approaches

The bottom-up approach would alleviate the issue of reporting differences, since the idea is to not use it only for global reporting but to also support root cause analysis at FL level, becoming more of a feature than a bug. The top-down approach is mostly already in use but can be improved upon.

The main issue of choosing could be in the implementation work required. Are there sufficient benefit for developing and maintaining the process cost models or ABC based models, if the company accounting system stays in standard accounting, remains to be decided.

6.4 How should the CoPQ model for frontlines be

The recommendation of this thesis is to use the integrated approach: using what is currently available in the top down, reporting based approach and expand where necessary, and to develop process cost models in FLs for key processes along with digitalization and Quality 4.0 maturity progression. For example Tang (2004) used process costing models in constructions projects. This approach satisfies the needs to both global and FLs. FLs can make projects which solve root-causes and remove waste and inefficiency. When doing this through the chosen method of DMAIC, in the process mapping part in the measure phase a process cost model can also be developed, which adds to the understanding of the current state of processes. This model can be updated for the improved process in Improve and Control phases.

By extension of the Taguchi Loss function concept of Loss to Society, it is advised to start considering the cost to the environment as part of Cost of Poor Quality. This reflects both the current industry environment and the company strategy and would provide further attention to the environment topic. This is also relevant since quality and environment issues are usually combined in to one role of Quality and Environmental Manager.

6.5 Where can Quality 4.0 technologies aid CoPQ estimation at case company?

Quality 4.0 technologies can make the detection of poor-quality results and the capture of related data, and consequent cost or cost calculation easier and quicker. The cost of sensors such as load cells, RFID chips, proximity detectors, vibrometers, pressure sensors and bar codes sensors has come down so re-evaluating what the company could measure becomes prevalent. Computer vision and motion detectors can be used to better understand what kind of errors and wastes there are in the processes. These technologies enable much of the previously manual work, done by employees to be automated.

The gathered data can be further transmitted to other devices or a central system to support analytics. The speed and coverage of transmission has improved drastically from traditional CoQ implementations, where most of the examples and studies come from a time before 4G,

handheld mobile devices, wearable technology, or edge computing in equipment. Still in some areas of work in certain FLs the lack of connectivity might be an issue.

Data mining can be used to allocate Cost of Poor Quality more accurately, as Riesener et al (2019) have done for complexity costs. Basically, that means assigning the indirect and burden rate costs to each product, product variation and project. The use of data mining can offer a possibility to do easier, faster, and more accurately than before.

Machine learning could be used to categorize feedbacks and issues coming from the field to find similar cases and get early warnings of epidemic issues. Currently a lot of time needs to be used to understand the wealth of information coming in and some cases that are low priority individually might get neglected initially.

Preventive CoPQ could be achieved through prediction and early detection, signals of problems at multiple sites can be noticed quicker. Learning from past feedback data and what where the effects can be developed into prescriptive analytics, information what action to take or take it automatically. Machine vision can be used to detect and categorize waste in installation work as well as inspect the work. In the planning phase, a Digital Twin of elevator combined with a decision support system would prevent configurations that are not suitable.

In the end, better information about cost of poor-quality leads to better, more informed decision making, by both human and machines

6.6 How Cost of Quality supports Quality 4.0 adoption and implementation

CoQ allows to build the business case for Quality 4.0. In Sony (2020b) the number one barrier for the Quality 4.0 implementation was the high cost of implementation and ROI not being clear. A complete level of Cost of Quality understanding will enable business cases with better confidence.

When choosing where to apply Quality 4.0 technology, many of the applications rely on reducing Cost of Goods Sold. The reduction will not only be in CoPQ – internal and external

failure costs, but also in how prevention and appraisal will be done. The technologies enable to build system with better prevention capabilities so reduction of appraisal costs will also be substantial. If the company doesn't know the appraisal and prevention costs of a process or business system, using only the CoPQ will lead to a less accurate, weaker business case for a Quality 4.0 application.

CoPQ when meaning only failure costs will not be enough in Q4.0 since new quality maturity will reduce the importance of failure costs, automated prevention activities will replace the need for appraisal costs, so the major Cost of Quality costs will likely become prevention costs.

The progress for Quality 4.0 could be measured with ratios of prevention, appraisal and appraisal costs. We should expect prevention costs to initially rise as Quality 4.0 requires significant investments, appraisal costs decrease as prevention activities replace the needs for appraisal, and failure costs to decrease significantly due to better control of processes, and prediction and earlier detection of issues.

7 CONCLUSIONS

The first research question was:

1. How can Quality 4.0 enable better Cost of Poor-Quality measurement?

Quality 4.0 technology can produce a step change in Cost of Quality accuracy, coverage and cost of implementation, cost of poor quality being one part of Cost of Quality. Detection of significant events and capture, transmission, recording and storage, sorting and processing, modeling and application of data can be done at a new level. Previous reasons for not adopting or not continuing CoQ initiatives should be suspect to re-examination, as the new technology and capabilities are introduced.

Cost of Quality will shift more towards prevention than appraisal – auditing and inspection will be less significant parts of quality activities and quality costs. This is due to the cyberphysical systems ability to eventually use prescriptive analytics and change its behavior to prevent defects. Also detection of issues can be automated to a large degree. be automated.

Quality 4.0 is not about mere technology. Designing the productive systems which incorporate new technology, should be a cross-functional effort, where quality has a natural place. Even though automation will reduce human labor, it will not be gone soon, so building effective sociotechnical systems of work requires the understanding of the human component, not only technology. Changing a work processes still poses the possibility of creating inefficiency and waste if introduction of new technology isn't assed properly. Effects to the components of Cost of Quality is useful tool in assessing changes, the managerial accounting new is insufficient in detail to allow for this.

The second research question was:

2. How should the case company develop its CoPQ-system in the frontlines?

The case company has until now limited it's Cost of Quality in FLs to only Cost of Poor Quality, and used a top-down approach in implementing it. It can be said to have used loosely Crosby's

model of Cost of Quality, limited to only the Cost of Non-conformance in Crosby's model, what the company calls Cost of Poor Quality. Extending the concept to Cost of Quality and using an Activity-based costing or a process model for CoQ could be beneficial. With these approaches enough detail is gained in using the system to understand root causes for issues. This also facilitates a bottom-up approach as each Frontline would need to map their key processes and cost drivers in them to use the system. Doing this top down for all processes would be costly and impractical with the current technology but will get cheaper as Quality 4.0 technology and practices are rolled out.

Without the implementation of process cost model or ABC, the value of the Cost of Quality system will be reduced to the top down approach, mainly to highlight quality to management's attention. Continuous reporting of set cost items to show progress of quality management as a whole is justified but explaining what caused it is subject to interpretation without proper linkage to processes and root causes. This management attention could also be achieved through performing a wider assessment from time to time, considering also the opportunity and intangible costs, to support for example strategic planning.

In the current corporate climate, extending the concept of Taguchi's Loss to society, the case company is suggested to start incorporating the extra cost to environment as part of Cost of Quality. This could be done with a carbon cost or carbon cost combined with referencing to industrial benchmarks in emissions, if available. This would also facilitate the awareness on the environment and on the emission, reduction targets of the company.

CoQ and Quality 4.0 are integrated in the sense that Quality 4.0 technology enables better CoQ measurement and CoQ could enable the investment needed for Quality4.0 technology. CoQ facilitates making better business cases for Quality4.0 initiatives, since work processes and their cost components are better understood. Also, potential areas for implementation could be revealed through examination of CoQ, finding out where failure costs and appraisal costs are a significant part. The split of costs to prevention, appraisal and failure costs, could also indicated the progress in Quality4.0 implementation, as the prevention costs should be expected to rise in proportion to the other two, and failure and appraisal costs to decrease as better quality levels are achieved.

Further empirical research could focus on evaluating how the cost of quality changes as companies progress in their implementation of Quality 4.0. Currently there were no studies found in the English literature about combining Quality 4.0 and Cost of Quality. In the case company, further inquire could focus on what is the current state of technology and competences regarding Quality 4.0. Also, from the case company Cost of Quality perspective, research into end-to-end cost for product or product line could be done, since the scope of this work was only focused on SL. This would highlight the effect of design choices to the whole value chain cost of quality.

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