

Universidade do Minho
Escola de Engenharia

Angélica Muffato Reis

Reviewing and designing predictive
performance indicators to reduce quality costs

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Doctoral Thesis
Doctoral Program in Advanced Engineering Systems for Industry

Thesis Supervisors
Professor Sérgio Sousa
Professor Lino Costa

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DEDICATION

In memory of my parents, Ilson and Anete, and of my stepfather, Carlos.

I miss you more than words can say.

ACKNOWLEDGEMENTS

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STATEMENT OF INTEGRITY

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Reviewing and designing predictive performance indicators to reduce quality costs

ABSTRACT

Besides the competitive environment, automotive electronics and other high-tech industries deal with the increasing complexity of products, processes, and systems, which is one of the major challenges for production quality. Accordingly, it is supposed that these industries have effective and cost-efficient quality control, and thoroughly elaborate quality and productivity continuous improvement systems, which are managed to meet strict technical standards. Therefore, by conducting a case study in a company in this quality-strict and data-rich environment, this thesis focused on four interconnected themes on Quality Management: the review and improvement of KPIs related to quality, the identification and quantification of relationships between them, practices for inspection planning and improvement, and modeling of inspection strategies considering quality costs. Among main findings, it can be underscored the relevance of reviewing and improving KPIs based on a set of attributes in order to ensure that metrics fully contribute to an organization's continuous improvement. As for inspection design and update, the evaluation of the company's practices showed that many aspects could be further improved, with findings being generalized by framing inspection planning on the continuous improvement tool PDCA. Lastly, the development and application of an inspection strategy model contributed to the literature on computational models and highlighted their potential as a decision-making aiding tool for inspection revision and improvement considering the CoQ approach.

KEYWORDS: Quality Costs, Inspection Strategy, Key Performance Indicators, Quality Control.

Revisão e *design* de indicadores de desempenho preditivos para reduzir custos de qualidade

RESUMO

Além do ambiente competitivo, a eletrônica automotiva e outras indústrias de alta tecnologia lidam com a crescente complexidade de produtos, processos e sistemas, o que é um dos maiores desafios para a qualidade da produção. Consequentemente, supõe-se que essas indústrias tenham um controle de qualidade eficaz e econômico, e sistemas de melhoria contínua de qualidade e produtividade minuciosamente elaborados, os quais são geridos de acordo com rígidos padrões técnicos. Portanto, ao realizar um estudo de caso em uma empresa neste ambiente rigoroso em questões relacionadas à qualidade e rico em dados, esta tese focou em quatro temas interligados na Gestão da Qualidade: a revisão e melhoria dos KPIs relacionados à qualidade, a identificação e quantificação das relações entre eles, práticas de planejamento e melhoria da inspeção, e modelação de estratégias de inspeção considerando os custos da qualidade. Entre as principais conclusões, destaca-se a relevância de revisar e aprimorar os KPIs com base num conjunto de atributos, a fim de garantir que as métricas contribuam plenamente para a melhoria contínua de uma organização. Quanto ao planejamento e melhoria da inspeção, a avaliação das práticas da empresa mostrou que muitos aspectos podem ser melhorados, e os resultados foram generalizados através de um enquadramento do planejamento da inspeção na ferramenta de melhoria contínua PDCA. Por fim, o desenvolvimento e aplicação de um modelo de estratégia de inspeção contribui para a literatura sobre modelos computacionais e destaca o seu potencial como ferramenta de auxílio à tomada de decisão para revisão e melhoria da inspeção considerando a abordagem dos custos de qualidade.

PALAVRAS-CHAVE: Controlo de Qualidade, Custos da Qualidade, Estratégia de Inspeção, Indicadores Chave de Desempenho.

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ABBREVIATIONS, INITIALS AND ACRONYMS LIST

ABC – Activity Based Costing
AIAG – Automotive Industry Action Group
ALR – Active Lot Release
AOI – Automatic Optical Inspection
AS – Analysis Station
BSC – Balanced Scorecard
CAD – Computer Aided Design
CI – Continuous Improvement
CoQ – Cost of Quality
CTQ – Critical to Quality
DEMATEL – Decision-Making Trial and Evaluation Laboratory
DMAIC – Define, Measure, Analyze, Improve, and Control
DPPM – Defective Parts Per Million
ECM – Engineering Change Management
EWAK – *Erst Sonderwerkzeug Anschaffungs Kosten* (Initial Costs for Special Tools)
FCT – Functional Testing Station
FMEA – Failure Mode and Effects Analysis
PFMEA – Process Failure Mode and Effects Analysis
FPY – First Pass Yielded
GRR – Gage Repeatability and Reproducibility
ICT – In Circuit Test
IP – Inspection Planning
IPB – Incidents per Billion
IQIS – Integrated Quality Improvement System
IRR – Internal Reject Rate
ISM – Inspection Strategy Model
ISO – International Organization for Standardization
KPI – Key Performance Indicator
MAE – *Maschinen und Einrichtungen* (Machinery and Equipment)
OPL – Open Points List
PAF – Prevention, Appraisal and Failure

PAV – Product Test and Alignment specification
PCB – Printed Circuit Board
PCBA – Assembled Printed Circuit Board
PCI – Process Capability Indices
PDCA – Plan, Do, Check, Act
PFMEA – (product) Failure Mode and Effects Analysis
PFMEA – Process Failure Mode and Effects Analysis
PMS – Performance Measurement System
PPM – Parts per Million
PW – Performance Workshop
QFD – Quality Function Deployment
QG – Quality Gate
QIM – Quality Inspection Manufacturing
QMM – Quality Management and Methods
QMS – Quality Management System
ROI – Return on Investment
ROII – Return on Investment in Inspection
RQs – Research Questions
SC – Special Characteristic
SPC – Statistical Process Control
SPI – Solder Paste Inspection
SQL – Structured Query Language
SUB – Subjective
TFOR – Total Fall Off Rate
TS – Testing Station
VDA – German Association of the Automotive Industry
VTP – Virtual Test Places
WS – Work Station

1 Introduction and Motivation

A Quality Management System (QMS) is responsible for the overall performance of the organization and the attainment of its quality objectives. For that, it is necessary to have an appropriate set of metrics to assess and monitor performance. Accordingly, a Performance Measurement System (PMS) comprehends the whole processes of setting goals, developing a set of performance measures, collecting, analyzing, reporting, interpreting, reviewing, and acting on performance data (Bititci, 2015). That is to say that a PMS is a vital part of a company's managerial system. Despite the great attention of scholars and practitioners to designing a PMS, there are also other important processes in its life cycle: implementing (Keathley-herring, 2017), using, and reviewing (Braz *et al.*, 2011). Closely related to PMS, the key performance indicators (KPIs) in production systems have received much interest from researchers in recent years. They are defined as “a set of metrics to reflect operation performance, such as efficiency, throughput, availability, from productivity, quality and maintenance perspectives” (Kang *et al.*, 2016). KPIs must be defined to identify problems and take actions that maintain a desired trajectory, *i.e.*, controlled processes, with quality levels equal to the pre-defined ones. In a sequence of activities, the results of a process influence the following processes. By controlling preceding indicators, it can be possible to determine predictive relationships, which can provide opportunities not only to improve the quality of products but also to reduce associated quality costs. Nonetheless, there is a literature gap when it comes to assessing the functioning and relationships of KPIs in practice, which this thesis aims to target. It does so by analyzing how a company reviews and update quality-related KPIs and if there is a predictive relationship between internal and external KPIs.

Still, Quality itself is a multidimensional concept that needs to be translated into quantitative aspects. A possible approach for translating quality into tangible aspects is to quantify the activities that add costs, determining the Cost of Quality (CoQ) for a given system. As such, it offers a way to reconcile manufacturers' two conflicting objectives: minimizing cost and maximizing quality of conformance. The most common CoQ approach defines categories of Prevention, Appraisal, and Failure (PAF) costs. Considering this approach, one can estimate the Total CoQ and predict the cost when taking actions in a system. For example, more and tighter inspection will normally induce a higher product quality – in terms of meeting product specifications – but will also result in higher costs of inspection, scrap, and rework than in a zero-inspection production system. Through the analysis of the costs and variables involved in this system, it is possible to quantify the trade-offs among different inspection strategies and establish ways of optimizing economic aspects, reducing quality costs.

Nonetheless, it is of interest for this thesis to understand how a company designs and improves its inspection and control methods, and whether the CoQ is taken into consideration. Although there are different ways to estimate the CoQ, the use of computational models is common in literature. However, these models vary in terms of CoQ approach, mathematical modeling, uncertainty consideration, and scope, and there is no single method to design and review inspection strategies. From this background, this thesis builds on the existing literature, to develop, extend and apply a computational model that employs Monte Carlo sensitivity analysis to assess different inspection strategies based on the CoQ.

The analysis of KPIs relationships, KPIs review and update, inspection planning and improvement, and the impact assessment of inspection strategies on the CoQ has been conducted for a case study in the automotive electronics industry. Besides the competitive environment, automotive electronics and other high-tech industries deal with the increasing complexity of products, processes, and systems, which is one of the major challenges for production quality (Colledani *et al.*, 2014). Accordingly, it is supposed that these industry segments have effective and cost-efficient quality control, and thoroughly elaborate quality and productivity continuous improvement systems, which are managed to meet strict technical standards (Schiffauerova and Thomson, 2006). Therefore, conducting a case study in this data-rich and quality-strict environment to evaluate KPIs, inspection planning and reviewing processes, as well as gathering data for an inspection strategy model is both appropriate and relevant.

1.1 Research Questions

Considering the opportune business environment context of the automotive electronics industry, this thesis aims to answer the following Research Questions (RQs):

RQ1. How does a company accomplish the review and update of its quality-related KPIs?

RQ2. Is there any causal/predictive relationship between quality-related KPIs?

RQ3. What are current practices for the design and revision of inspection and control methods and how can they be improved?

RQ4. What is the best inspection strategy that must be in place to minimize quality costs?

1.2 Objectives

The aforementioned RQs can be linked to the following objectives:

1. To review and improve current KPIs in the case study and suggest recommendations for practical KPI improvement processes based on the literature.
2. To identify and quantify relationships between internal and external quality-related KPIs.

3. To identify current practices for the planning and improvement of inspection processes.
4. To develop a computational model to define inspection strategy that minimizes the total CoQ.

1.3 Thesis Structure

This thesis is structured into six chapters (see Figure 1). Following this introduction, Chapter 2 presents the background research for this thesis and establishes its justification within the broader research context. Next, Chapter 3 outlines the research design, including the procedures for data collection and analysis. The subsequent chapter presents the case study context, *i.e.*, all the relevant Company information for the study, though not disclosing the confidential matters. Chapter 5 presents the results and discusses the findings. Finally, Chapter 6 concludes with a summary of the main implications and limitations of the study, as well as some directions for further research.

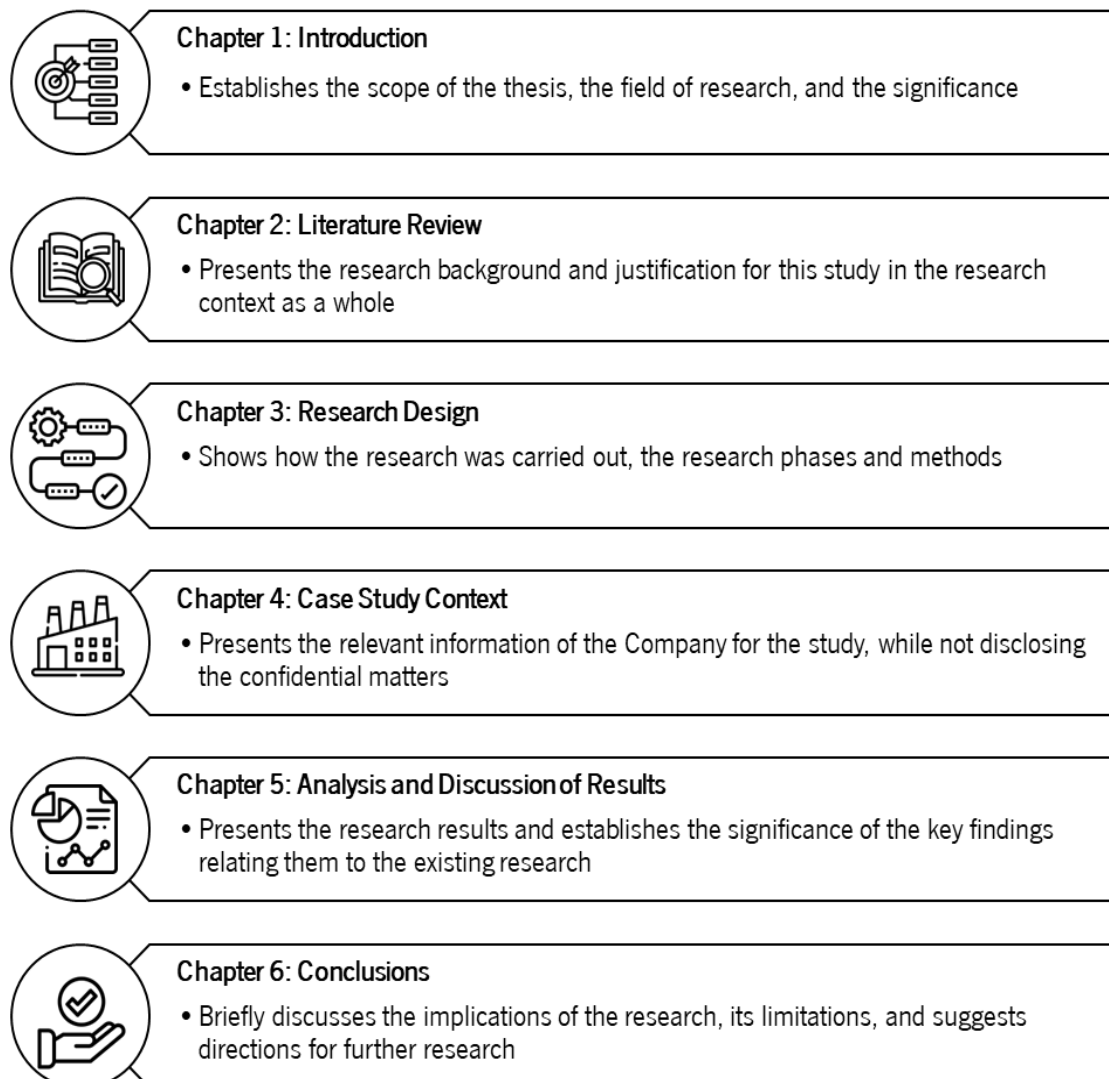


Figure 1 – Structure of the thesis.

2 Theoretical Background

This chapter establishes the theoretical foundation for this thesis by presenting the concepts related to Quality Management Systems and Performance Measurement (Section 2.1), Capability Indicators (Section 2.2), Quality Cost models and assessment (Section 2.3), and Inspection Planning, Improvement, and Control Strategy Models (Section 2.4). Each section ends with conclusions and considerations, which highlight the relevance of the respective theme for the thesis and, when appropriate, the relative research gap.

2.1 Quality Management System

A Management System is an organizing framework that enables companies to manage the interconnected parts of their business to achieve their objectives. These objectives cover many facets of the organization's maneuvers, including financial success, safety operations, product quality, legislative and regulatory conformance, and worker management (Kaur *et al.*, 2021). The level of complexity of the system depends on each organization's specific context. In small organizations, it might simply mean having strong leadership from the business owner, providing a clear definition of what is expected from each employee and how they contribute to the organization's overall objectives, without the need for broad documentation. On the other hand, more complex businesses operating in highly regulated sectors may need extensive documentation and controls to accomplish their legal requirements and meet their organizational objectives (International Organization for Standardization [ISO], 2022).

The focus of a QMS is the overall performance of the organization and the attainment of its quality objectives. Therefore, a QMS is defined as a formalized system that documents processes, procedures, and responsibilities for achieving the established vision and quality targets of the organization, along with its policies and goals (Defeo, 2016). The conversion of goals into results is done through managerial processes – sequences of activities that produce the intended quality results.

Managing quality makes extensive use of three managerial processes, a.k.a. “the Juran trilogy”: i) Quality Planning ii) Quality Control, and iii) Quality Improvement (Defeo, 2016). This trilogy marked the start of the era of Quality Management (Zonnenshain and Kenett, 2020). These processes have different objectives and serve different purposes as each one has its unique sequence of activities. They have been widely used in all industries while helping meet customer and regulatory requirements and improving effectiveness and efficiency continuously (Teixeira *et al.*, 2015).

Quality Planning is a structured process for developing products (both goods and services) that ensure that customer needs are met by results, thereby ensuring that the final “quality gap” is at a minimum

(Defeo, 2016). The concept of the quality gap is described in Juran's Quality Handbook, by John Early and John Coletti, as the difference between customers' expectations for a product or service and their perception of what they actually received (Defeo, 2016). This difference is the sum of smaller gaps, namely, understanding, design, process, operations, and perception gaps, as shown in the diagram in Figure 2.

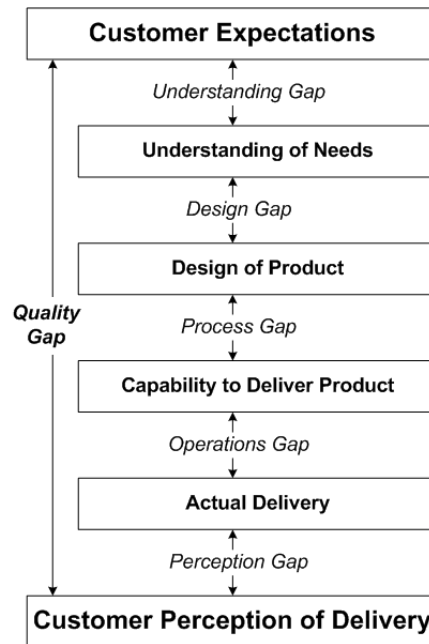


Figure 2 – The quality gap. Adapted from: (Defeo, 2016).

From a product manufacturing company's perspective, the structured process of Quality Planning consists of a standardized series of steps: i) establish the project; ii) identify the customers (both internal and external) and discover their needs; iii) develop the product features which respond to the customer needs; iv) establish goals for the product features and the process to meet them; v) and prove that the process is suitable and capable of meeting the product goals under operating conditions (Defeo, 2016).

The second managerial process, Quality Control, is a universal managerial process for conducting operations to provide stability, *i.e.*, to prevent adverse change and to "maintain the *status quo*" (Defeo, 2016). It establishes measurement systems and standards of performance, evaluates actual performance, compares actual performance to goals, and acts on the difference. The input-output diagram for the quality control process proposed by Joseph Juran and Blanton Godfrey (Defeo, 2016) is depicted in Figure 3. The feedback loop at the bottom of Figure 3 represents the continuous nature of Quality Control, where current performance is constantly compared against established performance as a means to improve product quality.

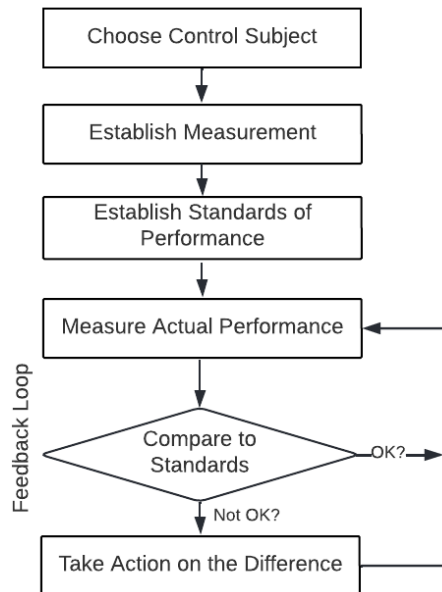


Figure 3 – The quality control process. Adapted from: (Defeo, 2016).

The primary function of the last process of the trilogy, Quality Improvement, is to establish a strategy to permanently remove chronic problems and waste, which is usually done via special projects (Bisgaard, 2008). It comprises eight steps and ensembles a generic version of the Define, Measure, Analyze, Improve, and Control (DMAIC) framework (de Mast and Lokkerbol, 2012). The eight steps of Quality Improvement are as follows: i) prove the need for improvement; ii) identify specific projects for improvement; iii) organize to guide the projects; iv) organize for diagnosis—for the discovery of causes; v) diagnose to find the causes; vi) provide remedies; vii) prove that the remedies are effective under operating conditions; viii) provide for control to hold the gains (Stephens, 2004). Through this process, Quality Improvement aims to create breakthroughs to unprecedented levels of performance. Figure 4 below summarizes the three quality managerial processes described above.

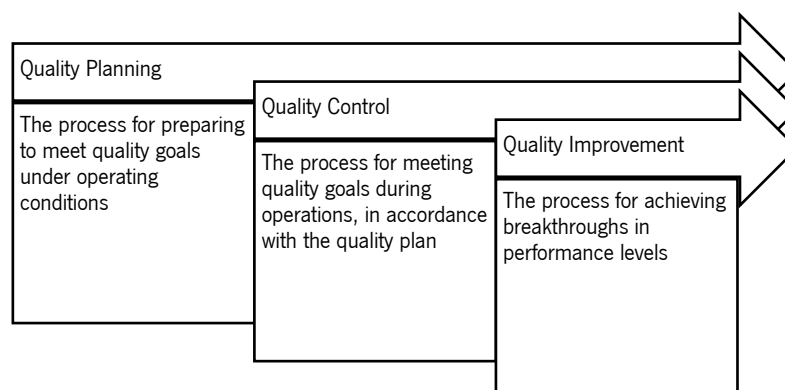


Figure 4 – Juran Trilogy. Adapted from Bisgaard (2008).

Another well-known improvement tool is the PDCA cycle, originally developed by Walter Shewhart and Edwards Deming in the 1950s and was developed to encourage the use of small-scale improvements for

continuous performance improvement while allowing for rapid assessment of improvement actions (Juran and Godfrey, 1998). Since then, with the support of other quality tools, such as Pareto charts and flowcharts, it has experienced wide application in the industry (Realyvásquez-Vargas *et al.*, 2018). Nowadays, supported by new technological concepts, it has the potential to aid the CI shift towards the industrial paradigm I4.0 (Peças *et al.*, 2021). In addition, PDCA is also presented as a component of ISO management systems standards, for example, ISO 9001, the leading international standard for the development of quality management systems (ISO 2015).

It is widely recognized that quality goals must keep shifting according to the endless change drivers: new technology, new competition, threats, and opportunities. Organizations that have adopted QMS have to provide the means to evaluate the impact of those changes and revise the goals accordingly. In addition to stating what will be done and by when a project must show how the team will measure whether it has achieved its stated goals. This can be done with the support of Performance Measurement Systems.

2.1.1 Performance Measurements

Neely *et al.* (2005) define performance as the efficiency and effectiveness of the action within the business context. Organizations achieve their goals by satisfying their customers with greater efficiency and effectiveness than their competitors. For these authors, effectiveness is the extent to which customer requirements are met, and efficiency is the measure of how well the organization's resources are used to meet a certain level of customer satisfaction. Therefore, “performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action” (Neely *et al.*, 2005). Such a process is an integral element of the quality planning and control cycle and provides the means to capture performance data that can be used to inform decision-making (Neely *et al.*, 1997).

Performance measures must be made not only to plan and control but also to diagnose how the quality management systems work in terms of feedback, which can be done based on KPIs analysis (Sanchez-Marquez *et al.*, 2020). For performance measurement to be carried out, performance measures must be chosen, implemented, and subsequently monitored. According to Globerson (1985), the KPIs used in measuring and improving performance must be those that truly capture the essence of organizational performance. The lack of well-defined performance criteria through which the performance of individuals and the organization can be assessed makes it hard to plan and control the operation of any organization, as well as to motivate its employees. The whole process (or processes) of setting goals, developing a set of performance measures, collecting, analyzing, reporting, interpreting, reviewing, and acting on performance data is defined as a Performance Measurement System (PMS) (Bititci, 2015).

PMS includes software, databases, and procedures that measure performance completely and consistently (Lohman *et al.*, 2004).

Performance measures need to be positioned in a strategic context and managers should use their periodic review sessions to evaluate the validity of the unit's strategy and the quality of its execution (Kaplan and Norton, 2007). Performances measures aligned with the organization's strategy not only provide information if the strategy is being implemented but also encourage behaviors consistent with it. The reverse is true as highlighted by (Neely *et al.*, 1997): the plethora of poorly designed measures encourages undesirable behaviors. Several other works also mention the importance of performance measures being aligned with the organizational strategy (Bititci *et al.*, 2001, 2016; Lucianetti *et al.*, 2019; Rodriguez *et al.*, 2009).

To develop good performance measures, some examples of characteristics that must be considered are shown in Table 1.

Table 1 – Characteristics of performance measures.

Characteristic	Description
Derived from strategy and should have an explicit purpose	Performance measures need to be positioned in a strategic context, as they influence what people do (Neely <i>et al.</i> , 2005) and managers should use their periodic review sessions to evaluate the validity of the unit's strategy and the quality of its execution (Kaplan and Norton, 2007)
Clearly defined	Performance measurement must be easy to understand (Neely <i>et al.</i> , 1996, 1997), and have clear and accurate syntax and semantics (Dominguez <i>et al.</i> , 2019)
Provide timely and accurate feedback	The systems that exist inside or outside the company may be inadequate to provide accurate timely information necessary to make a good decision because of the inability to quantify or even assess the potential loss (Defeo, 2016)
Relevant	Any indicator through which organizational improvement or deterioration may be detected is a relevant criterion (Globerson, 1985). To keep performance indicators relevant, evolution management must be adopted considering KPI's traceability, modification, and change propagation (Dominguez <i>et al.</i> , 2019)
Visual impact	Visual management techniques that integrate strategic and operational perspectives to engage people in a conversation on the strategy and performance of the organization should be applied (Bititci <i>et al.</i> , 2016), assuring the expressiveness and understandability of the KPIs (Dominguez <i>et al.</i> , 2019)
Focus on improvement	The management team must identify improvement opportunities and prioritize changes based on the collective view of the maturity of their performance management practices (Bititci <i>et al.</i> , 2015)
Consistent	The performance measures must maintain their significance as time goes by (Neely <i>et al.</i> , 1997). There should be mechanisms to automatically check consistency between the KPIs and their related business elements, for change propagation (Dominguez <i>et al.</i> , 2019)
Precise	Be exact about what is being measured (Neely <i>et al.</i> , 1997)
Objective	Not based on opinion (Neely <i>et al.</i> , 1997)
Cost-effective	It is necessary to check if the data collection process is cost-effective. The data used for the performance measurement can be already part of the process or may need further data collection, the initial approach is less dependable than the built-in one (Globerson, 1985)
Acceptability by the user community	Acceptability by the user community must be considered when implementing performance measures (Dominguez <i>et al.</i> , 2019). Imposition by top management for a strong focus on a selected set of indicators can have important motivational effects. However, if mid-level managers and employees do not sufficiently understand or agree to such prioritization, tensions and dissatisfaction are likely to arise (Gutierrez <i>et al.</i> , 2015; Jordan and Messner, 2012)

Another important issue regarding performance measures is the definition of their attributes. Table 2 presents a list of attributes with their descriptions that were organized and synthesized by (Dominguez *et al.*, 2019) using a unified taxonomy that captures the overall features of KPIs.

Table 2 – Main performance measure attributes. Source: Based on Domínguez *et al.* (2019) and Kaplan and Norton (2007).

Feature	Attribute	Description
Basic features	Identifier	Letters by which a KPI is represented.
	Name	Effective name to avoid ambiguities.
	Description	A textual description explaining the meaning of the measure.
Calculation features	Hardness	The hardness of a KPI is related to its subjective or objective nature. An indicator is soft when it is “not directly measurable, qualitative, <i>e.g.</i> , customer’s satisfaction, company’s reputation, employees’ motivation”, and it is hard whether it is “measurable, quantitative, <i>e.g.</i> , the number of customers, time to produce a plan”.
	Calculation rule	Refers to the specific formula that gives rise to the calculation
	Value type	Especially in KPIs of quantitative type, it is necessary to specify the type of data in which the KPI is expressed (integer, double, DateTime, boolean, etc.), together with the unit of measure (percentage, units of weight, length, currency, etc.).
	Filter	In many cases, a KPI may be accompanied by one or more conditions that play the role of filters such as <i>TimeFilter</i> , <i>ProcessStateFilter</i> , <i>LastInstancesFilter</i> or <i>ComposedFilter</i>
	Frequency	It refers to the periodicity with which the KPI is calculated. Each KPI must have a timing context property, that specifies if the KPI is calculated either in real-time, on-demand, or periodically.
	Target	Since the use of a KPI is ultimately linked to the achievement of a particular business goal, the relationship of a KPI must be associated with a target value.
	Status options	The range of values of a KPI can be divided into several intervals, so that each interval represents a status with a particular meaning, for example with three statuses differentiated as good, acceptable, and bad, as a traffic light
	Source	The source of a KPI refers to the entities, their data relationships, and properties that are required to compute a KPI. This information can be stored in databases, repositories, files, and other sources.
	Measured aspects	It is necessary to consider the different perspectives under which performance measures are proposed, the reasons or rationale why an indicator has to be defined and the scope must be provided.
Related human resources	Owner	A stakeholder in the enterprise responsible for the achievement of a defined KPI.
	Responsible person	Who is in charge of the indicator being calculated.
	Informed person	Who is interested in the KPI and should be informed of its results.
	Audience	Groups that typically utilize the KPI, <i>e.g.</i> , operators and supervisors.
KPIs relationships	Hierarchical structure	Dependencies between KPIs can be explicitly specified representing the components used in the computation formula, leading to basic, compound, or aggregated KPIs.
	Cause-and-effect relationships	The cause-and-effect relations in a PMS demonstrate outcomes and trade-offs among leading and lagging measures.

Designing a performance measure involves much more than simply specifying a name and a robust formula. Issues such as the purpose of the measurement, the frequency of the measurement, and the source of the data must be considered (Neely *et al.*, 1997). Basic features comprise the elementary features of KPIs, namely, their identifier or label, their name, and their description. Calculation features refer to quantitative aspects of KPIs, such as the frequency of measurement and its formula. Related human resources indicate those that are responsible for and interested in the KPI, whereas KPIs relationships can pertain to two categories: hierarchical structure and cause-and-effect relationship, which are described in the following section.

2.1.1.1 KPI relationships

This section presents the two main typologies of KPI relationships, as mentioned in Table 2. First, hierarchical relationships, which are represented by dependencies between KPIs that can be explicitly specified representing the components used in the computation formula, leading to basic, compound, or aggregated KPIs. Secondly, cause-and-effect relationships, that indicate causal relations among KPIs and can demonstrate outcomes and trade-offs among leading and lagging measures.

2.1.1.2 Hierarchical structure

When combined, groups of KPIs can form Composite Indicators. Composite Indicators help measure multidimensional performance by conveying relevant information into a single figure and have increasingly been accepted as a useful tool for benchmarking performance comparisons, and policy analysis (Zeng *et al.*, 2021). Performance measures should not only be related to the strategical level of the organizations, but also the other organizational hierarchical levels, namely tactical and operational levels. In this way, they are linked to the decision-making and control processes at the lowest levels of the organizational hierarchy (Lohman *et al.*, 2004) and provide a transparent view of the status of all departments within the organization (Ante *et al.*, 2018). These links should be structured logically considering the intrinsic relationships among the performance measures into multiple categories, which have explicit cross-links (Kang *et al.*, 2016). For Ante *et al.* (2018), a structured framework of performance indicators is crucial for measuring the gap between the current state of operations and the desired state, and in many cases, it can be used to identify the path of progress in terms of overcoming productivity gaps.

According to Nardo *et al.* (2008), a composite indicator should ideally measure multidimensional concepts which cannot be captured by a single indicator, supporting decision makers at the strategical level, yet, they are easier to interpret than a battery of many separate indicators making it possible to include more information within the existing size limit. Wohlers *et al.* (2021) proposed KPIs for

mechatronic systems in order “to combine measured values from data sources to reduce the complexity of information and simplify the assessment of the system status response condition”, and they stated that, in general, the proposed KPIs have significantly reduced the amount of data that users need to interpret.

Many authors suggest a diagram for KPIs with three different levels: strategic, tactical, and operational. The first level starts with one indicator, which parts into two or more indicators at the tactical level, each of which branches off into two or more indicators at the operational level. This diagram is usually named as a “indicators hierarchical system” (Kang *et al.*, 2016; Lohman *et al.*, 2004), but since the finished diagram resembles a tree with a trunk and multiple branches, it is also labeled as “KPI Tree” (Ante *et al.*, 2018; Bumba, 2020). Despite different names, the overall purpose of this KPI structure is the same. The topmost level (*i.e.*, strategic) corresponds to the corporate vision, and financial and market objectives. At the intermediate level (*i.e.*, tactical), there are objectives regarding the maintenance of high productivity and quality, speed of response, flexibility, and lead times. And finally, the last level (*i.e.*, operational) is related to the raw measurement elements that are monitored and collected at the operational level, such as loss of materials and the number of failures. Table 3 contains examples of works that dealt with KPIs hierarchy structure and the different terms employed by them. Next, Figure 5 depicts a general hierarchical structure of KPIs with its three levels.

Table 3 – Hierarchical structure of KPIs and its varied nomenclature.

Reference	Strategic	Tactical	Operational	Structure name
(Ante <i>et al.</i> 2018)	Key performance results	Monitoring KPIs	Improvement KPIs	KPI Tree
(Kang <i>et al.</i> , 2016)	Comprehensive KPIs	Intermediate KPIs	Supporting elements	KPI Categorization
(Lohman <i>et al.</i> , 2004)	Clusters	KPIs	Performance indicators	Hierarchy of Metrics

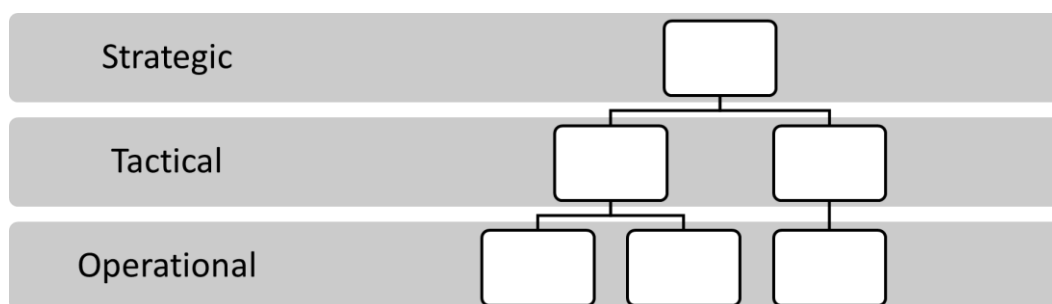


Figure 5 – Hierarchical structure of KPIs.

2.1.1.3 Cause-and-effect relationships

Another aspect related to KPI relationships that have been discussed for several decades in the PMS literature is the cause-and-effect relations among KPIs or measures at various levels of the firm (Kaplan and Norton, 1992; Neely *et al.*, 2005). The beneficial effects of identifying cause-and-effect relations allegedly refer to improved predictions, decision-making, communication, learning, and goal congruence

(Kaplan and Norton, 2007). When the focus of measurement is on past results, a performance measure is considered a lagging indicator. If the focus is on events that have the potential to influence results, it can be considered a leading indicator. Thus, lagging PIs provide information about past events and support reactive actions to improve results while leading PIs provide information of events that support proactive actions to improve results (Reis *et al.*, 2020). Usually, financial indicators are judged as lagging outcomes while non-financial indicators can be considered as leading predictors (Wang *et al.*, 2018)

KPIs must be defined to identify problems and take actions that maintain the desired trajectory, *i.e.*, controlled processes with quality levels equal to the pre-defined ones. In a sequence of activities, the results of a process influence the following processes. By measuring indicators that precede and lead up the following processes, predictive values can provide the opportunity to introduce control measures and, *e.g.*, improve customer satisfaction indexes (Sanchez-Marquez *et al.*, 2020). Studies that explore such relationships are examples of what Deming called analytic studies (Provost, 2011). In general, an analytic study is one that increases knowledge about the system of causes that affect the process. Analytic studies are among the most important uses of measurement data because they support a better understanding of processes.

According to Malina *et al.* (2007), there are three criteria for the establishment of a cause-and-effect relation between KPIs: (a) independence, (b) time precedence, and (c) predictive ability.

- a) The independence criterion states that events X (the cause) and Y (the effect) are logically independent. Furthermore, one cannot logically infer Y from X but only can do so empirically.
- b) The time precedence criterion states that X precedes Y in time, and the two events can be observed close to each other in time and space.
- c) The predictive ability criterion is that the observation of an event X necessarily implies the subsequent observation of the other event Y.

Kaplan and Norton (1992) introduced the notion of a causal Balanced Scorecard (BSC), arguing that cause-and-effect relations exist among proper KPIs, *i.e.*, leading measurements in nonfinancial areas can be used to predict future financial performance. The four strategic perspectives are learning and growth, process, customer, and financial. Since these relations help individuals to see how their actions affect future performance, it fosters organizational focus and goal congruence (Kaplan and Norton, 1992). However, Norreklit (2000) claims that rather than a causal connection between the strategic perspectives analyzed, there is a logical one, and Wang *et al.* (2018) point out additional deficiencies of the BSC: the dependent on subjective experts' assessments and difficult to quantify the concept, lack of data-driven ways to select the KPIs and track the causations between predictors and outcomes, and the unduly

“backward-looking” and absent “forward thinking” about future scenarios. On the application of BSC, Rigo *et al.* (2022) combined BSC to assess the competitiveness among solar photovoltaic energy installers and establish cause-and-effect relationships among identified competitive factors. KPIs were then developed to monitor competitive factors associated with organizational strategic objectives.

In the context of predictive maintenance and industry 4.0, Pilar Lambán *et al.* (2022) defined, developed, and implemented four KPIs in a laboratory for the study of real-world applications. The authors collected data from different sources (*e.g.*, sensors, equipment, etc.) and highlighted the relevance of KPIs monitoring and visualization for improving quality rates and maintenance schedules. Though, in general, the literature lacks analysis of real-life cases of practical problems encountered during the implementation and operability of KPIs (van Camp and Braet, 2016).

Indeed, there are few studies incorporating mechanisms for identifying, quantifying, and projecting upstream the existing relationships between KPIs. These studies can be primarily divided in tools for graphically (Brundage *et al.*, 2017) and analytically (Rodriguez *et al.*, 2009) managing and monitoring these relationships.

Since it can be useful to visualize KPIs relationships, especially in more complex organizations with a dense data and metrics network, some works have focused on the visualization of indicators relationships. Brundage *et al.* (2017) explored graph-based visual representations of the analytic relationships between KPIs, namely, node-link diagrams and matrix-based visualizations. The authors describe the challenge of visualizing relationships given KPIs in different units, which hampers the performance of what-if analysis to understand how changing one metric influences different KPIs. The authors also mentioned a heat map to visualize the sensitivity of KPIs relative to a change in an underlying metric and combined these several tools into a prototype for coordinated visualization. Buytendijk *et al.* (2010) also recognized the importance of visual tools to identify causal relations, such as strategic maps, but suggested the association of the latter with scenario analysis. Nevertheless, the authors do not focus on KPIs relationships but rather on organizational objectives and the preparedness of decision-makers in face of uncertainty.

Within the second main focus, studies have included statistical analysis, optimization and simulation models, business analytics and machine learning. In an early work, Rodriguez *et al.* (2009) suggested an approach to identifying quantitative relationships in the performance management context. Their proposed methodology has four phases: design and analysis of the PMS, initial data treatment, identification and projection of KPI relationships, and the presentation and analysis of results. Particularly, for the establishment of KPI relationships, the authors underscore the relevance of filtering,

homogenizing, and centering data. The first step comprises the statistical analysis of each KPI, followed by a time homogenization process in which a common frequency is established. The last step attributes each KPI to the same degree of importance and the result is a standardized-centered data matrix. Next, the authors suggest principal component analysis and structural equation model be applied to all evaluated KPIs to find cause-and-effect relationships. These relationships are validated and graphically presented.

Martinez *et al.* (2022) analyzed the relationship between product manufacturing quality and machine conditions. After collecting data from automated screw-fastening operations, the authors used statistical analysis through linear correlation coefficients to determine correlations between KPIs. The authors found that linear models do not explain the total rework ratio of present operations, but they could estimate from stronger correlations that preventive maintenance operations based on forecasting could reduce 2-3% of rework and defect generation rates.

Also, Zhu *et al.* (2014) proposed a multi-KPI coordination model to identify and balance the relationship among KPIs employed to evaluate manufacturing equipment. The evaluation architecture is based on KPI definition and utility, where the actual value and the benchmark are compared, and the statistical analysis of quality performance data is summed to data collection on equipment status. The model is applied to a case study in a chemical industry where a multi-objective optimization strategy leads to an efficient solution coordinating production ratio and unit energy consumption. May *et al.* (2015), also focused on energy consumption and efficiency, developed production-tailored and energy-related KPIs and supported companies in the interpretation of causal relationships and related decision-making.

On the topic of business intelligence and analytics, Lechevalier *et al.* (2018) highlighted the importance of advanced analytics in the field of quality management in manufacturing and presented a model-based Tool for Advanced Analytics in Manufacturing (TADAM) that helps manufacturing engineers build a neural network from a given KPI and the variables contributing to this KPI. Given technological development, machine learning can then generate a trained neural network used to predict KPI values. Moreover, Wang *et al.* (2018) employed statistical analysis and machine learning in a framework for predictive and prescriptive KPI analytics within computer industries. The resulting strategic maps can be used by companies to enhance and forecast their performance. Nevertheless, the authors underscored the challenges of identifying KPIs in a data-driven manner, considering interrelationships among KPIs to develop strategic maps, and incorporating leading and lagging indicators into performance forecasting.

Moreover, Wang and Zhou (2021) proposed a mathematical model based on stochastic optimization for KPI control to be integrated into complex queuing systems. The model was extensively validated

through numerical studies and a real case study in a painting plant. Bhadani *et al.* (2020) used dynamic simulation to evaluate crushing processes in manufacturing and processing operations and suggested KPIs based on ISO 22400 standard to monitor equipment and process performance. Cedillo-Campos and Sánchez-Ramírez (2013) used systems dynamics to model the procurement, production, and distribution processes within an automotive company. The authors employed general logistics performance metrics in the model and identified key relationships among them, which were validated through the design of experiment analysis.

Therefore, beyond solely internal KPIs relationships, it is also possible to identify and quantify relationships between internal and external metrics. Sanchez-Marquez *et al.* (2020) for instance, analyzed KPIs of BSC and proposed a method to diagnose the QMS of a company in the automotive industry. They established relationships between internal (within the company) and external (customer related) KPIs through statistical analysis, and the strongest identified KPI relationship was that of warranties with almost all internal metrics, *e.g.*, with First Time Through.

Also, Sokolov *et al.* (2021) examined how internal scrap costs can directly correlate to externally received customer complaints. The results show that there is no significant correlation between scrap costs and customer complaints, suggesting there are other factors that can contribute to a defective product reaching the customer.

Extending the discussion towards supply chain and logistics performance, Chand *et al.* (2020) used multi-criteria decision analysis to rank KPIs associated with supply chain performance and established the relationship between single metrics and overall supply chain performance. The DEMATEL (Decision-Making Trial and Evaluation Laboratory), a technique based on graph theory and visual planning, was used to develop a causal relationship structure. The authors applied the proposed KPI relationship-based decision-making framework to mining equipment and earthmoving machinery manufacturing firms (Chand *et al.*, 2020). Torbacki and Kijewska (2019) also employed the DEMATEL method to evaluate the relationships between logistics and manufacturing performance indicators. Next, Schmidt *et al.* (2020) proposed a model to establish root causes for poor logistics KPIs. The authors employed causal networks and a cause-and-effect tree to establish links between metrics and analyzed deviation histograms of underlying factors and statistical correlation to identify root causes. The authors had the internal supply chain of an injection molding tool manufacturer as a case study. As a suggestion, it was mentioned that a continuous application of the root-cause analysis could establish permanent control loops and aid continuous improvement (CI).

Considering the discussion on the topic of emission-reduction goals, it is worth mentioning that performance indicators analysis is also crucial for organizational sustainability, as shown in Perello-Marín *et al.* (2022). The authors evaluated KPIs from companies in the car manufacturing sector and established links between KPIs and the Sustainable Development Goals and sustainable KPIs in the economic, environmental, and social spheres.

2.1.2 PMS Lifecycle

Despite the great attention of scholars and practitioners to designing KPIs and PMS (Globerson, 1985; Lohman *et al.*, 2004; Lucianetti *et al.*, 2019; Neely *et al.*, 1997, 2005), there are also other vital processes in a KPI life cycle (Matos *et al.*, 2020), namely: implementing (Keathley-herring, 2017), using, and reviewing KPIs (Braz *et al.*, 2011; Gutierrez *et al.*, 2015). These phases are represented in Figure 6 along with key objectives and goals within a business strategy. Changes in business strategies as well as in the PMS create challenges for the organization in terms of adaptation, which must be managed accordingly.

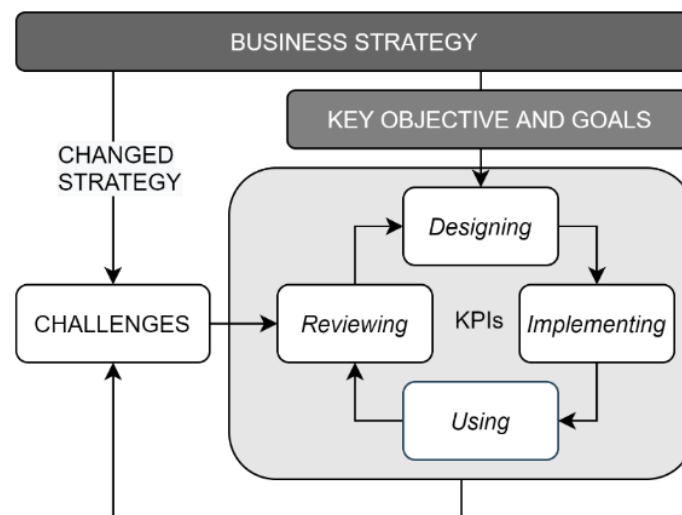


Figure 6 – The KPI lifecycle. Source: adapted from (Almström *et al.*, 2017).

The design phase of the PMS translates the views of the needs of customers and other stakeholders into strategic business objectives and KPIs (Neely *et al.*, 2005). The necessary and sufficient conditions and characteristics that PMS must meet are still a challenge that must be properly addressed by researchers to keep its developmental progress (Goshu and Kitaw, 2017). Regarding the implementation phase of KPIs, Neely *et al.* (1996) pointed out that the practical reasons frequently mentioned for implementing a PMS usually fall into five general categories: monitoring performance, identifying areas that need attention, intensifying motivation, improving communication, and strengthening responsibility.

As soon as the implementation begins, there are also fear, politics, and subversion: people begin to worry that the measures might expose their shortcomings, so they seek to undermine the credibility of the measures in different ways, even gaming the system (Neely *et al.*, 2000). On account of these issues, Gutierrez *et al.* (2015) specified some drivers to facilitate KPIs implementation: top management commitment, workshops to ensure common understanding among employees, and training sessions to promote proactive behavior.

Within the use phase of the KPIs, “assessing the implementation of the strategy” and “challenging the strategic assumptions” are the two main subdivisions (Nudurupati *et al.*, 2021). In other words, as the competitive environment of a company changes, the KPIs must be adjusted likewise (Almström *et al.*, 2017). In addition, new insights from experience gained during the lifecycle of KPIs should initiate a review of the set of KPIs.

The KPIs can be revised at four levels: i) revision of the strategy assumptions; ii) revision by changing KPI priorities, deleting, adding, and/or replacing them; iii) revising an individual KPI definition; iv) revising the KPI target value (Almström *et al.*, 2017; Bititci *et al.*, 2001; Neely *et al.*, 2000). According to Wouters and Sportel (2005), to improve a KPI it is important first to investigate which performance measures and reports exist and judge their usefulness. In their study, they found that developing many metrics simultaneously in a company has led to many “almost-finished” metrics with just a few completely implemented. Therefore, they suggested developing and implementing metrics one by one, considering how much time people have available for developing and implementing new measures, to quickly achieve tangible results (Wouters and Sportel, 2005).

Challenges faced by companies that wish to improve their KPIs are related to: decentralized reporting history; deficient insight into cohesion between metrics; uncertainty about what to measure; little communication between users and developers of performance measures; fragmented IT infrastructure; and data availability limitations (Gutierrez *et al.*, 2015; Lohman *et al.*, 2004). Indeed, many authors indicate that more empirical research is necessary to describe and understand the variety of implementation processes that organizations follow in different contexts (Braz *et al.*, 2011; Gutierrez *et al.*, 2015; Melnyk *et al.*, 2014; Sousa *et al.*, 2015).

2.1.3 Conclusions and Considerations

While there are several studies on what constitutes the quality of a KPI concerning its support for decision-making and management control and how to assess this quality (Braz *et al.*, 2011; Gutierrez *et al.*, 2015; Sousa *et al.*, 2015), more empirical research is needed to describe and understand the variety of implementation processes that organizations follow in different contexts (Melnyk *et al.*, 2014). It is

necessary to build an understanding of the precise definitions of existing KPIs, the rationales behind these, the data used, the limitations that users experienced with them and ideas that people are working on to improve the existing system, and how changes in information system can impact existing reports (Reis *et al.*, 2022). These gaps underscore the relevance of reviewing and improving current KPIs, as referred to in objective 1 of this thesis.

Regarding the KPIs relationship, although influential literature points to cause-and-effect relations as essential for the success of PMS, empirical support is minimal (Malina *et al.*, 2007; Rodriguez *et al.*, 2009). A key item on the performance measurement research agenda is the identification and development of predictive performance measures, *e.g.*, related to the statistical process control, to show within the company that something is going out of control before too much damage has been done (Neely *et al.*, 2005). Indeed, according to Kang *et al.* (2016), the intrinsic relationships of KPIs of different aspects of operation activities are still largely not understood, therefore they suggest studying KPIs for multi-stage production and applying them on the factory floor. In sum, the literature review on this topic allowed the identification of research opportunities related to KPIs relationships and predictive performance indicators, which connect to the identification and quantification of relationships between Performance Indicators, highlighting the relevance of objective 2.

2.2 Capability Indicators

Capability indicators are integrated in the steps iv) and v) of the Quality Planning process, described in Section 2.1, which refers to establishing objectives for product features and proving the manufacturing process is suitable to attend the former. Regarding the “quality gap”, changes in related processes would cause the so-called “operations gap” (Figure 2). Variation in a production process may occur due to variation in the process of making the product and variation in the measurement process, therefore, it is necessary to understand the capability of both the manufacturing process and the measurement process (Defeo, 2016). In other words, for answering the question "Am I able to detect this failure?", one should carry on a Measurement Process Capability study, and for answering "Am I able to produce without this failure?", a Process Capability study. The prime application of these concepts is during the planning of the operating processes for the evaluation of the ability of a process to produce products or services that meet specifications.

2.2.1 Production

Process Capability Indices (PCIs) attempt to predict a proposed production system's performance, *i.e.*, they serve as predictive performance indicators. By identifying key drivers of quality in the production

system, these indicators can serve as guidelines for designing production systems for quality (Inman *et al.*, 2013). Various capability indicators have been proposed over the years. There are studies for instance adopting them as a decision criterion for acceptance sampling plans, supplier selection, tolerance design, and other optimizations (Yum and Kim, 2011).

The behavior of a process is often described by a probability distribution. To assess its adequacy, the hypothesized distribution must be compared with the corresponding specifications, *i.e.*, the upper specification limit (USL) and the lower specification limit (LSL) (TC69, 2014). The higher the value of process variance in an operation (*i.e.*, the misadjustment), the higher the value of the failure rate and non-conforming parts. Figure 7 displays the effect of misadjustment on the failure rate.

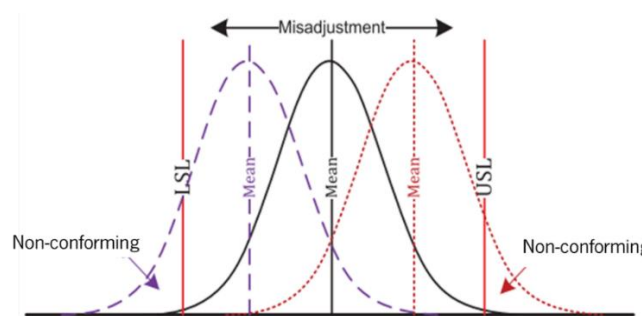


Figure 7 – Effect of misadjustment on failure rate. Source: adapted from Mohammadi *et al.*, (2015).

A capability indicator attempts to summarize the process performance and hence is a function of the process distribution and the corresponding specification. C_p is the process capability index, which is defined as the tolerance width divided by the process capability, irrespective of process centering (TC69, 2014). For quality characteristics following a normal distribution, it has been the convention to take the interval from $\mu - 3\sigma$ to $\mu + 3\sigma$ as the benchmark against which to measure the process capability, where μ is the mean and σ is the standard deviation. This is known as the six-sigma spread, which indicates the width of this interval. For a normal distribution, 99.73% of the values lie within this interval. The ratio of the specification interval (USL-LSL) to this six-sigma-spread, is known as C_p , which is expressed according to Equation (1).

$$C_p = \frac{(USL - LSL)}{6\sigma} \quad (1)$$

P_p is the process performance index which is defined as the tolerance width divided by the process performance, irrespective of process centering (TC69, 2014). It is, therefore, the measurement of the maximum capability or performance of a process, which would be achievable with an ideal centering of the process. Typically, this is expressed as the tolerance width divided by six times the sample standard deviation (s), as shown in Equation (2).

$$P_p = \frac{(USL - LSL)}{6s} \quad (2)$$

In contrast to C_p and P_p , the following critical indicators (*i.e.*, C_{pk} , P_{pk} , C_{pk-ST} and P_{pk-ST}) also include the process location.

C_{pk} is the minimum process capability index that accounts for process centering (TC69, 2014). It relates the scaled distance between the process mean and the closest specification limit (either USL or LSL) to half the total process spread. Assuming one quality characteristic of interest, depending upon the situation, the specification for this quality characteristic can be one of the following types:

- Unilateral (one-sided, only USL or only LSL, with target not specified)
- Bilateral (two-sided, with target specified)

Considering the process mean and standard deviation denoted by μ and σ , respectively, and assuming that the quality characteristic is normally distributed, the following formula, presented in Equation (3), presents the C_{pk} :

$$C_{pk} = \text{Min} \left\{ \frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma} \right\} \quad (3)$$

A major reason for quantifying process capability is to compute the process' ability to repeat itself and the ability of the process to meet its requirements (Defeo, 2016). For processes that are in a state of statistical control, a comparison of the variation spread of 6σ to the tolerance limits permits straightforward calculation of the percentage of the defective material. A centered process that is just meeting specification limits has thus a C_p of 1, then, 99.73 % of the values of the quality characteristic fall within the limits of the tolerance interval. For each one million parts, 2700 will be defective, *i.e.*, 2700 DPPM (defective parts per million), as shown in the first row of Table 4. Accordingly, the greater the C_{pk} , the smaller the number of nonconforming parts per million.

Table 4 – Capability process indices in defective parts per million.

Cpk value (if Cpk=Cp)	Variation	Meaning	Fraction nonconforming (DPPM)
$C_p=C_{pk}=1,00$	$\pm 3\sigma$	Tolerance is as large as the process variation range (99,73%)	2700
$C_p=C_{pk}=1,33$	$\pm 4\sigma$	Tolerance is about 1/3 large as process variation range (99,73%)	63,4
$C_p=C_{pk}=1,67$	$\pm 5\sigma$	Tolerance is about 2/3 large as process variation range (99,73%)	0,57
$C_p=C_{pk}=2$	$\pm 6\sigma$	Tolerance is 2 times as large as the process variation range (99,73%)	0,002

There is another important indicator called P_{pk} , the minimum process capability index, which indicates how the actual process is performed over a period, as indicated in Equation (4).

$$Ppk = \text{Min} \left\{ \frac{\mu - LSL}{3s}, \frac{\mu - LSL}{3s} \right\} \quad (4)$$

In sum, while Cpk is the potential of a process to meet a specification (*i.e.*, short term), Ppk is how the process actually did in the long term. Other differences can be seen in Table 5.

Table 5 – Differences between Process Capability indexes and Process Performance indexes.

Process Capability Indexes	Process Performance Indexes
Cp, Cpk	Pp, Ppk
"Short-term" capability	"Long-term" capability
Uses, " σ " as an estimate of standard deviation	Uses " s " as the standard deviation
Only within subgroup variation	Overall variation
Does not account for the shifts and drifts between subgroups	Does account for the shifts and drifts between subgroups
Potential capability	"As viewed by the customer" capability

2.2.2 Measurement

A measurement system is a system that measures a quality characteristic, and it usually consists of a gauge and an appraiser operating the gauge (Shirodkar and Rane, 2021). The term has usually different meanings in Germany and United States areas. In Germany, "measurement system" is only related to a measurement machine, without the influence of method and operator, while in the United States, it includes all measurement processes with the influence of method and operator, according to the Automotive Industry Action Group (AIAG). The AIAG is a North American entity that created recommendations and a framework for quality improvement.

Because the measurement system can be affected by various sources of variation, repeated readings on the same part do not yield the same, identical result, but vary due to common and special causes (American Society for Quality Control, 2010). Therefore, the actual process variation differs from the observed process variation, as depicted in Figure 8.

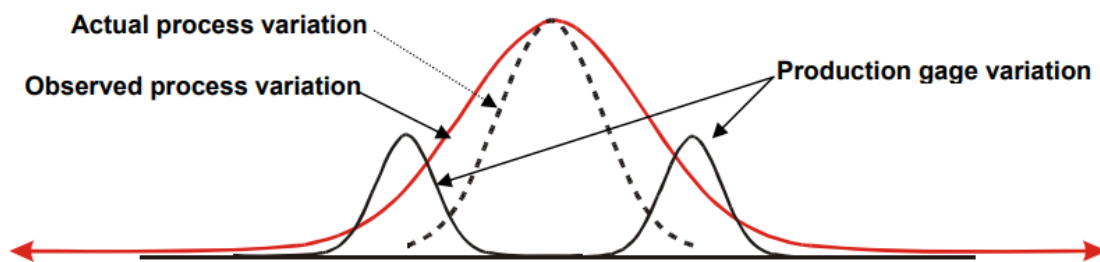


Figure 8 – Production gage variation. Source: (DaimlerChrysler. *et al.*, 2010).

Some of the characteristics of a measurement system that can be studied are Gage Repeatability and Reproducibility (GRR) (Shirodkar and Rane, 2021). Repeatability is the variability in repeated measurements of the given characteristic with the same operator, same gauge, same location, and same part, while Reproducibility represents more typical operating conditions where there is a variation from

multiple sources. Therefore, GRR allows describing the precision of the measurement system relative to the specification limits. Other important characteristics of a measurement system should also be studied, such as bias, linearity, and stability (American Society for Quality Control, 2010).

Considering produced features close to the specification limits, a reliable decision on whether the feature lies within or outside the specification cannot be made depending on the measurement uncertainty during an inspection (Mueller *et al.*, 2020), therefore, during the inspection operation, two types of error may be generated by the inspection procedure: type-I error, and type-II error. Type-I error indicates false rejections of the conforming quality, whereas type-II error indicates false acceptance of non-conforming quality, as shown in Figure 9 (Farooq *et al.*, 2017). The type-II error is also known as the consumer risk and is usually more serious (Shetwan *et al.*, 2011).

	Conforming	Non-conforming
Declared conforming	Ideal	Type-II error
Declared non-conforming	Type-I error	Ideal

Figure 9 – Type-I and Type-II errors.

As type-II error effects are felt by the customer, it can lead to significant losses associated with the loss of customer trust and loss of prestige. However, type-I errors also contribute to additional and unnecessary costs associated with the need to rework products that, in fact, are good (Hamrol *et al.*, 2020). For example, due to an unnecessary-repair cost incurred when identifying false defective-workstation-outputs, the overall process can be slowed down with a consequent extra cost (Galetto *et al.*, 2020). Therefore, the capability of the measuring device is very important since it predicates the correctness of the measured data. One of the methods for assessing the capability of the measuring device is by means of capability indices C_g and C_{gk} . These indices assess the measuring devices for skewness and repeatability. Skewness expresses the difference between the agreed reference value and average value of the test results, while the measurement repeatability expresses the conformity tightness between subsequent measurement results achieved under the same measuring conditions (DaimlerChrysler *et al.*, 2010).

The calculation of the C_g index is set by the relations expressed in Equations (5), (6), and (7).

$$C_g = \frac{0.2(USL - LSL)}{6 s_g} \quad (5)$$

$$s_g = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x}_g)^2} \quad (6)$$

$$\bar{x}_g = \frac{1}{n} \sum_{i=1}^n x_i \quad (7)$$

Where x_i is the i th measured value, n is the number of values, $\bar{x}_g$ is the mean of the measured values, s_g is the corrected standard deviation, USL is the upper specification limit and LSL is the lower specification limit.

For C_{gk} , the relation is expressed by Equation (8).

$$C_{gk} = \frac{0.1T - |\bar{x}_g - x_r|}{3s_g} \quad (8)$$

Where x_r is a reference value chosen in the middle of the measured dimension range, and T is the tolerance. To obtain a more effective and efficient inspection plan, it is possible to use more accurate inspection tools when detecting the nonconformities (with higher C_g and C_{gk}), decreasing the number of non-detected items that reach customers and, consequently, enhancing customer satisfaction (Karimi-Mamaghan *et al.*, 2020). Investment in inspection precision leads to reducing the monitoring or maintenance activities frequencies, and subsequently, the associated cost will also be reduced (Mirdamadi *et al.*, 2013). Precise machining equipment and accurate inspection tools provide better quality but are often more expensive to acquire and operate, therefore, it is necessary to balance all these costs to reach an economical optimum for the inspection plan (Tuominen, 2012).

2.2.3 Conclusions and Considerations

Loss of process capability, from the pre-production phase to an advanced stage of production can be seen as an indicator of process degradation, suggesting that non-critical quality variables may eventually become critical (Sousa *et al.*, 2018). Therefore, it is important to control the process through PCIs. Even within a single organization, PCIs may be used in relation to products and processes of many different kinds, each with its own specific requirements and problems. As a result, it is not really possible to give a coherent "worldview" of the state of "PCI art" (Kotz and Johnson, 2002). Indeed, as time has passed, assessments of usefulness and ways of interpreting PCIs have developed in a sometimes-confusing variety. Nevertheless, this section builds on the most widely used indicators within capability studies, summarized in Table 6, which are relevant to this thesis because of their relationship to the broader field of Inspection Planning. Particularly, the PCIs presented here serve as a background for the upcoming Section 4.3.2, which displays the PCIs studied by the Company where the case study for this thesis was carried out, within each defined Inspection Strategy. This topic is related with objective 3.

Table 6 – Capability indicators/indexes. Source: (DaimlerChrysler *et al.*, 2010; TC69, 2014).

Process	Question	Activity	Purpose	Object	Index of analysis		Description of Activity - AIAG	Description of Activity - ISO22514
Measurement	Am I able to detect this failure?	Measurement machine capability analysis	Short-term estimate of measurement system variation	Measurement Machine	Cg	Index of repeatability	Measurement system analysis	Measurement system capability
					Cgk	Index of bias and repeatability		
		Measurement process capability analysis	Long-term estimate of measurement system variation	Machine Method Operator	GRR	Gage repeatability and reproducibility		Measurement process capability
Production	Am I able to produce without this failure?	Production machine capability analysis	Short-term analysis of machine performance	Measurement Machine	Cm	Machine capability index	Machine capability	Machine capability
					Cmk	Minimum machine capability index		
		Production process capability analysis and Statistical production process assurance	Short-term analysis of machine-related influences.	Measurement Machine Operator Material Method Environment	Cp	Process capability index	Process capability and Statistical Process Control	Process capability and Statistical Process Control
					Cpk	Minimum process capability index		
			Pp		Process performance index			
			Ppk		Minimum process performance index			
Long-term analysis of all possible process-related influences, from a larger, more representative period for the series production.								

2.3 Quality Costs

The measurement of quality performance has both non-financial and financial dimensions. PMSs including non-financial indicators offer a more comprehensive picture of performance drivers, because they measure performance areas beyond the financial results (Dossi and Patelli, 2010). Examples include customer satisfaction and process quality. Financial measures, on the other hand, can be exemplified by monetary performance indicators, such as scrap cost, warranty cost, and inspection cost - all money-related measures (Farooq *et al.*, 2017). Quality cost is a type of financial measure, and it represents activities to prevent failures, activities of appraisal, and the costs associated with defective items, converting such activities and defects into financial indicators. Moreover, quality costs can be identified, measured, and improved, and should be considered an important metric for any manufacturing industry as a specific set of performance indicators. Quality costs can be divided into four general categories (Gryna, 1998):

- *Internal Failure Costs* represent the deficiencies discovered before delivery, which are associated with the failure (nonconformities) to meet explicit requirements or implicit needs of customers. Examples are costs related to scrap, rework, replacement, and failure analysis.
- *External Failure Costs* are costs associated with deficiencies that are found after a product is sent to the customer, including lost opportunities for sales revenue. Examples are warranty charges, litigation, and liability, complaint handling, returns, rework on returns, lost sales, penalties, and allowances.
- *Appraisal Costs* are incurred to determine the degree of conformance to quality requirements, such as raw material inspection, in-process inspection, document review, evaluation of stocks, final inspection, inspection of material and services, and quality audit.
- *Prevention Costs* are those incurred to keep failure and appraisal costs to a minimum, for example, product and service design and redesign, process quality planning, training, and quality circles, process design, supplier relations, audit and screening, and preventive maintenance.

Internal and external failure costs can be understood as the cost of poor quality, whereas appraisal and prevention costs refer to the cost of good quality (Ashraf *et al.*, 2015). The total CoQ is the sum of these two costs. From a QMS and PMS perspective, it is key to be able to estimate and foresee quality costs. Particularly, the CoQ approach serves to model the quality of a system through the costs incurred in providing that quality. As such, it offers a way to reconcile manufacturers' two conflicting objectives:

minimizing cost and maximizing quality of conformance (Mohammadi *et al.*, 2013). As quality costs have many components and can be relatively hard to foresee, several CoQ approaches have been proposed in the literature in an attempt to capture these costs. CoQ approaches can be divided into five generic groups: Prevention, Appraisal and Failure (PAF) model, Crosby's model, opportunity cost model, process cost model, and ABC model (Schiffauerova and Thomson, 2006).

2.3.1 Quality Cost Approaches

Juran (1951) initiated the concept of quality costing and the economics of quality. Feigenbaum (1956) later proposed the now widely accepted quality cost categorization of PAF costs. Most CoQ approaches are based on the PAF classification. The basic assumptions of the PAF model are that investment in prevention and appraisal activities will reduce failure costs and that further investment in prevention activities will reduce appraisal costs. On the other hand, Crosby (1979) sees quality as "conformance to requirements" and defines the CoQ as the sum of the price of conformance and the price of non-conformance. The cost categories of Crosby (1979) model are similar to the PAF scheme. The price of conformance is the cost involved in assuring that things are done right the first time, which includes actual prevention and appraisal costs, while the price of non-conformance is the money wasted when work fails to conform to customer requirements, usually calculated by quantifying the cost of correcting, reworking, or scrapping, which corresponds to failure costs.

In the process approach to quality costing, a.k.a. Process Cost Model, the total process cost is regarded as being the sum of the cost of conformance and the cost of non-conformance, as in Crosby's model. The cost of conformance is the whole of process costs made when producing a "first time right" product (*i.e.*, no rework or other non-standard operations are necessary to make the product conform to specifications), whereas the cost of non-conformance are all costs associated with a process operated under other conditions than those required to produce first-time-right products. These costs can be measured at any step of the process (Porter and Rayner, 1992). Process cost modeling goes beyond a simple tool to measure the financial gap between the actual performance of a process and its potential performance and must contribute to the quality improvement process itself.

Activity Based Costing (ABC) is an approach to the classification of costs based on their processes and activities. It was developed by Cooper and Kaplan (1988) as an alternative method that can be used to classify costs. ABC method first performs the splitting of the work into significant activities. Then, it quantifies the consumption and causality links between the activities considering three drivers: resource, cost, and activity. Indeed, the ABC is an alternative approach that can be used to identify, quantify, and

allocate quality costs among products, and therefore, helps to manage quality costs more effectively (Schiffauerova and Thomson, 2006). In addition, ABC systems consider value-added and non-value-added activities, and its long-term goal is to eliminate non-value-added activities and to continuously improve processes, activities, and quality so that no defects are produced. The difficulty to identify and evaluate the drivers remains the main drawback of the ABC method (Mirdamadi *et al.*, 2013).

Finally, the Opportunity (or Intangible) Cost approach considers losses related to customers who refuse to buy a product because of problems they have had in the past, and losses due to consumers who turn away from a product because of publicity about a recall or lawsuit are examples of an intangible quality cost (Batoul and Ansari, 1987). Therefore, Batoul and Ansari (1987) added two more dimensions to the four-dimension quality-cost concept introduced by Feigenbaum (1956): cost of quality design and cost of inefficient utilization of resources.

2.3.2 Quality Costs Assessment

The true accuracy of costs depends on the underlying data, therefore, knowledge of how these data are obtained and the purposes for which they are used can provide good indications of the precision that can be reasonably sought or expected (Dale and Plunkett, 1991). Mirdamadi *et al.* (2013) describes three methods for performing cost assessment: analogue, parametric, and analytical.

Analogue Cost Estimating is a technique used to estimate a cost based on historical data for an analogous system or subsystem and seems impossible to automate in an optimization process.

Parametric method consists in linking the costs to other quantifiable parameters by using mathematical relationships. It begins with the identification and collection of all data considered as influent on the cost indicator. The next step tries to find mathematical patterns linking the performance indicator to the parameters selected in the previous step, and finally, the last step consists of to validate the mathematical model by facing it to several well-known cases (Mirdamadi *et al.*, 2013).

Finally, *analytic* approaches are considered as all methods that aim to evaluate the cost of a solution (or another relevance indicator) by analyzing the activities needed during its whole lifecycle (Mirdamadi *et al.*, 2013). Mirdamadi *et al.* (2013) cite as an example the ABC method, which they modified in their paper to evaluate the costs of the activities in different states of a product life cycle (*i.e.*, tolerancing, process, and inspection planning). Process-based cost models are also an example of an analytical approach, which Zaklouta and Roth (2012) used to assess the assembly line fixed costs for each examined inspection strategy of their work.

Quality costs are the “measurement system” to compare the different inspection strategies with each other (Oppermann *et al.*, 2003). The cost of the quality processes, including inspection, should be less than the cost of poor quality. Therefore, as with any other business investment, it is necessary to calculate the total return on investment (ROI), or being specific in this case, the “total return on investment in inspection (ROII)”, as termed by Verna *et al.* (2022). There are many works proposing inspection strategy models based on quality costs. These strategies usually propose and investigate a model for the allocation of an economically appropriate level of inspection effort by finding a balance among different cost components related to the inspection process (Shetwan *et al.*, 2011). Each model differs regarding the means to achieve this objective. In the following topics, cost elements of the surveyed literature about quality costs of inspection strategies are presented, divided into inspection costs, internal failure costs, and external failure costs.

2.3.2.1 Inspection Cost

Considering the PAF classification of CoQ, inspection costs are related to the appraisal category. There are many costs to consider when designing an inspection process. Some examples are those involved in setting up the inspection process, machines (measuring equipment, inspection machines), labor, space, and the time spent. According to Sousa and Nunes (2019a), these inspection costs can be estimated with historical data, which is typically available in companies. This is confirmed by Farooq (2019), where the author states that although the data from the company did not include specifically the cost of the inspection strategy, it was possible to calculate it based on the data received, hence, to calculate the cost of alternative inspection strategies.

In the inspection strategy models, some authors considered inspection cost as a sum of fixed and variable costs (Farooq *et al.*, 2017; Shetwan *et al.*, 2011), wherein the fixed cost is related to a fixed amount of capital for preparing inspection tools, and variable costs depend on the number of inspected products and the quality characteristics to be inspected (Karimi-Mamaghan *et al.*, 2020), or on the costs associated with different scenarios (Farooq *et al.*, 2017; Lim *et al.*, 2015; Shetwan *et al.*, 2011). In scenarios where it is necessary to conduct a reinspection, for example, costs can be greater because it corresponds to unplanned work, that can cause work overtime costs and production delays (S. Sousa and Nunes, 2019a).

2.3.2.2 Internal Failure Cost

Internal Failures represent the defects discovered before delivery of the product to the customer. The costs associated with internal failures vary depending on several factors, such as (1) the failure rate, (2) the reaction plan regarding the defective products, and (3) the different types of defects and the different stages at which defects are first detectable.

1) The failure rate:

A defect rate or failure rate is the proportion of defects in all the produced items. In the literature, some works assumed a certain constant and deterministic failure rate for each stage, however, the defect rate may change periodically. Since a production system suffers from deterioration (such as aging, corrosion, or abrasion), one could expect the production system to shift from an in-control state (stable process) to an out-of-control state (unstable process), at which point it should start to produce nonconforming items (Shih and Wang, 2016). Figure 10 exemplifies the difference between these in- and out-control states.

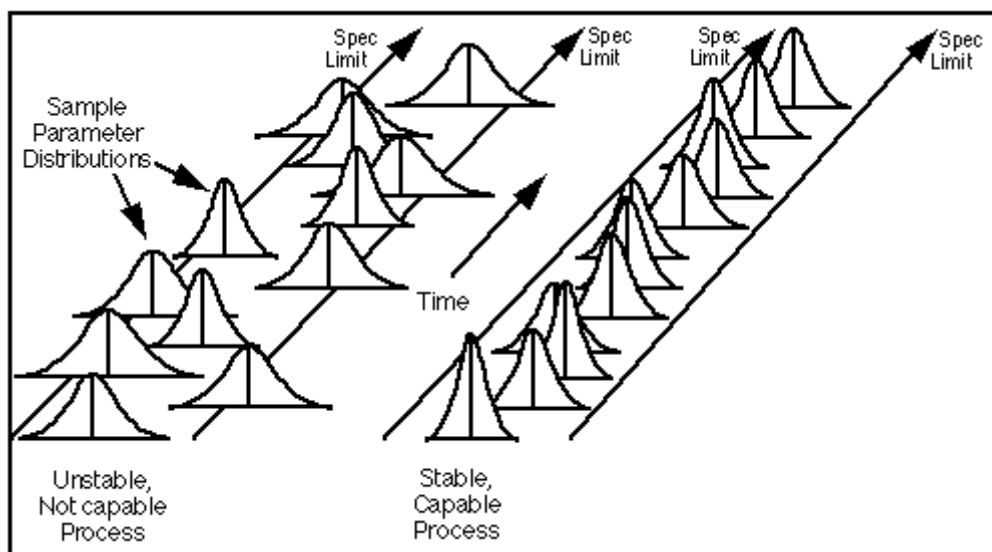


Figure 10 – Unstable process vs. stable process. Source: Available online at <https://www.npd-solutions.com/proccap.html>.

The failure rate also depends, for example, on the quality investment (Hsieh and Liu, 2010), changes in supplier, specification errors, damaged material (Veatch, 2000), and misadjustment of an operation (Karimi-Mamaghan *et al.*, 2020; Mohammadi *et al.*, 2015). Therefore, some authors assumed a random failure rate under a specific distribution, or with specified probabilities to occur, or who considered the effect of failure rate as uncertain.

In the case where Farooq *et al.* (2017) developed the model, neither defective products nor false positives on the assembly line were counted, making it difficult to estimate the quality of the non-compliance rate. Therefore, a range of the defect rate was defined through the Design of Experiments, a branch of techniques used to determine the individual and interactive effects of various factors that can influence the output results of measurements (Anderson and McLean, 2018). Veatch (2000), who proposed a model to determine when inspection of the received material is appropriate using lot inspection, considered the defect rate in a distribution built from two years of data using Bayes' empirical (Maritz, 2018). The failure rate distribution introduced much more variability in the number of defects than if the defect rate were fixed at its average.

Unlike Farooq *et al.* (2017) and Veatch (2000), who somehow based the defect rate on real data instead of assuming a random one, other authors assumed that different internal failures may occur with specified probabilities at different stages in the overall process (Hamrol *et al.*, 2020; Lim *et al.*, 2015; Mirdamadi *et al.*, 2013; Shetwan *et al.*, 2011; Tuominen, 2012). Tuominen (2012) modeled different occurrence probabilities for different defect types. Hsieh and Liu (2010) assumed a defective rate at the production site changing linearly in terms of quality investment. Crostack *et al.* (2005) proposed a simulator in which the information about a characteristic, its distribution or conformity rate, and the specifications can be defined, and the simulator can model these distributions dynamically including the deviation of the distribution.

Some authors considered that each station of the production line may stay at either in-control condition or out-of-control condition, which may lead to different nonconforming product rates (Nunes and Sousa, 2019). The system starts in the in-control state in which the production process is stable with a low defect rate and is capable of producing reliable products. As time goes by, the system may switch to the out-of-control state in which the production process is undependable, and the defect rate gets worse. Zhu *et al.* (2016) used the Markov chain method (Douc *et al.*, 2018) to calculate the steady-state probability distribution. Oppermann *et al.* (2003) performed a simulation of the quality costs in case of variable defect rate around the average value in a range of 5%. Tirkel (2016) made a sensitivity analysis considering variations of 1%, from 0.96 to 0.99, regarding the probability of a lot staying in control and deteriorating to out-of-control.

By reducing the misadjustment/process variance and bringing the process mean closer to its target, the number of products that are prone to extra costs of rework/repair (internal quality costs) also reduces, therefore, tolerance allocation ensures a certain level of product quality, minimizing the costs. According

to (Mirdamadi *et al.*, 2013), some approaches for tolerance allocation are based on the Taguchi loss function, a mathematical function describing the (monetary) loss to society that occurs whenever a product or a component quality characteristic does not meet its specifications (Taguchi *et al.*, 2007). One could incorporate the Taguchi loss function in place of the explicit failure costs, eliminating a complex process to convert the quality cost into a monetary metric, as done by Mohammadi *et al.*, (2015), Karimi-Mamaghan *et al.*, (2020) and Abdul-Kader *et al.* (2010). Lim *et al.* (2015) alert that doing so is necessary an optimization method that can handle the non-linearity of the loss function.

2) The reaction plan for defective products:

Depending on the waste management strategy, the handling of rejected parts usually considers the costs of reworking, replacing, and scrapping a non-conforming product. The question of whether to inspect a final or semi-finished product can be asked after every manufacturing operation. If the answer is yes, then after inspection, the item(s) may be deemed as being either conforming or nonconforming. Conforming items will then go on to the next operation. There are several possible outcomes for nonconforming items: (i) they may be replaced with a conforming item which is then sent for the next processing operation; (ii) they may be sent back for rework/repair; or (iii) they may be simply scrapped. The decision about the appropriate outcome depends on the associated cost and knowledge of whether the non-conformity is repairable/re-workable or not.

The internal failure cost related to reworking a defective unit depends on the average time of repair, the average cost of materials, and equipment usage Sousa and Nunes (2019a). When the cost of a unit is very low, usually the rework is worthless, as in Farooq *et al.* (2017), where they did not consider rework for the rejected non-conformed units. In Zaklouta and Roth (2012), however, they consider the station requirements, fixed cost, and labor allocations at the inspection and rework steps, and the costs were calculated based on the expected number of products per assembly being inspected or reworked and the associated time needed relative to the available station time. In addition, the repair may be treated as perfect when the parts repaired are considered defect-free, or imperfect, when the repaired parts are assumed to have the same total defect rate as parts that are inspected and accepted (Veatch, 2000). Replaced parts may incur the same costs and have the same defect rates as original parts (Veatch, 2000).

3) The different types of defects:

Since quality rarely depends on a single characteristic, there may be different types of defects, which must be considered when applying costs. Different types of defects cause different consequences and some defects, even though not fulfilling the original specification, can be overlooked if the consequence

is insignificant. On the other hand, some defects can cause serious consequences and are therefore critical (Tuominen, 2012). In addition, defects must also be divided into different stages at which they are first detectable. Tuominen (2012), for example, simplified the possible defects into five main types and considered the different stages at which defects are first detectable. However, there are some works that did not consider the cost of internal failure as defect-dependent (*e.g.*, Shetwan *et al.* (2011)).

2.3.2.3 External Failure Cost

It is cheaper to fix a problem at the source than in subsequent processes, the worst case being when the end customer detects the problem, in which stage it is considered as an External Failure Costs. From the viewpoint of the top management, the primary objective of the inspection is to prevent external failure cost (Shiokawa and Ishii, 2019). When calculating costs associated with external failures, one should consider several factors, such as the probability of a defective product reaching the customer and the different types of defects. Tuominen (2012) studied four companies and reports that their calculation methods for estimating the costs of external failures were slightly different, *e.g.*, some included lost production volumes, and others calculated only direct rework or penalty costs.

There are two types of costs involved in external failures: tangible and intangible costs. Tangible costs are material, transportation, labor, production, and testing of the product at the customer facility. Intangible costs are loss of goodwill, company image, and customer dissatisfaction (Farooq *et al.*, 2017). While the first type has measurable costs, the intangible costs, according to (Abdul-Kader *et al.*, 2010), are hard to estimate, if not impossible.

Although there are many measurable items to consider, most of the reviewed papers represented them as aggregated, identifying as warranty cost, penalty cost, or quality loss cost. For example, Mohammadi *et al.* (2015) and Karimi-Mamaghan *et al.* (2020) translate the cost of nonconforming products shipped as warranty cost in their model, without evidence on how this cost may be obtained. Hsieh and Liu (2010) assume in their study that market prices, penalties on defective components and post-sale costs for defective products are given values. According to Sousa and Nunes (2019a), external failure costs may be defined in contracts or estimated based on historical data. On the other hand, Hsieh and Liu (2010) claim that varying values of penalties and post-sale costs for defective products will certainly influence the strategic interaction of the supplier and the manufacturer, hence leading to the possibility of redesigning a contract based upon these values to influence both members' equilibrium strategies in a collaborative way.

Other authors, instead of presenting external failure costs as aggregate values, explicitly consider the items of external failures in their models. Davrajh and Bright (2013) determined it as replacement costs to the customer, considering a 'significance factor' the customer was required to enter through specification of a product rating, and assuming the selling price of the product as determined through market related research. Shetwan *et al.* (2011) contemplate replacement and repair costs, where replacement considers the sale price and repair deals with the direct cost of materials to repair a defective unit. Besides repair and replacement, Hamrol *et al.* (2020) add also the possibility that a defective product may not affect its intended use and is not noticed by the user, in other words, the product may be considered fitness for use.

As already stated, different types of defects result in different costs of internal failure, and this relationship also extends to external failures. Some authors suggest estimating the occurrence probability of external failures through FMEA (Failure Mode and Effect Analysis) method (Arndt and Lanza, 2016; Mirdamadi *et al.*, 2013). An external failure can occur if a related internal failure has occurred and was not detected at any checkpoint or may be triggered by a combination of internal failures rather than a single one. That is, some failures might occur in the absence of defects; *e.g.*, as a result of unrecognized design deficiencies that do not appear as defects (Lim *et al.*, 2015). Although Lim *et al.* (2015) mentioned this possibility, neither his model nor any other included it.

Indeed, the appearance of external defects is not constrained only by the inspection of quality characteristics during a given manufacturing process, but may also be due to its supplier process, to poor product design, improper handling during logistical operations, material contamination, product packaging, product storage, and so on. Therefore, the costs resulting from external failures must be balanced not only with the appraisal costs but also with the costs incurred to avoid them, *i.e.*, prevention costs. In addition, a review of the IP is required whenever new types of external defect types appear, to control and avoid them.

A summary of the surveyed literature about quality costs assessment for inspection strategies is presented in Table 7.

Table 7 – Literature overview of aspects considered within quality costs assessment for inspection strategies.

References	CoQ approach	Inspection Cost	Internal failure costs					External failure costs			
			Failure rate	Reaction Plan			Types of defects	Fitness for use	Rework	Replacement	Loss of quality
				Rework	Scrap	Replacement					
(Abdul-Kader <i>et al.</i> , 2010)	General	Fixed	Variable	x	x	x	One				x
(Azadeh <i>et al.</i> , 2015)	General	Variable	Variable	x		x	One				x
(Hamrol <i>et al.</i> , 2020)	General	Variable	Variable				One				
(Crostack <i>et al.</i> , 2005)	Process Cost Model	Fixed	Variable	x	x		One				
(Davrajh and Bright, 2013)	PAF	Fixed	Fixed				Multiple			x	
(Farooq <i>et al.</i> , 2017)	PAF	Fixed	Variable		x		One				x
(Foumani <i>et al.</i> , 2020)	General	Fixed	Variable	x	x		Multiple				x
(Galletto <i>et al.</i> , 2020)	General	Variable	Variable	x			Multiple				
(Hamrol <i>et al.</i> , 2020)	PAF	Fixed	Variable	x	x		Multiple	x	x	x	
(Hsieh and Liu, 2010)	General	Variable	Variable				Multiple				x
(Jafari-Marandi <i>et al.</i> , 2019)	Process Cost Model	Fixed	Variable			x	One				x
(Karimi-Mamaghan <i>et al.</i> , 2020)	General	Variable	Variable		x		Multiple				
(Lim <i>et al.</i> , 2015)	General	Variable	Variable	x			Multiple				x
(Mohammadi <i>et al.</i> , 2015)	General	Fixed	Variable		x		Multiple				x
(Nunes and Sousa, 2019)	PAF	Fixed	Variable	x	x		Multiple				x
(Oppermann <i>et al.</i> , 2003)	Process Cost Model	Fixed	Fixed	x			Multiple				
(Shetwan <i>et al.</i> , 2011)	General	Fixed	Variable	x	x		One		x	x	
(Shih and Wang, 2016)	General	Variable	Variable	x			One				x
(Sousa and Nunes, 2019b)	PAF	Fixed	Variable	x	x		One				x
(Sousa and Nunes, 2021)	PAF	Fixed	Variable	x	x		One				x
(Tansurat and Chattinnawat, 2019)	General	Variable	Fixed	x	x	x	One				x
(Tirkel, 2016)	Process Cost Model	Variable	Variable				One				
(Tuominen, 2012)	Crosby s Model	Variable	Variable	x	x		One				x
(van Volsem <i>et al.</i> , 2007)	General	Fixed	Fixed	x			Multiple				
(Veatch, 2000)	General	Fixed	Variable		x	x	One				x
(Verna <i>et al.</i> , 2022)	General	Fixed	Fixed			x	One				x
(Zaklouta and Roth, 2012)	PAF	Fixed	Fixed	x	x	x	Multiple				x
(Zhu <i>et al.</i> , 2016)	General	Fixed	Variable	x	x		One				x

2.3.3 Conclusions and Considerations

The financial dimension of Quality Performance is well explained by the CoQ approach. CoQ measurement enables companies to derive benefits such as reduction of the total cost, CI, prioritization of improvement projects, customer satisfaction, improved profitability, financial performance, market share, and competitiveness. These benefits account for the importance of planning the measurement and management of CoQ elements (Psomas *et al.*, 2021).

CoQ assessment is under-researched and has significant potential to be explored further (Psarommatis *et al.*, 2020). More work needs to be done to shed light on the impact of several factors on the measurement of CoQ. The determination of detailed elements of quality cost categories, as operationalized constructs, is a gap in the quality cost literature that researchers should fill (Psomas *et al.*, 2021). This is related with objectives 3 and 4 of this thesis, because the inspection plans could be assessed and improved based on their impact in the total CoQ.

A challenge encountered during the CoQ measurement is in identifying elements of the four dimensions (prevention, appraisal, internal failure, and external failure). Once these data are inputs for the inspection strategy models, this difficulty ends up affecting the implementation of the models, as pointed out by (Nunes and Sousa, 2019). Moreover, the validity and generality of a cost assessment made for a specific situation are limited to its industrial framework as the input parameters are contextual (Mirdamadi *et al.*, 2013).

Since quality cost data are expressed in figures, which are sometimes treated by people as being very precise, there is a danger that quality costs may give an impression of precision that is not warranted (Dale and Plunkett, 1991). Actual cost accuracy depends on the underlying data. Knowledge of how these data are obtained and the purposes for which they are used can provide good indications of the precision that can be reasonably sought or expected (Dale and Plunkett, 1991). Table 8 discusses how the performance indicators related to quality costs may be gathered.

Although the estimation of cost model variables may not be straightforward in real cases, prior knowledge of the production process and historical data can help (Verna *et al.*, 2022). To utilize quality cost data in control processes, the information must be both gathered and reported to the relevant people in a timely manner. It is necessary to have an assessment method that is flexible, sensitive, fair, and fast (Sousa and Nunes, 2019a). If these requirements can be met, quality cost data can be a powerful source of information for quality management.

Likewise, CoQ assessment concerning Inspection Strategy Models (ISM) has significant potential to be explored further (Dimitrantzou *et al.*, 2020; Psomas *et al.*, 2021). There is a lack of studies on economic analysis or detailed impacts on CoQ that justifies necessary investments in processes (Saihi *et al.*, 2023).

Table 8 – Discussion on indicators for quality cost assessment.

Nomenclature	Comments
Estimated average unitary cost of not delivering a unit according to plan/customer order	It depends on the probability of having defective units at the customer; the probability of sending defective units to the next process; the cost of repairing defective units after sending defective units to the next process; and the consequences of arriving defective products to the customer. It can be estimated based on customer contracts, on historical data of costs related to defective units based on similar products and customers (Sousa and Nunes, 2019a), and based on the unit costs of customer complaints based on complaint reports (Hamrol <i>et al.</i> , 2020).
Estimated average cost of passing a defective unit to the next process	This factor can be estimated based on customer contracts and historical data on costs related to defective units based on similar products and customers (S. Sousa and Nunes, 2019a). The source for this data may be expert knowledge (Hamrol <i>et al.</i> , 2020).
Estimated average cost of repairing a defective unit	It depends on the average time of repair, the average cost of materials, and equipment usage (S. Sousa and Nunes, 2019a). Calculations carried out in the planning department may be used (Hamrol <i>et al.</i> , 2020).
Estimated average unitary re-inspecting cost	It can be estimated as stated for the average unitary inspection cost but can be greater because it corresponds to unplanned work, may use overtime, and can cause delays in production (Sousa and Nunes, 2019a).
Estimated average unitary inspection cost	This cost can be estimated based on the average time of inspection and the average cost of materials/equipment usage. These can be estimated with historical data, typically available in the company (Sousa and Nunes, 2019a). To determine these costs, calculations carried out in the planning department may be used (Hamrol <i>et al.</i> , 2020).
Estimated proportion of false defectives given by the measurement system	For calibrated equipment, there is a maximum error under specific conditions of measurement. Based on the probability distribution of products it can be estimated the proportion of false defectives. For non-calibrated equipment, RandR studies can be made to estimate the precision of the measurement system and obtain an estimation of the measurement error (Sousa and Nunes, 2019a). Estimation can be done with the use of databases holding the results of the MSA analysis, expert knowledge, or the results of specially conducted tests (Hamrol <i>et al.</i> , 2020).
Estimated proportion of false non-defectives given by the measurement system	Similar to the estimated proportion of false defectives given by the measurement system. A company can define product specifications tighter than initial customer specifications so that errors are forced on one side of the specification. This can make the false defectives given by the measurement system increase while reducing the false non-defectives (S. Sousa and Nunes, 2019a). Estimation can be done with the use of databases holding the results of the MSA analysis, expert knowledge, or the results of specially conducted tests (Hamrol <i>et al.</i> , 2020). Zaklouta and Roth (2012) assumed the type I equal to the type II error, while Sousa and Nunes (2021) considered type I twice as much as type II.

The review has shown the estimation of quality costs by budgeting inspection and failure costs. When such budgeting is performed separately for different elements of CoQ, without simultaneous consideration, the resulting solutions only sub-optimize the overall CoQ. Conducting inspections may affect the detection of internal failures and, in turn, the related internal and external failure costs (Lim *et al.*, 2015). Therefore, it is necessary to consider all the salient elements of CoQ simultaneously to determine an optimal plan for prevention and appraisal activities.

Therefore, this review of quality cost models and assessment provides the basis for the development of a new model to select the quality control strategy that minimizes quality costs, which is related to the fourth objective of this thesis.

2.4 Inspection

This section characterizes the specific activities for achieving manufacturing quality: inspections. A quality inspection plan sets out a schedule of inspections that must be carried out at critical control points within a process to verify whether things are progressing the way they should be. Quality inspection activities are often classified as non-value-adding processes; however, they are essential to support value-adding processes and need to be thoroughly planned (Kukulies *et al.*, 2014).

Their planning, a.k.a. Inspection Planning (IP), is the activity of designating the stations at which inspection should take place and providing those stations with the means for knowing what to do, plus the facilities for doing it (Defeo, 2016).

2.4.1 Inspection Planning

Inspection Planning (IP) encompasses the establishment of many arrangements, such as: 1) relevant inspection characteristics (which), 2) inspection point (when), 3) inspection type (how), 4) inspection extent (how much), 5) inspection place (where), 6) inspection personnel (who), and 7) inspection equipment (whereby) (Colledani *et al.*, 2014; Karimi-Mamaghan *et al.*, 2020; Liangsiri, 2007).

Besides these seven aspects already well-recognized within the literature, IP also relates to and depends on other factors, such as 8) the planning of the test and measurement control and the definition of capability/uncertainty studies (S. Sousa *et al.*, 2018), and 9) defect handling decisions (Soares *et al.*, 2021). These factors are interrelated because they impact each other. For example, the Measurement Process Capability (*i.e.*, IP arrangement 8) influences the inspection decision equipment (*i.e.*, IP arrangement 7, whereby) as it estimates the possible errors of false rejections of the conforming quality and false acceptance of non-conforming quality (errors type I and II), which will influence the failure rate and failure costs (Farooq *et al.*, 2017).

Furthermore, it is also necessary to determine the 10) data-recording systems related to the IP, as consistent and repetitive information properly documented is essential for the success of quality management (Gookins, 1999). These IP arrangements are shown in Table 9 in relation to examples of aspects to consider in the product development stage.

Table 9 – Inspection Planning arrangements linked to examples of considerations in the Development Stage.

#	IP arrangements	Considerations in the Development Stage
IP1	Determining characteristics to inspect (Which)	Explicit customer requirement, safety requirement, legal requirement, product functionality requirement
IP2	Determining inspection time (When)	Incoming inspection, process inspection, final inspection
IP3	Determining inspection type (How)	Continuous, discrete
IP4	Determining inspection quantity (How much)	100%, sampling inspection, no inspection
IP5	Determining inspection location (Where)	External inspection, in a laboratory, in a measuring room, in the production line
IP6	Determining inspection personnel (Who)	External personnel, quality assurance personnel, manufacturing personnel, automated inspection
IP7	Selection of inspection equipment (Whereby)	Measuring or testing equipment
IP8	Planning of the Production and Test Measurement Control	Machine and process capability studies
IP9	Determining reaction plans	Rework, scrap, replace, reinspect
IP10	Determining inspection documentation and data recording system	Preparation, evaluation, recording, and displaying of data. Control plan, test instructions, work instructions

Source: Adapted from (Basse *et al.*, 2015; Defeo, 2016; Farooq *et al.*, 2017; Gookins, 1999; Karimi-Mamaghan *et al.*, 2020; Liangsiri, 2007; Soares *et al.*, 2021; Sousa *et al.*, 2018)

Certain features are more critical than others because they are critical for the functioning of the product. They are called key product characteristics, key characteristics, or Critical to Quality (CTQ) characteristics, and are outputs from a process that are measurable on, within, or about the product itself (Defeo, 2016). Their determination (IP1) contemplates multiple sources, according to (Defeo, 2016), including customer requirements, industry and government standards and regulations, the need to protect human safety and the environment, the need to avoid side effects to stakeholders, employees, or to a neighboring community, product Failure Mode and Effect Analysis (FMEA) and Process Failure Mode and Effect Analysis (PFMEA), and results of the design of experiments.

To specify if a product has met the designed CTQ characteristics, it is necessary to perform activities such as testing, detection, and certification. For doing so, the production process is interrupted, and products are checked whether they can meet standard specifications, therefore nonconforming products may (if possible) be reworked to bring them into conformance or be completely scrapped (Mohammadi *et al.*, 2015). A common consequence of wrong characteristics identification in the IP is the occurrence of no-fault-found failures made visible during the use phase of the product (Colledani *et al.*, 2014). In other words, the identification of the CTQ characteristics is essential for the overall success of IP since all characteristics which are neglected might cause fatal damages to tools, personnel, products, or

customers and, on the contrary, unreasonable inspections cause inefficient test steps and increased process complexity (Colledani *et al.*, 2014).

Since quality rarely depends on a single characteristic, consideration has also been given to the analysis of multivariate capability. Considering multiple variables simultaneously is important, particularly when those variables are correlated (Polhemus, 2017). Once there are many potential critical variables and their monitoring and control imply non-added value activities, IP must identify the relative importance amongst product variables to select adequate control mechanisms (Sousa *et al.*, 2018).

The inspection time decision (IP2), in a far-reaching view considering the influence of the supply chain in a product quality, may occur in several phases of the production. Defeo (2016) mentions the most usual:

- on receipt of goods from suppliers, usually called incoming inspection, supplier inspection, or inbound inspection;
- following the setup of a production process to provide added assurance against producing a defective batch, called setup approval;
- during the running of operations, called process inspection (in a multistage manufacturing system one must define whether or not to inspect a final or semi-finished product at each processing workstation (Shetwan *et al.*, 2011));
- prior the delivery of goods from one processing department to another, usually called lot approval or tollgate inspection;
- prior to shipping completed products to storage or to customers, usually called finished-goods inspection or outbound inspection;
- before performing a costly or irreversible operation;
- at natural peepholes in the process.

The IP3 is related to the different approach depending on whether the characteristics are attributes or variables. For attributes, the product is in a state of good or bad, and the gaging is on a basis of pass or no-pass, while for variables, the product can be evaluated along a scale of measurement (Defeo, 2016).

The amount of inspection (IP4) to decide the acceptability of a lot, which can vary from no inspection to sampling, to 100% of inspection. The inspections can be external to the production process, in a laboratory, in a measuring room, or within a production line (IP5). They can be either subjective, performed by workers, *e.g.*, external personnel, quality assurance personnel, manufacturing personnel, automated inspection (IP6), or automatic, performed by inspection machines, the whereby decision (IP7).

The IP7 depends on the inspection tools and machining equipment and their specific features (*e.g.*, cost, time, detection/failure rate, and capability) (Karimi-Mamaghan *et al.*, 2020).

Even though everything is defined, since a production system suffers from deterioration (such as aging, corrosion, or abrasion), one could expect the production system to shift from an in-control state to an out-of-control state, at which point it should start to produce nonconforming items (Shih and Wang, 2016). Therefore, it is important to plan the Production and Test Measurement Control (IP8) to ensure consistency in the inspection process over time (Sousa *et al.*, 2018) and to quantify the total impact of uncertainties and variations in the process (Mirdamadi *et al.*, 2013).

The determination of reaction plans for the encountered defective units (IP9), *i.e.*, whether to rework, scrap, replace, and reinspect, has a great impact on the failure costs. This selection can be supported by a decision-making model that assesses cost effects related to the quality and productivity of each destination option. The steps, facts and actions involved in the decision can be systematically modelled, including the identification and accounting of effects on quality and productivity (Soares *et al.*, 2021).

The last IP arrangement is to determine the inspection documentation and data recording system (IP10). The inspection documentation encompasses documents such as the control plan, test instructions, and work instructions. The data recording system is essential for successful quality control. Considering inspection-related performance indicators, such as customer complaints and defective units within a process, it is possible to monitor these variables and trigger the need for corrective action within the inspection process whenever one or more substantial changes occur (Sousa and Nunes, 2021). By considering quality inspections throughout the entire product lifecycle, interdependencies between inspection activities can be identified and turned into valuable information (Kukulies *et al.*, 2014). Indeed, Madrid *et al.* (2016) argued that inspection data is eventually used to improve production in progress, rather than reused to optimize product quality during design activities. They claim inspection data is not used at its full potential due to informational, technical, and organizational barriers (Madrid *et al.*, 2016).

Zaklouta (2011) points out that manufacturing process improvement often coincides with a need to change inspection strategy choice, thereby indicating that manufacturing process and inspection strategy selection should not be performed independently of each other. Therefore, a collaborative IP, integrating both the inspection plan and the production plan, is critical to improve profit (Shiokawa and Ishii, 2019). Moreover, to achieve a more comprehensive model that leads to the minimum nonconformity of products and high availability and performance of the production system, it is also suggested the integration of the IP with maintenance planning (Karimi-Mamaghan *et al.*, 2020).

Although many works are supporting the IP arrangements presented, there is a lack of studies reporting the practices for the design of inspection and control methods in companies, and to which degree the CoQ is considered within the IP.

2.4.2 Inspection Improvement

During the product and process development stage, IP is defined based on customer requirements and the optimal allocation of the company's internal resources (Kukulies *et al.*, 2016). During the manufacturing stage, based on the dynamic quality situation of the manufacturing system, a revision of the established IP is necessary to (i) ensure the product quality to the customer, (ii) reduce failure costs, *e.g.*, caused by ineffective or inefficient inspection activities (Kukulies *et al.*, 2016), and (iii) to reduce appraisal costs, *e.g.*, by adjusting inspection processes that are obsolete due to sufficient process capability or by eliminating redundant testing activities (Kukulies *et al.*, 2014). Moreover, new customer orders, new product designs, new process changes, new regulations, and so on, are all occasions for scrutiny by the quality engineers, who have to adjust inspection plans accordingly (Gookins, 1999), *i.e.*, IP must be continually evaluated over time to be adapted according to the Company's CI process. Given IP interlinkages and complexity, Table 10 exemplifies possible changes in the Manufacturing Stage related to each one of the IP arrangements (not exhaustive examples list).

When facing internal and external disturbances, companies can stabilize and even increase the performance of their business processes by implementing closed and quantifiable quality control loops, also known as feedback loops (Kukulies *et al.*, 2016; Schmitt *et al.*, 2012). Even though the advantages of feedback mechanisms are renowned in quality management, the design of quality control loops is ordinarily not optimized in practice (Schmitt *et al.*, 2012). Likewise, inspection processes in manufacturing systems are often considered as inflexible static output resulting from the initial planning process during product and process development (Kukulies *et al.*, 2016). Consequently, there is a lack of revision of inspection activities as part of quality control (Filz *et al.*, 2021).

Aiming at overcoming this question, Kukulies *et al.* (2016) proposed a holistic approach for IP covering the systematic change and adaption process of inspection activities during the manufacturing stage based on the engineering change management (ECM) paradigm and Knowledge Management, however, their theoretical approach was not applied in a case study, and they claim it is necessary to analyze whether efforts spent on planning and adapting ongoing quality inspection processes are justified in terms of quality cost reduction. Verna *et al.* (2021) developed an Inspection Strategy map, a tool to support designers in choosing the most appropriate inspection strategy from an effectiveness and cost

standpoint. Filz (2021) proposed a framework for systematic planning of quality inspection strategies separated into five steps: generation and assessment of inspection strategies, selection, and implementation of the best strategy as well as monitoring and review. Ahmed *et al.* (2021) discussed how to enhance IP in the early stages of product development by using previous knowledge related to products that have features and functions in common.

Table 10 – Possible changes of IP arrangements during the Manufacturing Stage.

#	IP arrangements	Possible changes in the Manufacturing Stage
IP1	Determining characteristics to inspect (Which)	Add inspection characteristics
		Adapt inspection characteristics
		Remove inspection characteristics
IP2	Determining inspection time (When)	Stop incoming inspection
		Include finished product inspection
IP3	Determining inspection type (How)	Change to inspection by attributes
		Change to inspection by variables
IP4	Determining inspection quantity (How much)	Suspension of inspection
		Increase/decrease sample size
		Define dynamic sampling
IP5	Determining inspection location (Where)	Relocate inspection to different manufacturing sections
		Relocate to in-line/off-line inspection
IP6	Determining inspection personnel (Who)	Change personnel
		Expand/reduce personnel
		Qualify personnel
IP7	Selection of inspection equipment (Whereby)	Change inspection equipment
IP8	Planning of the Test Measurement Control	Reanalysis when the characteristic specifications changed
		Reanalysis when unexpected process results and/or defective parts increase
		Reanalysis when commissioning new, relocated, or reconditioned production equipment
IP9	Determining reaction plans	Change the defect handling decision
IP10	Determining inspection documentation and data recording system	Edit Control plan

In sum, it is underscored that when facing internal and external disturbances, companies can stabilize and even increase the performance of their IP, which can be achieved through a CI approach. Although the advantages of feedback mechanisms are renowned in quality management, the design of quality control loops is not common in practice.

2.4.3 Inspection Strategy Models

Quality control is one of the major concerns in manufacturing systems and quality managers always deal with complex and multifaceted decisions about allocating inspection resources and facilities most efficiently and economically (Azadeh *et al.*, 2015). Since each individual decision within the IP affects decision situations in its following stages, the overall decision situation can be characterized as a multi-stage decision problem (Basse *et al.*, 2015). More and tighter inspection will normally induce a higher product quality – in terms of meeting product specifications – but will also result in higher costs of appraisal and prevention costs. Quantifying this trade-off and establishing ways of finding an economic optimum is considered an *Inspection Strategy Model* (ISM) in this thesis.

There are many works proposing ISM in different sectors and different products, for example in the automotive industry (*e.g.*, vehicle induction braking system in (S. Sousa and Nunes, 2019a)) and in the consumer goods manufacturing industry (*e.g.*, aerosol can in (Farooq *et al.*, 2017)). In addition, there are also ISM for serial multistage manufacturing systems and for markets with high levels of customization (Davrajh and Bright, 2013; Jafari-Marandi *et al.*, 2019) and models considering a supply chain context. Table 11 shows a list of works that model inspection strategies, their respective objectives, and applications.

Table 11 – Inspection Strategy Models within literature.

References	Objective	Application context (if applied)
(Abdul-Kader <i>et al.</i> , 2010)	To develop an optimization model considering the cost of adjusting manufacturing processes with the aim of reducing or eliminating rejected pieces	Seat manufacturing company
(Arndt and Lanza, 2016)	To describe an approach to enable globally operating companies to efficiently plan their efforts for quality control in their respective production network taking the specific site roles into account	Global network
(Azadeh <i>et al.</i> , 2015)	To find optimal inspection policies in serial multistage production processes to minimize total inspection cost where the cost components are described using fuzzy numbers	A serial multistage manufacturing system
(Crostack <i>et al.</i> , 2005)	To investigate and evaluate the inspection strategies with respect to quality, cost, and time using the “quinte” simulator	Manufacturer of mobile hydraulic products manufacture of stub shafts
(Davrajh and Bright, 2013)	To develop a model to determine when to perform an inspection at a given inspection station	Markets with high levels of customization / reconfigurable inspection equipment
(Farooq <i>et al.</i> , 2017)	To evaluate inspection strategies using the COC approach to find a global optimum by developing an intermediate scenario between single and double acceptance sampling strategies	Consumer goods manufacturing industry/three-piece tin plate aerosol can
(Foumani <i>et al.</i> , 2020)	To find a suitable trade-off between inspection time and internal and external quality costs to increase reliability benefits	Stochastic scheduling of a two-machine flow shop robotic cell with controllable inspection times
(Hamrol <i>et al.</i> , 2020)	To propose an approach to the planning and optimization of quality inspections within a multistage manufacturing process based on quality costs and the value added to the production process by inspections.	Surgical scissors
(Jafari-Marandi <i>et al.</i> , 2019)	To propose a cost-driven decision-making framework to formulate costs of the spatial distribution of microstructural defects and the corresponding control actions, based on in-situ melt pool images	Laser-based additive manufactured process (thin wall fabrication)
(Karimi-Mamaghan <i>et al.</i> , 2020)	To develop an agile integrated inspection-machining planning model to simultaneously make inspection and machining decisions considering cost, quality, and time	Solid frame with 15 different quality characteristics in a car manufacturing company
(Lim <i>et al.</i> , 2015)	To model a mixed integer linear programming applicable to a prevention-appraisal-failure framework	Lamp manufacturing and an order entry process
(Mirdamadi <i>et al.</i> , 2013)	To investigate the adaptability of a modified activity-based costing model in evaluation of cost regarding the activities in tolerance allocation, process planning and IP	Automotive industry (cover intermediate shaft part)
(Mohammadi <i>et al.</i> , 2015)	To develop an optimization framework for process IP based on a mixed-integer linear programming model that tries to make a trade-off between cost and quality.	Solid frame with 15 different quality characteristics in a car manufacturing company
(Nunes and Sousa, 2019)	To provide a stochastic dynamic programming model for designing the quality control plan in a manufacturing process, which allows obtaining the desired level of control with the lowest cost.	Multi-stage manufacturing systems

References	Objective	Application context (if applied)
(Oppermann, Sauer, and Wohlrabe, 2003)	To describe quality cost models to compare the behaviors of different technological processes and of different inspection strategies (no inspection/statistical process control/100% inspection)	Surface-mount technology production line (for printed circuit board)
(Shetwan <i>et al.</i> , 2011)	To develop optimal and heuristic solution to allocate control stations to manufacturing systems	Serial multistage manufacturing system
(Shih and Wang, 2016)	Quality control policy is proposed for determining the optimal production run length, where the production system is subjected to random deterioration from an in-control state to an out-of-control state and in which the elapsed time until the process shift is assumed to be a general shift distribution	-
(Shiokawa and Ishii, 2019)	Propose a method of collaborative IP that integrates the inspection plan with the production plan in the production sector	-
(Sousa and Nunes, 2019)	To propose a model to select the control strategy that minimizes quality costs considering parameters uncertainty	Vehicle induction braking system
(Tansurat and Chattinnawat, 2019)	Designing a three-echelon supply chain model including multiple suppliers, multiple manufacturers with multi-stages inspection, and multiple customers	Supply chain example
(Tirkel, 2016)	Proposes an approach for modeling the efficiency of in-line inspection in semiconductor wafer fabrication	Semiconductor wafer fabrication
(Tuominen, 2012)	To compare different inspection strategies and for creating an understanding of the structure of the costs of bad quality in automotive manufacturing	Front subframes (a.k.a. engine cradles) or instrument panel supports (a.k.a. cross car beams).
(Veatch, 2000)	Model to determine when inspection of incoming material is appropriate	Thermal printer for digital photographs
(Zaklouta and Roth, 2012)	Analytic COC framework inspection strategy scenarios	Welded automotive assemblies
(Zhu <i>et al.</i> , 2016)	To develop an optimal inspection policy for the multi-station manufacturing system subjected to quality shifts to minimize total quality-related cost.	Mobile phone shell production

These strategies usually propose and investigate a model for the allocation of an economically appropriate level of inspection effort by finding a balance among different cost components related to the inspection process (Shetwan *et al.*, 2011). Each model differs regarding the means to achieve this objective. The CoQ assessment of these models had already been presented in Section 2.3. Herein, some considerations about the approaches used are presented into three categories: objective function, solution technique, and sensitive analysis.

2.4.3.1 Objective function

Generally, different inspection strategies consider cost and quality with a dual objective of minimizing costs and increasing quality. A way to do this is attaching costs to quality of conformance by using the CoQ approach, transforming this dual objective into one objective of cost of quality minimization, allowing easier comparison of the manufacturing process and inspection strategy options (Zaklouta and Roth, 2012). In addition to efficiency (in terms of cost) and effectiveness (in terms of quality), Karimi-Mamaghan *et al.* (2020) state that an inspection plan should be also agile (in terms of time). In fact, inspection time plays a major role in the total manufacturing costs in manufacturing processes (Shetwan *et al.*, 2011). For this reason, some models include time as an optimization goal (Arndt and Lanza, 2016; Crostack *et al.*, 2005; Karimi-Mamaghan *et al.*, 2020). However, even in articles that do not explicitly address the issue of time as an optimization objective, it may be somehow embedded within the cost of quality assessment.

2.4.3.2 Solution technique

The solution approaches are classified into problems that can clearly be formulated and fully mathematically solved (Farooq *et al.*, 2017; Jafari-Marandi *et al.*, 2019; Sousa and Nunes, 2019a; Tuominen, 2012; Veatch, 2000), and problems that need further means. Table 12 presents the solution techniques used in ISM considering quality costs.

Mohammadi *et al.* (2015) state that some models in the literature use programs such as simplex and dynamic programming-based optimization algorithms for providing an optimal solution for small-size problems, but as most of the real-world problems have large sizes, solving them by mathematical programming approaches would take considerable computational time. Nevertheless, to be relevant in practice, the model must be easy to use in terms of computational complexity, so the computer systems necessary must be based on simulations without the need for extraordinary computer and software requirements (Sousa and Nunes, 2019b). Therefore, as the problem considers more parameters, the

speed of estimation regarding the computation time required to solve the problem becomes evident and it is necessary to take this into account when choosing the solution approach.

Table 12 – Solution Techniques.

Reference	Solution technique	Sensitivity Analysis
(Abdul-Kader <i>et al.</i> , 2010)	Mathematical modelling	No
(Azadeh <i>et al.</i> , 2015)	Particle swarm optimization	Yes
(Crostack <i>et al.</i> , 2005)	Simulation	No
(Davrajh and Bright, 2013)	Mathematical modelling/simulation	No
(Farooq <i>et al.</i> , 2017)	Mathematical modelling	Yes
(Foumani <i>et al.</i> , 2020)	Stochastic bi-objective optimization	Yes
(Hamrol <i>et al.</i> , 2020)	Mathematical modelling/added value	Yes
(Hsieh and Liu, 2010)	Non-cooperative game models	No
(Jafari-Marandi <i>et al.</i> , 2019)	Multi-Layer Perceptron/ Self-Organizing Map/Self-Organizing Error-Driven Neural Networks /Fluid Genetic Algorithm	No
(Karimi-Mamaghan <i>et al.</i> , 2020)	Differential Evolution algorithm and a machine-learning based Iterated Local Search, integrated with the Taguchi Loss Function and Monte Carlo methods	Yes
(Lim <i>et al.</i> , 2015)	Integer and linear programming	No
(Mirdamadi <i>et al.</i> , 2013)	Modified Activity-Based Costing model	Yes
(Mohammadi <i>et al.</i> , 2015)	Mixed-integer mathematical programming integrated with the Taguchi Loss Function and Monte Carlo methods and genetic algorithm to obtain near-optimal solutions	Yes
(Nunes and Sousa, 2019)	Dynamic programming	No
(Oppermann, Sauer, Wohlrabe, <i>et al.</i> , 2003)	Mathematical modelling	Yes
(Shetwan <i>et al.</i> , 2011)	The heuristic method with local search	Yes
(Sousa and Nunes, 2019b)	Mathematical modelling/Monte Carlo method	Yes
(Tuominen, 2012)	Mathematical modelling	Yes
(Veatch, 2000)	Mathematical modelling	Yes
(Zaklouta and Roth, 2012)	Mathematical modelling/discrete event simulations	Yes
(Zhu <i>et al.</i> , 2016)	An integrated algorithm combining heuristic rule and tabu search	Yes

Tirkel (2016) generated a set of Pareto optimal solutions by applying an aggregated objective function. Davrajh and Bright (2013) formulated mathematical equations and compared model-based inspection criteria strategies using simulations performed in *Labview*. Lim *et al.* (2015) formulated the model as a zero-one polynomial program, which can be solved directly using a mixed-integer nonlinear programming solver or in a mixed-integer linear programming solver after performing an appropriate linearization step, and they also compared the speed of estimation regarding the computation time required in each solution.

Crostack *et al.* (2005) used a simulator called Quinte, and due to its limitations (there is no animation for the simulation, only limited process distributions can be modelled, and it is difficult to modify or enhance components or functions), they also showed its possible integration with the commercial simulation software Arena®.

Shetwan *et al.* (2011) study developed a heuristic method with local search and suggested biologically inspired optimization algorithms as interest for further study, which were used by Mohammadi *et al.*

(2015) and Karimi-Mamaghan *et al.* (2020). Mohammadi *et al.* (2015) applied a genetic algorithm to obtain near-optimal solutions and Karimi-Mamaghan *et al.* (2020) developed a novel hybrid metaheuristic algorithm based on a differential evolution algorithm and a machine-learning-based iterated local search algorithm. Both also integrated their algorithms with the Taguchi Loss Function and Monte Carlo methods. The proposed model and solution algorithm proposed in Karimi-Mamaghan *et al.* (2020) were also validated through a set of experiments against optimal solutions and benchmarked against four approaches and two learning-based metaheuristics.

2.4.3.3 Sensitivity analysis

The sensitivity of the assessment is the “ability of the method to integrate and take into account the variations of the input data” (Mirdamadi *et al.*, 2013). Variations of the input data, even seemingly insignificant, must be considered, and sensitivity analysis will reveal the real impact.

Several authors have considered sensitivity analysis in their work to discuss the robustness of the optimal solution regarding the variations of the design variables and environmental parameters. Karimi-Mamaghan *et al.* (2020), for example, investigated the sensitivity of their objective functions regarding several input parameters: process misadjustment, dispersion, the capacity of machines and inspection tools, production time, production and inspection rates, breakdown rate and retrieve time. Incorporating uncertainty into the model results in different inspection decisions compared to deterministic decisions (M. Mohammadi *et al.*, 2015). It is also important to consider uncertainty and disruption in the planning phase of an inspection-machining process (Karimi-Mamaghan *et al.*, 2020).

Lim *et al.* (2015) conducted a sensitivity analysis to examine the impact of the changes in cost parameters by changing a single cost factor in increments of 0.01 while holding the remaining costs constant, concerning prevention costs, inspection costs, and external failure costs for the two applications they performed. Tirkel (2016) also made a sensitivity analysis considering variations of 1%, from 0.96 to 0.99, regarding the probability of a lot, staying in-control and deteriorating from in control to out-of-control.

Sousa and Nunes (2019) carried out a sensitivity analysis of the variation effect of 10 parameters in the cost function, and as a result, two of them had the greatest effect: the estimated proportion of defective units in a controlled process and the estimated average cost of passing a defective unit to the next process.

Tuominen's (2012) model depends on estimated costs and probabilities, being subject to inaccurate input data, so they tested four different scenarios with different estimation errors: all the probabilities were given a 500% error, and cost estimates were given a 500% error, assuming that the non-fatal defect types cause no consequence costs, and assuming that the rare but fatal defect types could not be

prevented. They claim that the model is effective in supporting the decision-making process, as their sensitivity analysis reveals that the cost savings the model presents are apparent in the different inspection strategies.

Sensitivity analysis helps in identifying and implementing actions that will help mitigate adverse effects. Veatch (2000) model, for example, analyzes 350 externally supplied parts to a manufacturer of the thermal printer to determine when inspection of incoming material is appropriate and through the sensitivity analysis, the corrective action was considered critical because, without it, it would not be worth inspecting any of the 350 parts. In the case of Zhu *et al.* (2016), the sensitivity analysis helped justify the advantage of their proposed inspection strategy over the current outgoing inspection strategy in mobile phone shell production. In Zaklouta and Roth (2012), the sensitivity analyses revealed tradeoffs between the welding process, internal failure costs, and external failure costs, helping to determine the optimal inspection strategy. Farooq *et al.* (2017) illustrate the sensitivity analyses in 3-D, plotting conformance rates and external failure premium, and state that a contour plot can be utilized as a management tool for industry executives to select the most suitable and cost effect inspection strategy.

2.4.4 Conclusions and Considerations

This chapter identified various theoretical issues related to IP, IP improvement, and models employed by scholars by defining inspection strategies based on quality costs, *i.e.*, ISM.

Any solid inspection strategy, which includes all the proposed IP arrangements, will have to consider the needs of various stakeholders and make reasonable trade-offs between its objectives (Mandroli *et al.*, 2006). These stakeholders may be from different companies and different departments within each company, and the coordination and cooperation among them in achieving the right balance between these conflicting goals is seen as a key issue for success (Colledani *et al.*, 2014). Nevertheless, it is claimed that IP is often derived from a weak information basis and therefore relies on the experience of the quality planner (Filz *et al.*, 2021) or is based upon traditions, standards, and procedures that do not provide the optimum balance of assurance versus cost and time (O'Connor, 2001). In addition, there is a lack of in-depth analysis of the practices regarding these topics in real cases.

In addition, it was underscored that when facing internal and external disturbances, companies can stabilize and even increase the performance of their IP, which can be achieved through a CI approach (Kukulies *et al.*, 2016). This can be accomplished by implementing closed and quantifiable quality control loops, such as the PDCA cycle (Peças *et al.*, 2021). Although the advantages of feedback mechanisms are renowned in quality management, the design of quality control loops is not common in practice (Schmitt *et al.*, 2012).

While the more and tighter inspection will normally induce a higher product quality in terms of meeting product specifications, it will also result in higher costs of appraisal and prevention costs. By these lines, models for inspection adaption considering the cost of quality have been proposed extensively within the literature, *e.g.*, to find the most economical quality control option between 100% inspection, samples, or no control. However, most authors do not report the practical adoption of such models in the industry. This lack of practical application may be due to the complicated mathematical apparatus of the models (Hamrol *et al.*, 2020), or because the models simplify the problem too much by neglecting realistic conditions of industrial environments (Azadeh *et al.*, 2015), for example considering deterministic conditions while the manufacturing processes are generally stochastic. In addition, a lack of knowledge on how to measure the high number of parameters/variables of the models, including the quality cost elements, is considered a critical element that inhibits the use of these models (Hamrol *et al.*, 2020; S. Sousa and Nunes, 2021). Indeed, inspection processes in manufacturing systems are often considered as inflexible static output resulting from the initial plan made during Product and Process Development (Kukulies *et al.*, 2016).

Academic research on 'real-world' implementation of IP considering quality costs is still limited. It is complicated to consider all the different user requirements and contextual variables needed in real manufacturing processes (Hamrol *et al.*, 2020). Overall, the models underestimate or ignore some aspects of the real problem, which can result in the computation of either unrealistic or unfeasible solutions, or solutions that do not capture domain-related characteristics (Rezaei-Malek *et al.*, 2018). It is generally difficult to obtain a model of an optimization problem that reflects all aspects of the real decision-makers' difficulty. The errors and the uncertainty associated with the estimated values of process variables influence the accuracy of results (S. Sousa and Nunes, 2019a). Therefore, it is important to consider the sensitivity of the assessment, designing global robust inspection strategies by considering uncertainty and vagueness inherent in a real environment.

Methods and solution techniques have become more and more advanced and sophisticated, with increased computer capabilities and sophisticated simulation models playing a major role in this respect. One could wonder why are so many models built and so few used. Models have to be useful and usable in order to be employed by intended beneficiaries, accordingly, they should be judged on the basis of their utility in aiding decisions relative to alternative procedures.

Because different production systems have different dynamics and features, extensions of the common models would certainly be an important future research direction to provide an opportunity for testing new solution methodologies and algorithms in various applications.

On the other hand, introducing additional aspects may also reduce the scope of applications, and can potentially increase the difficulty of implementing and using the model. In other words, the gain in performance is often obtained at the expense of the simplicity and flexibility of the methods. While the contributors reviewed in this Section have made a good start, the research in IP considering CoQ aspects has not yet reached the level where it can have widespread applicability in industry.

As the models require estimations, the errors and the uncertainty associated with the estimated values of process variables and the costs influence the accuracy of the results. Actual cost accuracy depends on the underlying data, consequently, knowledge of how these data are obtained can provide good indications of the precision that can be expected. However, most articles do not make it explicit.

In sum, the ISM available within the literature find limited use in practice because they are context-specific, or the model assumptions do not hold.

Therefore, a research opportunity is to investigate the actual practices related to the definition of the inspection and quality control methods and quality costs (Objective 3) to evaluate the applicability of recent models to real cases and to convert them into a relevant and accessible form for a particular context. Considering the opportune business environment of an automotive electronics industry - given its increasing complexity of products and processes, rigorous quality control mechanisms, and elaborate quality and productivity systems, this thesis aims to cover this gap by investigating how and which type of changes in the IP take place at Manufacturing Stage, providing empirical evidence of inspection changes and their influencing factors in an organization, as well as a basis to develop a model to select the inspection strategy that minimizes quality costs in the context of Industry 4.0 (Objectives 3 and 4).

3 Research methodology

This chapter provides details on the rationale behind the research design employed, including the philosophical position, the reasoning approach, the methodological choice, the research strategies, the data-collection procedures, and the data analysis process. All decisions concerning the research design are justified based on the existing literature and on assumptions made on the way of inquiring into the world. The chapter begins with an overview of the research process in Section 3.1, which is the frame of reference for the methodological design of the thesis. The philosophical position on the nature of reality and the assumptions surrounding various ways of inquiring into the nature of the world are outlined in Section 3.2. The research design is then described in detail in Section 3.3, starting with the methodological choice, followed by a description of a set of elements to achieve coherence in the research design.

3.1 Research Onion

The “research onion” shown in Figure 11 summarizes the steps taken and choices made (indicated by red circles) to meet the research objectives, from the philosophy to the data collection and analysis methods employed in this thesis. These methodological choices are described next.

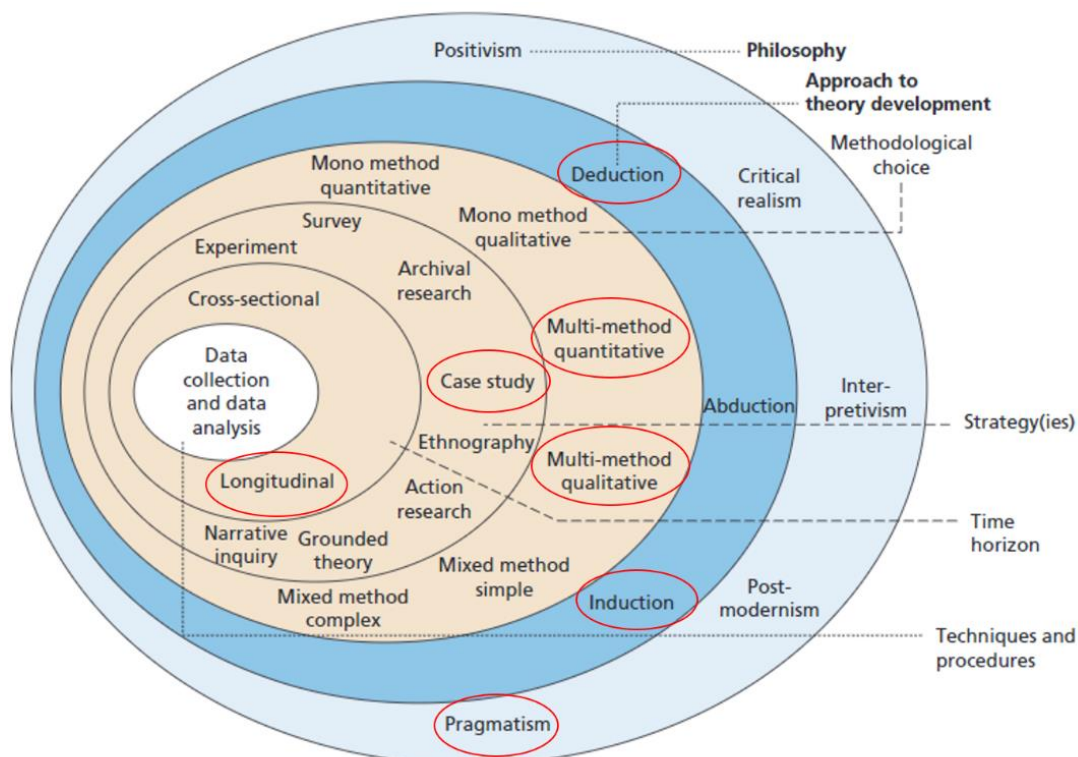


Figure 11 – The research onion (choices in red). Source: Adapted from Saunders *et al.* (2016).

3.2 Research Philosophy and Approach

Pragmatism involves employing a research design that is best suited to answer a research question. It contrasts the approaches taken by positivism or interpretivism philosophies, which are two mutually exclusive paradigms about the nature and sources of knowledge. Alternatively, it recognizes that there are many different ways of interpreting reality and argues for the integration of different and multiple methods (Saunders *et al.*, 2016). In this way, it is well aligned to a research approach that is both deductive and inductive. In the former, the researcher starts with a hypothesis and works her way towards rejecting or not rejecting it, while in the later, the researcher gains understanding of a problem and develops a theory based on it (Saunders *et al.*, 2016).

During different stages of the present research, the researcher was required to make use of a variety of methods to collect qualitative and quantitative data in order to grasp the complexity of the research problem, which are detailed in the following sections.

3.3 Research Design

3.3.1 Methodological Choices

To create a fruitful approach to data collection, a multi-method approach was employed, as indicated by the red circles in Figure 12. A multi-method approach can be defined as the employment of two or more different methods or styles of research within the same study. The decision to adopt this approach addresses many of the normative ideals for scientific research and reduces skepticism about the research results, leading to an increase in credibility (Hunter and Brewer, 2015).

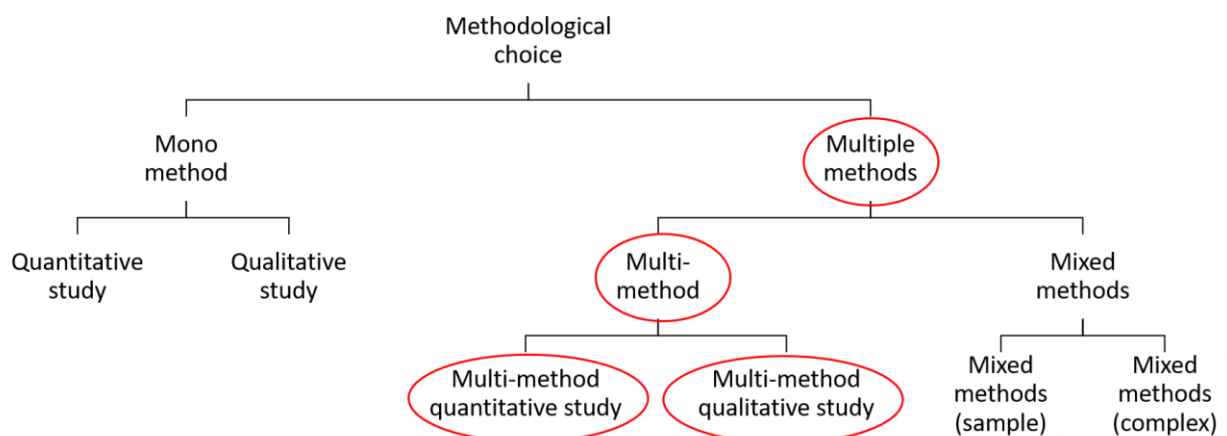


Figure 12 – Methodological choice: multiple-methods approach. Source: Adapted from Saunders *et al.* (2016).

There are many methods and combinations of methods available for use. The choices in multi-method research design involve i) which methods can be mutually adopted and ii) how the adopted methods are implemented simultaneously during the research process (Hunter and Brewer, 2015).

This research was designed in five main phases, as shown in the next Section 3.3.2. The use of multiple methods occurred during data collection and analysis, as well as in the interpretation of the findings (Saunders *et al.*, 2016). The details of the strategies applied in each phase are explained next and summarized in Table 13.

3.3.2 Research Strategies, Techniques, and Procedures

Before reaching the core of the research onion, the adjacent layer depicts the time horizon over which the researcher undertook her research, *i.e.*, a longitudinal study. The purpose of a longitudinal study is to examine changes in attitude, behavior, process, or phenomenon over a period of time. Data used in the longitudinal analysis is time-series data, which can be seen as a series of different cross-sections within a specific range.

The 'case' in case study research may refer to many types of case subjects, *i.e.*, a person, a group, an organization, an association, a change process, and an event (Saunders *et al.*, 2016). A case study strategy can incorporate multiple cases, and after choosing the ones to be studied and determining the boundaries of the study, it is necessary to delineate how to assess the dynamics of the topic being studied within its setting or context (Saunders *et al.*, 2016). In this thesis, within an organization as the subject of the case study, many issues were analyzed as embedded cases, *e.g.*, KPIs, production lines, and a CI event.

The research strategy adopted in this study consists of five phases. Research strategy may be defined as "a plan of how a researcher will go about answering her or his research question" (Saunders *et al.*, 2016, p. 186). Given the nature of each phase objective, different data collection techniques were used accordingly.

Table 13 shows the respective objectives, research methods, and main outputs of each research phase.

Table 13 – Research phases objectives, methods, and outputs.

Research phases	Objectives	Research methods	Main outputs
Phase I: Literature review	Identification of research gaps.	Literature review, systematic search	Chapter 2
Phase II: PMS revision and improvement	Review and improvement of current KPIs.	Research Strategy: Case Study Data collection: Document analysis, observation, interviews, secondary data, descriptive statistics	Sections 4.5, 4.6 and 5.1
Phase III: KPIs relationships	Identification and quantification of relationships between Performance Indicators.	Research Strategy: Case Study Data collection and methods: Document analysis, observation, interviews, secondary data, multivariate statistical techniques	Sections 4.6 and 5.2
Phase IV: Current practices related to Inspection Planning and Inspection Improvement.	Identification of practices for Inspection Planning	Research Strategy: Case Study Data collection and methods: Document analysis, observation, interviews, secondary data	Section 4.2, 4.3, 4.4, and 5.3
	Identification of practices for Inspection Improvement.	Research Strategy: Case Study Data collection and methods: Document analysis, participant observation, unstructured interviews, secondary data	Section 4.8 and 5.3
Phase V: Model development	Definition of indicators that allow quantifying the cost of quality of a given product.	Research Strategy: Case Study Data collection and methods: Document analysis, secondary data, interviews (CoQ assessments and model validation)	Sections 4.7 and 5.4
	Development and application of a model to select the control strategy that minimizes quality costs.	Research Strategy: Case Study, computational model Data collection and methods: Document analysis, secondary data, simulation, scenario analysis, sensitivity analysis	Sections 4.7 and 5.4

3.3.2.1 Phase I: Literature review

The theoretical foundations underpinning the research questions and findings of this thesis involved four main streams of literature, as elaborated in Chapter 2, Theoretical Background. The review provided the basis on which the contributions of this research were built. The literature streams, search strategies, sources, and research queries are presented in Table 14.

Table 14 – Literature review: streams, sections, type, sources, and keywords.

Stream	Quality Management	Performance Measurement	Quality Costs	Inspection Planning
Section of the thesis	3.1	3.1 and 3.2	3.3	3.4
Literature search type	Scoping review	Integrative review	Systematic review	Integrative and systematic review
Sources	Books and articles retrieved from Scopus, Science Direct, and Web of Knowledge	Scopus, Science Direct, and Web of Knowledge	Scopus, Science Direct, and Web of Knowledge	Scopus, Science Direct, and Web of Knowledge
Keywords	"Quality Management"	"Performance Measurement System" AND "design OR review OR implementation" "key performance indicators" AND "data analysis" OR "data analytics"	"cost of quality" AND "inspection strategy"	"cost of quality" AND "inspection strategy" Inspection AND (Planning OR Improvement)

Regarding the three applied search approach, a *scoping review* is a form of knowledge synthesis that addresses an exploratory research question aimed at mapping key concepts, identifying key characteristics or factors (Munn *et al.*, 2018). An *integrative review* combines empirical and theoretical research using diverse data sources to develop holistic understanding of the topic of interest by presenting the state of the science and contributing to theory development (Souza *et al.*, 2010). Finally, the *systematic review* seeks to recognize conflicting results, address variations, and identify areas for future research. It involves a more precise analysis addressing the feasibility, appropriateness, meaningfulness or effectiveness of a certain practice (Munn *et al.*, 2018).

The inclusion criteria were research indexed in the databases: Scopus, Science Direct, and Web of Knowledge. In addition, to be included, documents had to be available with full-text access in Google®, Google Scholar®, Microsoft Academic Search®, and ResearchGate® or sent by email to the author.

3.3.2.2 Phase II: PMS review and improvement

The main attributes of the analyzed KPIs were based on the literature and the data collected from information systems, technical reports, dashboards, and internal documents of the Company. All these sources were accessed to identify and assess the KPIs. The KPIs were described based on eleven attributes: title, objective, scope, target, formula, frequency of measurement, source of data, measurement responsible, user, notes and comments, and frequency of review, as described in Table 2 (Section 2.1.1).

During the participant observation process at the Company as a researcher, several KPIs could be confronted to the literature. The research presented in this thesis limited the scope of the analysis to

three of them, which were considered the most interesting in terms of the discussion surrounding KPI reviewing and improvement. Of these three selected KPIs, two replaced previous KPIs. Therefore, given the interest in the longitudinal approach of research on the life cycle of an indicator, these two previous KPIs that were replaced were also briefly included in the analysis.

After investigating the KPIs regarding to their attributes (Section 5.6), semi-structured interviews were conducted guided by a questionnaire consisting of relevant questions reported in the literature for the PMS analysis (Braz *et al.*, 2011):

- Are the measures clear?
- Are the measures practical?
- Are the measures easy to understand?
- Are data collection and analysis worth the cost?
- Are the objectives of the measure aligned with the objectives?
- Is it possible to act based on the data?
- Are the scales and units appropriate?
- Is there any possibility of ambiguity in the interpretation of the results?
- Can the data be analyzed quickly enough so that actions can be taken?
- Is the measure consistent no matter when it is performed?
- Is the frequency of measurements adequate?
- Can the data be promptly communicated and easily understood?
- Is the frequency of the review of targets adequate?

A total of five employees involved in the Quality Management of the Company were interviewed, including employees involved with the development, implementation, and use of the KPIs.

3.3.2.3 Phase III: KPIs relationships

In Phase III, the objective was to identify and quantify the relationships between the company's KPIs to know which are the internal KPIs with good predictability, causality, or correlation with external KPIs. This research fits operations management and many different methods can be applied (Boyer and Swink, 2008). According to the reviewed literature, methods applied for designing appropriate PMS include surveys (Bititci *et al.*, 2015; Lucianetti *et al.*, 2019; Neely *et al.*, 1996), case studies (Globerson, 1985; Lohman *et al.*, 2004; Sanchez-Marquez *et al.*, 2020b; Shin *et al.*, 2018; Wouters and Sportel, 2005), action research (Bititci *et al.*, 2016; Braz *et al.*, 2011; Neely *et al.*, 1997, 2000), and modeling and simulation (Hwang *et al.*, 2017). A case study is an appropriate research method for developing a

longitudinal study to review and update the company's PMS, attending the suggestion of several authors (Bititci *et al.*, 2015, 2016; Braz *et al.*, 2011; Wouters and Sportel, 2005).

Quantitative data analysis was carried out through statistical analysis on secondary data of the company to reveal relationships between internal KPIs and overall quality performance. This study involved the use of multiple-source secondary data, namely the time series-based type (Saunders *et al.*, 2016). Structured Query Language (SQL) was used to query it from the Company's databases. The first step was the initial data treatment, and the second step was the identification and projection of the KPIs relationships. Initial data treatment consisted of gathering time series data from KPIs, preprocessing, filtering, and homogenizing operations to make them stationary and apply the proper mathematical techniques for identifying relationships between the KPIs (Rodriguez *et al.*, 2009; Sanchez-Marquez *et al.*, 2020b). To test for statistically significant differences, Fisher's Exact Test for Count Data was performed using the R statistical software package. Differences with a p-value $<.10$ were considered statistically significant.

3.3.2.4 Phase IV: Current practices related to Inspection Planning and Inspection Improvement.

In this phase, the interest was identifying the practices applied during the IP design and Improvement in the Company. The main data source was secondary, consisting in document analysis. Nevertheless, primary data collection was also accomplished, consisting in observation of practices and informal interviews. The description of these practices is set in Sections 4.2 and 4.3, while a critical analysis and positioning according to the literature is made in Section 5.3.

After studying the IP process, which occurs in the Product and Process Development stage, it was evaluated how it evolves during the Manufacturing Stage. For doing so, *i.e.*, evaluating the Company's practices regarding the Inspection Improvement, the researcher participated in an event - called Performance Workshop (PW) (referred in Section 5.8) - as a participant observant. Therefore, both primary and secondary data collection were performed regarding this event. While the PW is described in Section 4.8, the results of this phase are presented in Section 5.3.2.

Moreover, in order to communicate the results in a visual manner while positioning them in a synergistic dialogue with the literature, a framework based on the PDCA cycle is proposed in Section 5.3.3.

3.3.2.5 Phase V: Model development

A computational model was developed and applied to evaluate how different inspection strategies impact the CoQ. Equations were developed to quantify the total CoQ for different IP scenarios. The CoQ

approach applied was the PAF (Prevention, Appraisal, and Failures). The model describes the relationship between the processing parameters and the CoQ response; therefore, this relationship can be used to predict the quality costs response to imposed processing parameters/performance indicators.

SQL was used to query secondary data available from the Company's databases providing part of the necessary input to the model. Document analysis and interviews were also necessary to gather the model inputs.

A computational model was developed in Microsoft Excel. Moreover, the uncertainty of certain parameters prompted the utilization of Monte Carlo simulation and sensitivity analysis, which was performed with an academic license of the add-in tool for Microsoft Excel, @RISK 8.1 from Palisade (<https://www.palisade.com/risk/>).

The equations behind the calculus of the total and unitary CoQ are explained in Section 5.4.2 for two scenarios (100% inspection and no-inspection). They are based on the PAF approach, and comprised the Failure related costs (C_{repair} , $C_{analysis}$, $C_{reinspection}$, and C_n) and the Appraisal costs ($C_{inspection}$). The $C_{reinspection}$ is not computed within the category of Appraisal cost, as it is incurred due to Internal Failure.

The discussion on the validation of the proposed model followed the attributes proposed by Landry, Malouin, and Oral (1983): conceptual validation, logical validation, experimental validation, operational validation, and data validation. For doing so, interviews took place with quality specialists inside the Company and the academia, who evaluated the validation of each attribute indicating a sense of confidence in a graphic matrix of five statements from low to high, as presented in Section 5.4.5.

4 Case Study Context

This chapter aims to present the business context of the case study of this thesis. Initially, a brief description of the company under study is given (Section 4.1). Next, from the second to the fourth sections, the activities for the development and engineering of products are presented, *i.e.*: Section 4.2 presents the Industrialization Process; Section 5.3 presents the process adopted by the company to set up the IP; and Section 4.4 presents the Production Process of a specific product, along with its manufacturing line and associated inspections. In Section 4.5, the company complaint handling system is presented. Given this overall overview, Section 4.6 presents the Company's KPIs related to internal (production) and external (complaint) processes and the available information regarding quality costs. Finally, Section 4.7 describes a CI event (*i.e.*, PW) of the company aimed to increase productivity.

4.1 Company

The company where the case study took place is a subsidiary of a large German international organization that operates across diverse business sectors: mobility, consumer goods, industrial technology, and energy and building technology. The company under study, henceforth referred to as the Company, is related to the mobility sector, more specifically, automotive electronics and car multimedia technologies. Along with the Company, there are three other subsidiaries that also deal with Car Multimedia technologies in the group.

Located in Portugal and having started its activities in 1990, the Company is a Tier 1 supplier that works with more than 45 customers in the automotive market and has more than 3400 employees.

The Company's certifications for quality include ISO 9001 and IATF 16949 (QMS for Automotive Industry) and has continuously transformed its activities to maintain its position as a world leader in the technology segment. The main quality-related earned awards were the European Award for Excellence in 2015, and the "Company" Quality Award in 2011 and 2008. In addition, the Company was "Recognized for Excellence", with five stars, by European Foundation for Quality Management in 2007.

The Company produces a wide-ranging portfolio of electronic products within the nine following product classes:

- 1) Driver Information and Infotainment Systems
- 2) Control connectivity Unit + Toll Collect
- 3) Instrumentation Systems
- 4) Professional Systems
- 5) 2-Wheeler and Power sports

- 6) Chassis Systems LWS
- 7) Chassis Systems APS
- 8) Bombardier
- 9) Test/Intellic

Developing software-intensive embedded systems is a significant challenge as embedded systems have become more complex and dynamic for integrating various constraints (*e.g.*, real-time performance, design, and functional safety) (Maruf *et al.*, 2022).

Inspired by the ideals of the Toyota production system, the group developed its production system philosophy (Bumba, 2020). CI is among the principles of this philosophy, implying that the organization's methods are continuously revised and serve as a starting point for future optimization measures. Within the Company, several types of CI projects are carried out reflecting this company principle, *e.g.*, Six Sigma workshops (Costa *et al.*, 2019), Cost Reduction Workshops (a.k.a. Ratio Project Planning) (Leite, 2013; Machado, 2021), and Performance Workshops (PW), just to cite a few. The PW is explained in more detail in Section 4.8.

This doctoral thesis was developed in the Quality Management and Methods (QMM) Department of the Company, which is composed of 8 teams, as represented in the organogram of Figure 13. Specifically, in the Quality Data team, responsible for the data management of the QMM.

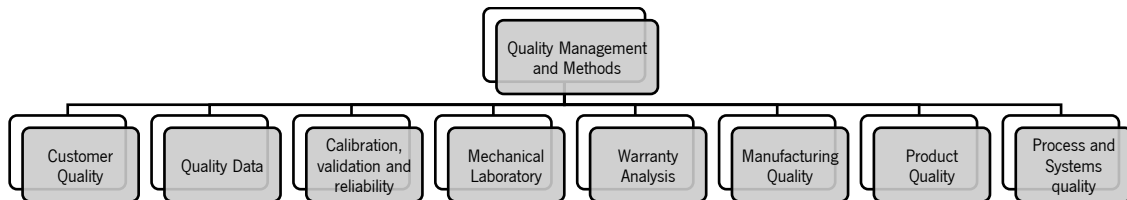


Figure 13 – Organogram of the Quality Management and Methods Department of the Company.

4.2 Industrialization Process

This section briefly explains the phases within the Industrialization Process of the Company. The industrialization process encompasses the development of a product to make it ready for mass production and the design of the assembly lines to produce the developed product. This overview is important to understand the following chapter because the IP relies on activities taking place during the Industrialization Process phases.

The company has a standard industrialization process that usually requires a typical set of activities, whose duration and effort are defined according to the complexity of each project. Straightforwardly, an industrialization project is composed of phases where prototypes are developed and subsequently evaluated at Quality Gates (QG). In the Company, there are four increasingly maturity levels of prototypes,

a.k.a. samples, labeled in alphabetical order from A (less mature) to D (more mature). Figure 14 represents the industrialization process, from the product concept phase to series production, and the associated QG.

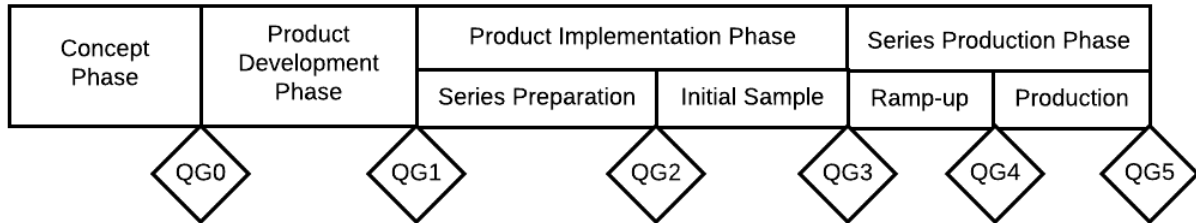


Figure 14 – Industrialization process of the Company.

The Concept Phase marks the kick-off of the project and seeks to develop the concept of the new product regarding the software architecture, the hardware, the product design, and the specifications. The concept is defined, evaluated, and validated, and the industrialization process schedule is created. In the Concept Phase, activities for A samples are released.

The next phase is Product Development when the first prototypes are built and validated internally. In the Product Development Phase, Sample A and Sample B are produced “in laboratory”, *i.e.*, not in a production line, and the concepts for product and process design are optimized.

The third phase is the Series Preparation, which encompasses the planning with the initial samples from the production line, *i.e.*, C samples. Indeed, in this phase, there is a greater emphasis on the production line, and new production and inspection technologies are temporarily integrated offline in the factory and go through the approval process. This ensures that production facilities and production processes are capable of producing products according to their specifications.

The fourth phase, Initial Sample, aims to verify the performance of the pilot series through the production of D samples. At this stage, the internal release of manufacturing equipment is done, and potential problems in the production line are identified and eliminated. The preliminary process capability is proven. After the approval of both the product and the production line is obtained internally, the so-called initial samples and Inspection Report is sent to the customer to receive external approval. Therefore, both the samples and the manufacturing process are approved by the customer after this phase.

Finally, in the Series Ramp-up Phase, the emphasis is on optimizing series production, by detecting and correcting the remaining failures before the production line has the required production capacity. At this stage, not all the root causes of defects are known, as quality management is still in the learning phase. Therefore, knowledge of the process behavior is collected, leading to the adjustment of the

inspection activities in progress. By producing small amounts of samples, problems that have not yet been solved are eliminated and the production flow is optimized, improving efficiency and process cycle time.

QG is a special milestone performed for product development and relocation projects, where a project is evaluated against measurement criteria and evaluated to determine whether it is qualified to proceed to the next phase. These gates or checkpoints serve to detect the problems and risks at an early stage so that corrective actions can be taken to meet project targets. Supposing that a product conception or design can pass through each gate, the product's quality is ensured. In sum, a quality assessment of the project is performed based on predefined measurement criteria, possible deviations are identified, their impact on the project's probability to meet the targets is rated, and a decision to proceed to the next phase of the project is made. Each QG in Figure 14 consists of the following:

- QG0: Review of product requirements and planning.
- QG1: Evaluation and release of the technical specification and design freeze.
- QG2: Completion of process development/production planning.
- QG3: Internal release of the entire scope of delivery (including the manufacturing process).
- QG4: Completion of validation (a prerequisite for the release of the product for delivery or intended use).
- QG5: Transfer to series support and project completion.

The traffic light arrangement is used for the rating levels in the QG assessment. Green-rated measurement criteria imply that they were achieved and no additional action is required. The yellow one implies that the measurement criteria are not achieved yet, but they will be after completing the stipulated required actions, *e.g.*, when the FMEA and PFMEA have been completed but the approval has not been signed in time. The red indicates that the measurement criteria are not achieved, and then a target adjustment is necessary, *e.g.*, when the defined cost target cannot be met. Figure 15 presents the overall QG idea based on the described traffic light arrangement.

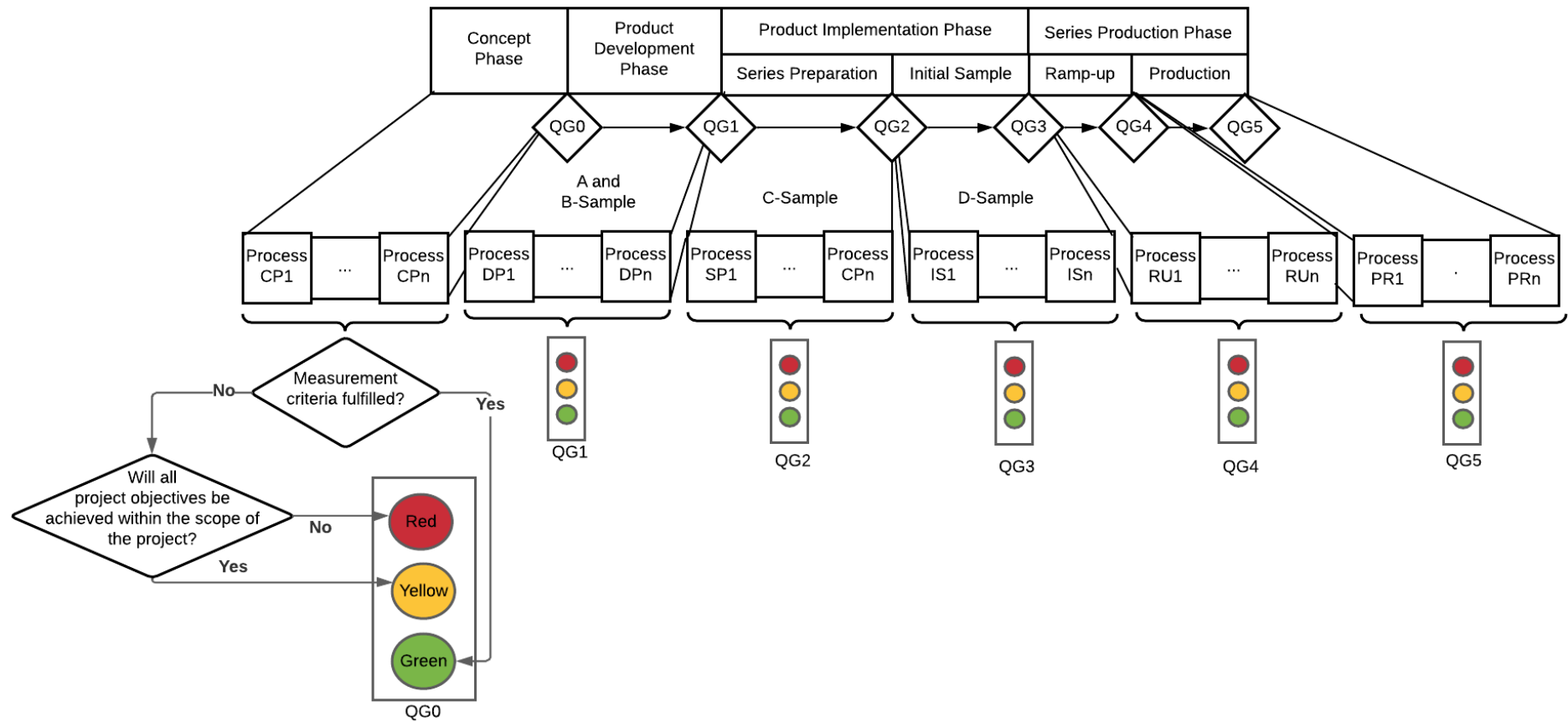


Figure 15 – Quality Gates based on the traffic light arrangement.

4.3 Inspection Planning

This section outlines the basic IP procedure in the Company and is divided into two subsections. The first subsection is related to inspection characteristics identification and analysis. Accordingly, inspection strategies must be developed, to define the test procedures, cases, and required resources. Thus, the second subsection deals with the inspection process conception and allocation.

4.3.1 Characteristics Classification

The input for the record of the quality characteristics comprises the drawings, computer aided design (CAD), part lists, functional analysis from FMEA and PFMEA, Quality Function Deployment (QFD), and the company planning guidelines. To define the characteristics to be inspected, it is also necessary to have information regarding legal and safety requirements, customer requirements, and lessons learned from previous customer complaints.

With the overall characteristics list at hand, a multidisciplinary team, a.k.a. Simultaneous Engineering team, decides if an inspection needs to be defined for each recorded quality characteristic. In case of a characteristic that can only be inspected by a destructive test, for example, they may decide to inspect a different one and/or monitor a process parameter. Therefore, the team creates a list of Special Characteristics (SC), which are a subset of product characteristics that require highlighted attention and must be safeguarded in the respective production process. The SC must be also negotiated with the customer.

Therefore, besides the safety-related SC, the legal-related SC, and the SC required by the customer, there are other *potential* SC. Potential SC are related to the robustness analyses of both i) the product functioning and ii) the manufacturing method.

Robustness is defined by Taguchi *et al.* (2000) as “the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in manufacturing or user’s environment) and aging at the lowest manufacturing cost.” The robustness analyses are made based on the FMEA and PFMEA, where the possible effects of each failure mode are assigned quantitatively based on a cause-effect relationship. This is carried out based on both the severity of the respective effect for the failure mode and the importance of the failure mode for the occurrence of the failure effect.

- i) The characteristics are functional robust if they are barely sensitive to variability, and “not functional robust” if they fail solely and immediately upon exceeding the tolerance band. Figure 16 exemplifies this difference.

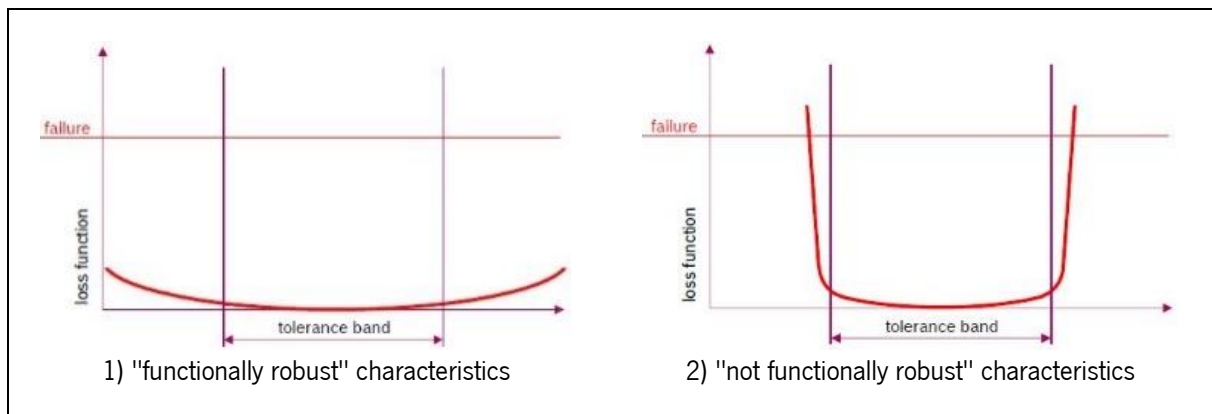


Figure 16 – Example of functional robustness analysis.

- ii) Regarding manufacturing method robustness, product characteristics are “not manufacturing method robust” if they are failure sensitive for the chosen manufacturing method, *i.e.*, there is a high likelihood of exceeding the tolerance limit when using the chosen method. Figure 17 shows the difference between a “robust” and a not robust” manufacturing method, where values beyond the tolerance band represent the manufacturing of non-conforming products.

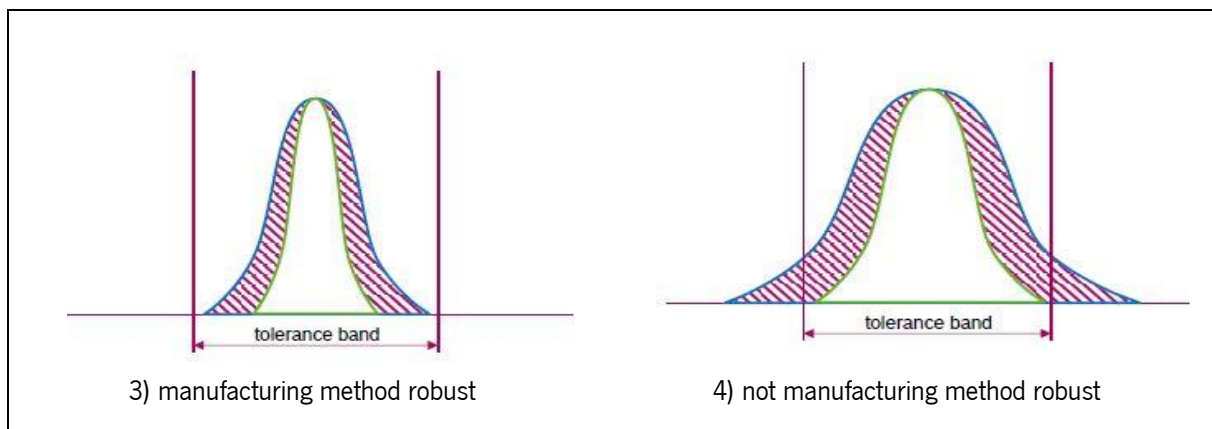


Figure 17 – Representation of manufacturing method robustness analysis.

Given both the Functional and Manufacturing method robustness analyses, Figure 18 presents a two-by-two framework used to help with the classification of characteristics. The intersection between not functionally robust characteristics and not manufacturing method robust results in the so-called Potential SC.

	Functionally robust characteristics	Not functionally robust characteristics
Manufacturing method robust	“Functionally robust” and “manufacturing method robust”	“Not functionally robust”, but “manufacturing method robust”
Not manufacturing method robust	“Functionally robust”, but “not manufacturing method robust”	“Not functionally robust” and “not manufacturing method robust” Potential Special Characteristics

Figure 18 – Matrix of the robustness analyses.

For the identified *potential*/SC with relevance for the functioning of the product, the process quality must be at least state of the art and be monitored based on defined metrics (*e.g.*, process capability,

failure rate). In case the required process quality (target value) is not achieved, the *potential* SC with functional relevance will become a *confirmed* SC with functional relevance.

Besides the analysis of product characteristics, there is also the process relevance analysis. Process-relevant characteristics are process variables and parameters that have a cause-and-effect relationship with the variation found in product characteristics (*e.g.*, cycle time, pressure, flow rate, and tool speed), *i.e.*, they are the ones relevant for follow-up processes, indicators of tool wear, and indicators of process behavior.

Based on the previous steps, the product and process characteristics are categorized in a 3-level classification, with A, B, and C classes, where:

Class A:

- confirmed SC.

Class B:

- potential SC.
- process relevant characteristics.
- “not functionally robust”, but “manufacturing method robust” characteristics.
- “functionally robust”, but “not manufacturing method robust” characteristics.

Class C:

- “functionally robust” and “manufacturing method robust”.
- “not functionally relevant” and “not process relevant”.

The flowchart presented in Figure 19 summarizes the overall process for the characteristic's classification.

4.3.2 Definition of Inspection Strategy

The determination of the suitable inspection strategy is based on the input information of the preceding characteristics classification. Inspection strategies can be divided into three groups: Group I, within the framework of part approval and production process, Group II, during series production, and Group III, additional inspection strategies.

Group I is subdivided into two parts: the product release (Group I-1), when the initial sampling is produced, and the process release (Group I-2), when Process Capability Analysis is carried out. Group II, in turn, is subdivided into three: process monitoring (Group II-1), failure sorting (Group II-2), and restart (Group II-3). Group III, finally, is related to Product Audit and encompasses the activities of Quality Testing, Reliability Testing, and Selective Testing.

The minimum for inspection is dictated according to the following characteristic classification:

- A-Characteristic: Inspection strategy from Group II-2.
- B-Characteristic: Inspection strategy from Group II-1 or Group II-2.
- C-Characteristic: Inspection strategy from Group I or Group II or Group III.

Each characteristic class implies a different inspection strategy and PCI study, as represented in Figure 20.

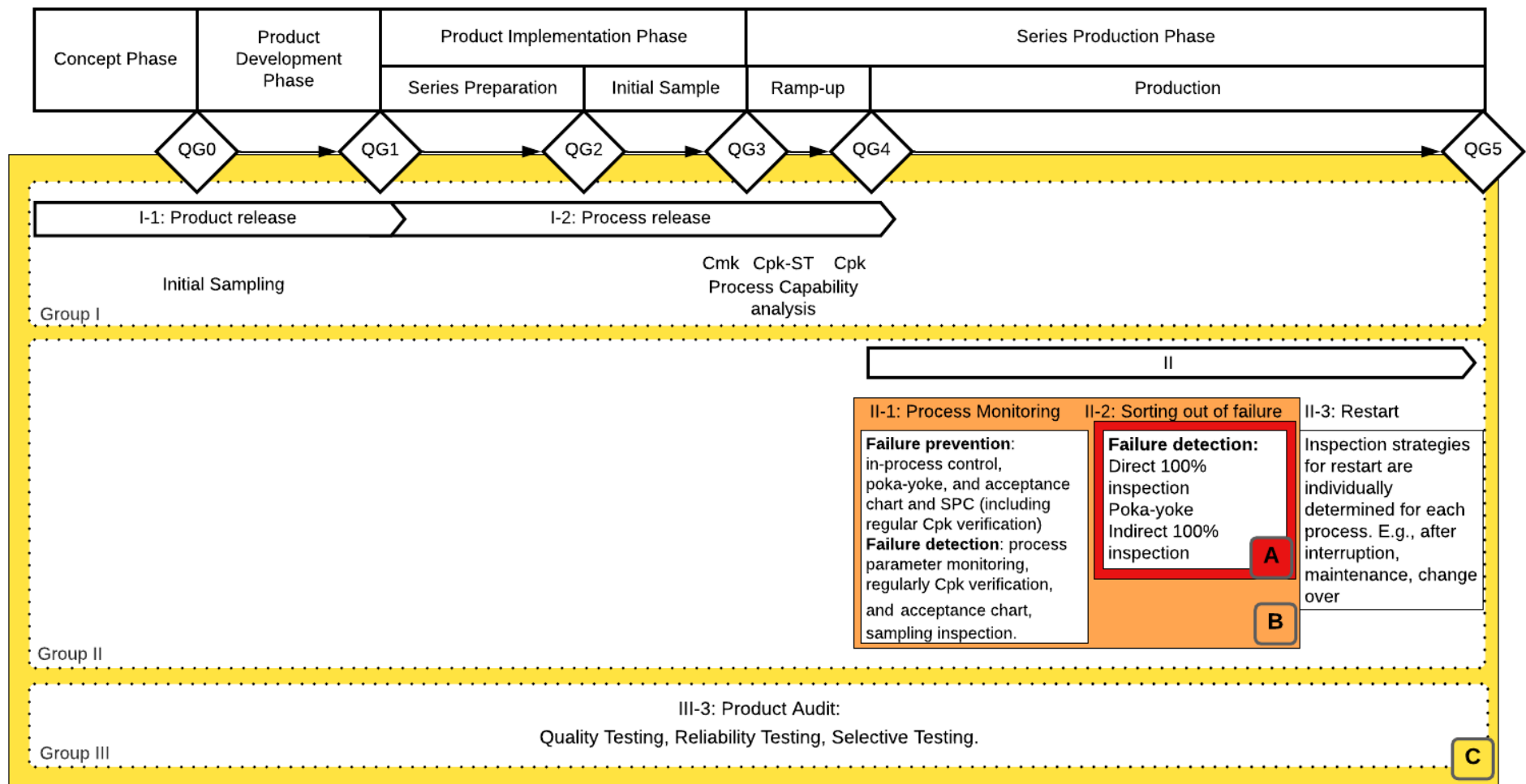


Figure 20 – Characteristics classification within Inspection Strategy groups.

After defining the Inspection Strategies, a suitable Inspection Method is planned along with the tolerances, and specifications. This includes, among others, the inspection type (IP3), the location and personnel (IP5 and IP6), the inspection procedure and equipment (IP7), the inspection timing (IP2) and sequence, and the quantity-related definitions (IP4).

The next phase, the Planning of the Measurement and Process Capability (IP8), comprises the definition of the requirements for controls in the ongoing series production. For each test and measurement system, it is necessary to plan the test/ measurement process suitability analysis and to define the requirements for controls in the ongoing series production, including sensors, measuring equipment, camera systems, etc. This planning comprises the following:

- Definition of capability/ uncertainty studies of test and measurement processes (measurement system analysis).
- Planning of the inspection equipment control, which must be calibrated at regular intervals for its proper functioning, measuring stability and accuracy.
- “Check the Checker”, *i.e.*, checking the test and measurement equipment during the series production (error proofing), including its documentation in the ongoing series.

In the definition of Reaction and Corrective Action Plans (IP9), the team defines which actions must be taken if products or processes do not fulfill the specified criteria. This includes especially the decision-making on whether products will be sorted, scrapped, reworked, or re-used by a “concession”. For scrapped products, it must be ensured that these cannot be used further and that they cannot be brought into circulation. This applies also to parts and their further handling which has been selected as “not ok” during inspections. Requirements for a substitute or rework and alternative process must be defined.

Therefore, the data recording method is defined (IP10), (*e.g.*, SPC control chart in software Q-DAS), which includes the preparation, evaluation, and displaying of data.

The overall IP is called “Management of Characteristics”. When this process ends, all the related information is transferred to technical documents, *e.g.*, PAV (a term that comes from the German language which means test and calibration specifications – Product Test and Alignment specification), control plan, process FMEA, product audit program, production and inspection instructions, inspection plans, and series production release. When necessary, the Management Characteristics process is reviewed and updated.

The (product) FMEA is developed at the organization headquarters, in Germany, while the (process) PFMEA is developed at the Company. The PAV comes to the Company arranged with all the functional and electric characteristics already defined and specified.

4.4 Production Process

Given the wide range of products manufactured by the Company, one product was selected to have its inspection process further evaluated. The selected product consists of an Infotainment System and has been associated with the largest number of complaints and internal failures. It consists in a multi-functional interactive hardware and software device that provides information (*e.g.*, fuel level, door security, parking assistance), communication (*e.g.*, phone calls using voice control technology, Bluetooth), and entertainment (*e.g.*, audio/video, radio, rear-seat entertainment) services (Yin, 2018). To familiarize the reader with the product, the parts that comprise the final assembly of a complete device are shown in Figure 21.

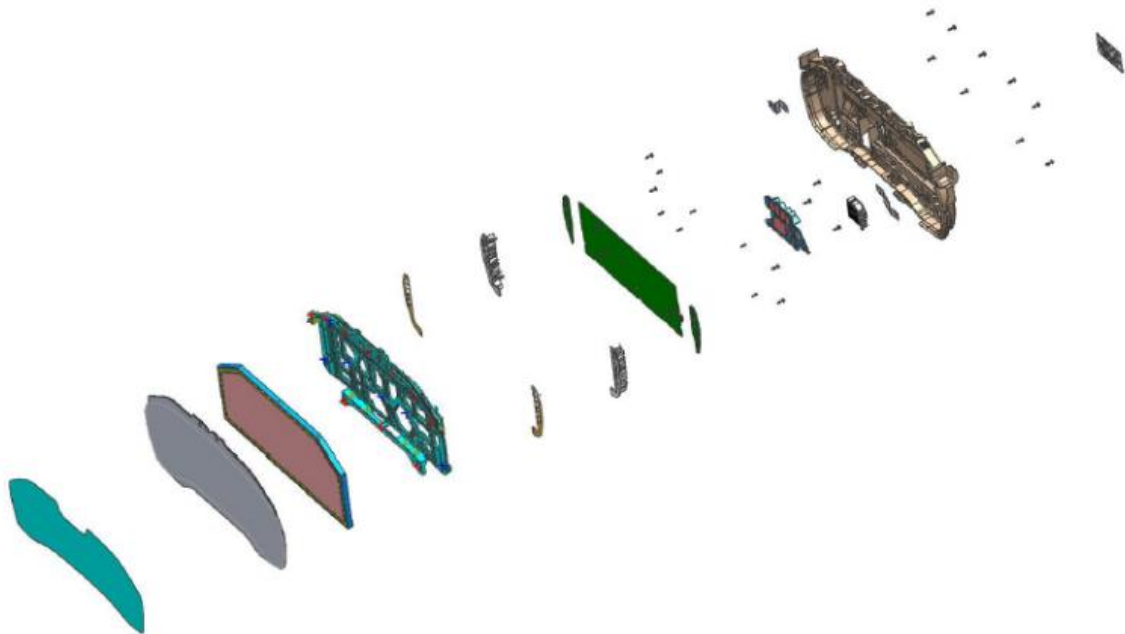


Figure 21 – Complete Device Isometric Exploded View.

Many components/sub-assemblies that compose the complete device are built in-house. Basically, there are distinct production chains, *e.g.*, to assemble a Printed Circuit Board (PCB), to bond the glass and the display, to assemble and glue this set to the carrier frame. In the Final Assembly Line, additional assembly parts, such as covers and screws, are assembled to produce a complete device.

There are 5 main lines/processes associated with the overall production, as represented in Figure 22. The following sections briefly explain each one of these processes, while the Final Assembly Line is further detailed afterwards.

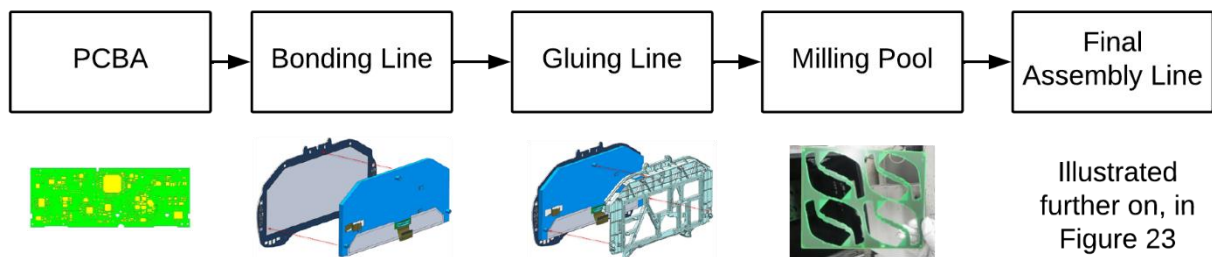


Figure 22 – Production lines linked with the product.

PCBA

PCB are electrically insulating boards made up of a complex printed electrical circuit, whose main function is to support and electronically connect a very large number of components, through the transmission of signals, electric current, and other properties. At the beginning of the considered process chain of PCB manufacturing, the initial component, an unassembled PCB, is transported via conveyor belts to a printer, where lead-free solder paste is applied by means of stencil printing. Subsequently, the PCBs are fed into an assembler, where individual components such as resistors, capacitors or microchips are mounted by several assembling heads, forming an Assembled PCB (PCBA), which is commonly defined as the “heart of the units”, and finally soldered by reflow oven.

Within either the automatic or manual insertion process, these boards go to the soldering ovens coupled to the line to solidify the solder paste. Before soldering, there is a Solder Paste Inspection (SPI), an automatic and objective inspection station that evaluates the solder paste (area, shape, height, weight, and XY position). After soldering, there are two more inspections:

- Automatic Optical Inspection (AOI): automatic inspection station that evaluates the position and integrity of assembled components.
- In Circuit Test (ICT): automatic and objective inspection station that functionally tests the printed circuit on the PCBA after soldering.

After these three inspections, the PCBAs are placed in a waiting container to be supplied to the production line, as soon as the order is given by the logistics department (Carvalho, 2019). Throughout the production system, there are other inspection systems, both subjective and objective, that test and verify the integrity of PCBAs and the components that compose them, in addition to the tests during the insertion process (SPI, AOI, and ICT).

Bonding line

In this line, the glass and the display are joined through the Optical Bonding process. Optical Bonding is a technology for the introduction of an optically clear material of matching refractive index between the

display and glass to guarantee its visibility when exposed to high brightness or direct sunlight (Cruz *et al.*, 2017). After this operation, the set is packed in a container and later supplied to the gluing line.

Gluing line

In this process, an adhesive liquid is dispensed on a support named carrier frame. After this process, the operator places the set in a container.

Milling pool

The last step for the PCBA, right before the final assembly line, is the milling pool. It consists of cutting the excess material from the board. After milling, the original piece produces single or multiple small slabs. In the first case, the cutter only cuts the contour of the PCBA, while in the second case the PCBA is cut in several places, giving rise to several smaller PCBAs, which are then identified and used in the final assembly line (Castro, 2017; Cerqueira, 2021).

Final Assembly Line

The Final Assembly Line comprises the stations represented in Figure 23. Some involve automatic and manual operations for assembly, labeled as Work Stations (WS), while others are Testing Stations (TS), the ones indicated in grey (FCT20, RUN50, FCT50, FCT60, SUB50, and AOI50). TS are called Virtual Test Places (VTP) in the Company. VTPs are grouped into test areas, like Automated Optical Inspection (AOI), InCircuit Testers (ICT), FunCtion Testers (FCT), and Subjective Inspection (SUB). The Quality Inspection Manufacturing (QIM) is an offline laboratory where one part per lot is examined. The Analysis Station (AS), where the defective units are evaluated, is also offline.

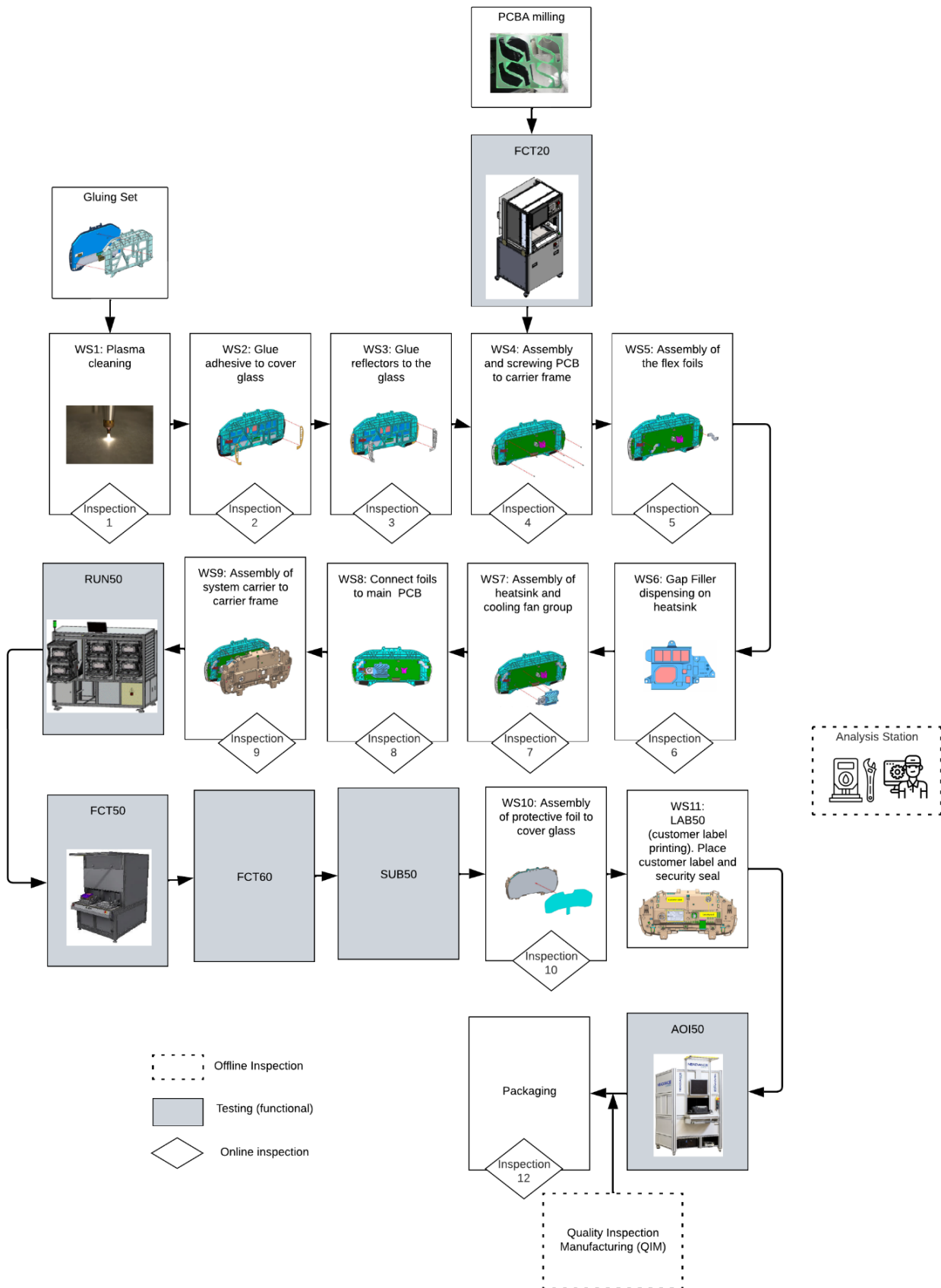


Figure 23 – Production flow for the Final Assembly Line.

It is beyond the scope of this thesis to discuss in detail the various workstations and test equipment. However, there are some basic concepts included here for understanding.

The process called Plasma Cleaning, in WS1, is a process to prepare the surfaces for the subsequent process of bonding. From WS2 to WS5, there are process for assembling parts into the device. Then, there is the first Functional Circuit Test (FCT). FCT is an automatic and objective inspection station that functionally tests the printed circuit on the PCBA at the beginning of the final assembly line (FCT20) and after it is attached to the other product parts constituting the complete device (FCT50 and FCT60). RUN50 is a station to heat the display to prepare for optical measurement in the FCT50 afterwards. SUB50 is a station for operator driven functional and subjective tests. LAB50 is where the customer label is printed, and AOI50 is a station for Automatic Optical Inspection (AOI).

The production test chain mainly covers hardware-related features (rather than software-related features). In the QIM, which is at an offline laboratory, one unit is inspected per lot in customer mode. Tests in customer mode are functional tests performed on the unit in the most realistic environment possible. The device is connected with external peripherals (*e.g.*, mobile phone, display, pen drive) to check communications (*e.g.*, GPS, Wi-Fi, Bluetooth) and display symbols. Functional tests in drive mode are carried out to read device parameters (*e.g.*, speed, LEDs, warning, etc.) and to check the correct content of the labels. In addition, different car models are simulated for the same device rather than only the default configuration. According to Yin (2018), the essence of an excellent infotainment system is good user experience, which sometimes can only be acquired by testing the infotainment system manually.

Ultimately, there is a packaging station. Its main goal is to ensure that only the products that passes the test chain are shipped to the customers, while also guaranteeing the correct reference and quantity of products packed in a pallet. Tasks in this station comprise reading of the products bar code, and packaging them into specific boxes.

In the packaging process, there is a system supporting quality control named Active Lot Release (ALR), which applies a pre-defined set of rules to several distinct products contained in a lot, before shipping it to the final client (Marinho, 2022). These ALR rules were defined in a hand-crafted approach and serve as a basis for lot-release decisions. When all the products in a lot adhere to them, the same is marked as valid and it can be shipped. Otherwise, it is resubmitted to the quality control process. Within the ALR system, the data about defective products and lots is stored, allowing the decision-makers to analyze past production problems.

4.4.1 Reaction Plan for Defective Products

While the Testing Stations (TS) are devoted to inspection/testing activities, the output of each WS is also checked against the required quality by both the operators and the WS themselves, during its

production/assembly. The parts classified as defective at any WS or TS are conveyed to the technical Analysis Station (AS), which is offline. In this AS, a technician checks whether the rejected part is actually defective.

When the defect is visually detected by the operators (*i.e.*, assembly and/or cosmetic defect), she/he must place a seal on the part indicating the location of the defect. Whenever possible, there is a verbal communication between the operator and the analysis technician to clarify the defect in more detail, especially when it is visual. There are intermediate places (*i.e.*, tables/trolleys) where products for analysis are provisionally placed.

When the analysis technician considers the part as not defective (labelled as “s-case” into the system), it returns to the WS or TS where it was previously considered as failed (or an even earlier station, depending on each situation) to be inspected again. Else way, when the part is confirmed as defective, the device will be disassembled, part by part, until the defective one is removed. The components that are being dismantled until the defective one is found can be reused or not, according to a pre-defined set of rules called “reuse matrix”, which is specific for each project. The defect is always classified according to a defect directory before replacing and scrapping its defective portion.

The technician has some equipment and can perform this repair in some cases, *e.g.*, to replace a foil that was improperly assembled. In other cases, when further analysis or intricate rework is necessary, the part is dispatched to the electrical laboratory. After repaired, the part returns to the process, as in the s-cases. This described handling process of a defective part from a TS is summarily represented in Figure 24. Products classified as failed in any WS follow the same procedure, from the AS onwards.

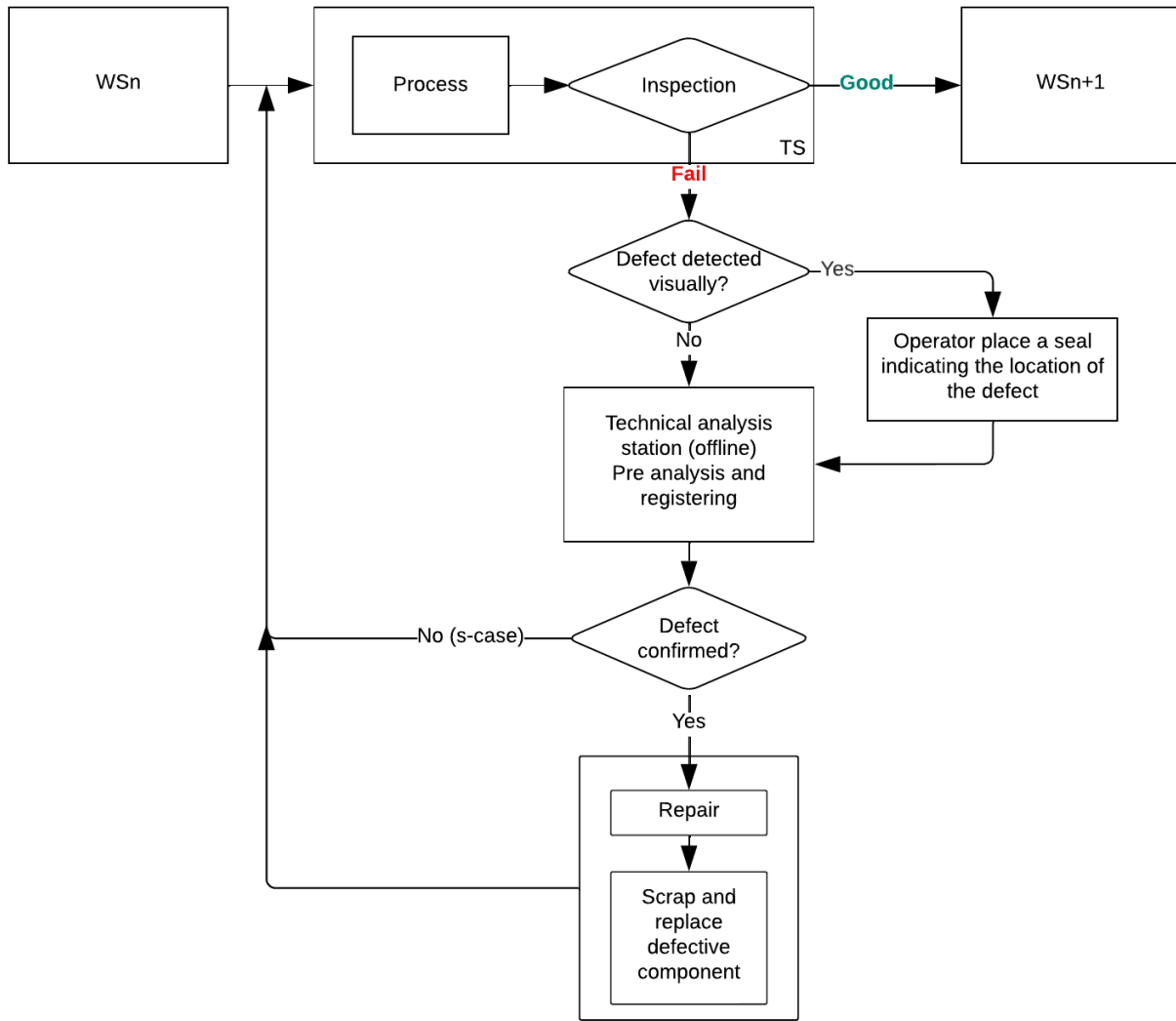


Figure 24 – Flowchart of defective parts handling.

4.4.2 Testing Stations and Quality Characteristics (A, B, and C)

In each station, several product and process characteristics are inspected to guarantee the expected functions of the product. These functions are translated into controls in the cyber-physical system by the testing teams in the Product Test and Alignment specification (PAV), which is the basis for testing software/algorithm.

In the testing level, the algorithm comprises not only the controls for the characteristics originally specified in the procedure described in Section 4.3, but also the ones necessary for the operation of the testing software. In other words, there are additional functions in the software of the testing equipment which are not the product characteristics *per se*, but are in the same list, and include commands and configurations to execute the tests. For example, when a device is inside a TS, it has to be moved along the axes towards the exact position to be measured by the equipment (*e.g.*, cameras/optical sensors). The movement commands are dictated by the same algorithm that performs/commands the required tests.

The quantity of different quality characteristics plus commands in each station of the production line represented in Figure 23 is displayed in Table 15, according to the data taken from a dashboard within the Company. However, there is no way to know exactly how many/which of these characteristics are A, B, or C. Given the high production volumes and the several different products, the testing data comprises millions of tests in the Company daily.

Table 15 – Examples and quantity of items in Product Test and Alignment per station.

Station	Quantity of testing items in PAV	Example of test item in PAV
WS1	10	
WS2	17	Check screw torque and angle
WS3	105	Check gap filler
WS4	163	Check screw torque and angle
WS5	91	Check heatsink tracking status
WS6	40	Foil flap presence
FCT20	167	Voltage measuring
WS7	0	-
WS8	235	Check foils and main connector
WS9	13	Pump supply pressure for A
WS10	0	-
RUN50	696	Measure operating current if Display On 100%
FCT50	1127	Check uniformity black
FCT60	701	Luminance measure
SUB50	385	LED function test (yellow, green, blue)
WS11	6	Check Status Tracking of the reflectors
WS12	56	Print Label/write to database - bold text
AOI50	159	Check cable routing feature
QIM	619	Check if Main connector at home position
Packaging	6	Verifies status tracking

4.5 Complaint Handling System

Figure 25 represents a supply chain and the flow of complaints from the final customer up to the suppliers, where a part labeled as Product 3 provided by a Tier 2 to the Company (Tier 1 Supplier), which produces Product 2 as part of Product 1 to the OEM, which finally produces the car which is then sold to the final customer.

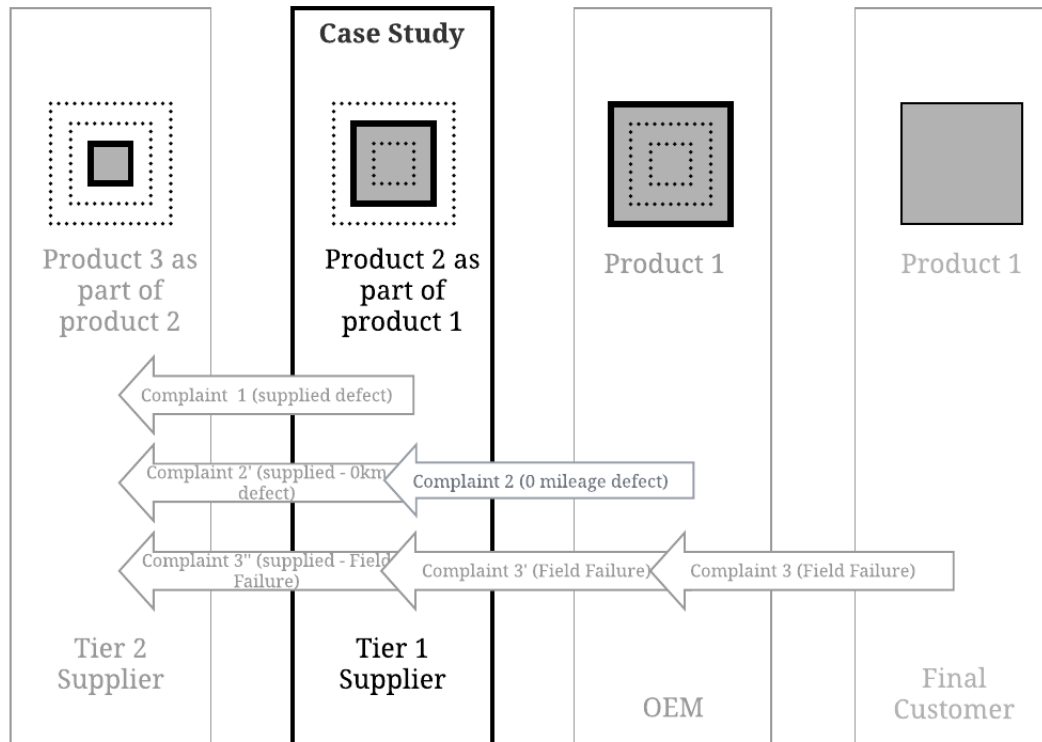


Figure 25 – Complaints flow in the supply chain.

When the Company acts as a customer and detects a defective supplied part, the complaint is made against an external supplier (labeled as Complaint 1 in Figure 25).

When the company acts as a supplier, the defects are divided into two types according to their origin, which can be from the customers' factories (OEM) (labeled as Complaint 2 in Figure 25), or the final customer (market) (labeled as Complaint 3 in Figure 25). When a defective part is detected by the OEM during initial use, incoming inspection, assembly, or final inspection, it counts as a "0 mileage defect". The term "0 mileage" may also be called "0 km" depending on the region. When the part fails after the car is sold to the final customer and during the warranty period, the claim counts as "field failure".

A "0 mileage defect" can be found before the part is assembled in the car (for instance during an incoming inspection done at an OEM), or after it has already been installed. In the Company, complaints about uninstalled products are usually related to cosmetic defects, for example, labeling errors. These defects are rarer, as they are more easily detectable through subjective inspection during production. When products are already installed in vehicles at OEM, they can reproduce failure modes that result in more critical defects, such as software or electronic problems.

In order to identify the root cause of a failure and to handle fault complaints, the standard procedure adopted by the Company is the 8D method (D for disciplines), installed by the German Association of the Automotive Industry (VDA) (VDA, 2017).

The 8D method is applied to all kinds of internal and external complaints. After completing it, a report is filled out to summarize how the root causes were determined and eliminated, and also what was done to contain the problem to prevent the root cause from happening again.

In the investigation phase, according to the defect analysis, the status of the device is changed to “claimed”, “analyzed”, “scrapped”, “blocked” or “to return”, and the defect liability for warranty is assigned to one of four options: (i) it is determined as the responsibility of the Company itself, (ii) of the customer, when the defect root cause occurred only after customer delivery, *i.e.*, due to misuse, (iii) in the specification, when requirements were fulfilled, and the product claimed is actually not defective, and (iv) open, when the defect is still under investigation.

For all customer complaints that are attributed to the company’s responsibility, there is a focus on understanding and addressing inefficiencies across (but not limited to) the associated root cause so that defects can be eliminated or minimized in the future. This analysis is carried out by a team made up of specialists from different areas.

There is a team within the Customer Quality (represented in the organogram in Figure 13) responsible for the data management for complaint process-related topics, *e.g.*, fulfilling the whole customer 8D reporting, and archiving the relevant information related to both the claim itself and the associated problem-solving outputs on Integrated Quality Improvement System (IQIS). IQIS is an SAP-based Information Technology system mainly used in the Company for the processing of external (and also internal) complaints with the 8D method. Once the 8D investigation finishes, a root cause can be assigned to the specific failure. The defects may be related to production, development, logistics, supplier, or others.

- Production-related complaints are logged for all quality issues originating on the shop floor, *e.g.*, a misplaced connection, over-tightening of a screw, contamination, etc.
- Development-related complaints arise because of quality issues that are rooted in the bad design of a part.
- Logistic-related complaints comprise quality issues related to the logistic services required by the customer, *e.g.*, wrong shipment, incorrect delivery of documents, etc.
- Supplier-related complains are the ones associated with defective supplied parts.
- “Others” relates to the cases when the fault was deactivated during analysis, and when there is not a detailed analysis.

This thesis mostly evolves around the production-related complaints. Regarding these, there is a list of defects according to which the production-related complaints are associated after the root cause

analysis. This defect directory is the same one used during production to assign a defect type before the reworking or scrapping of a defective part and is presented in Figure 26.

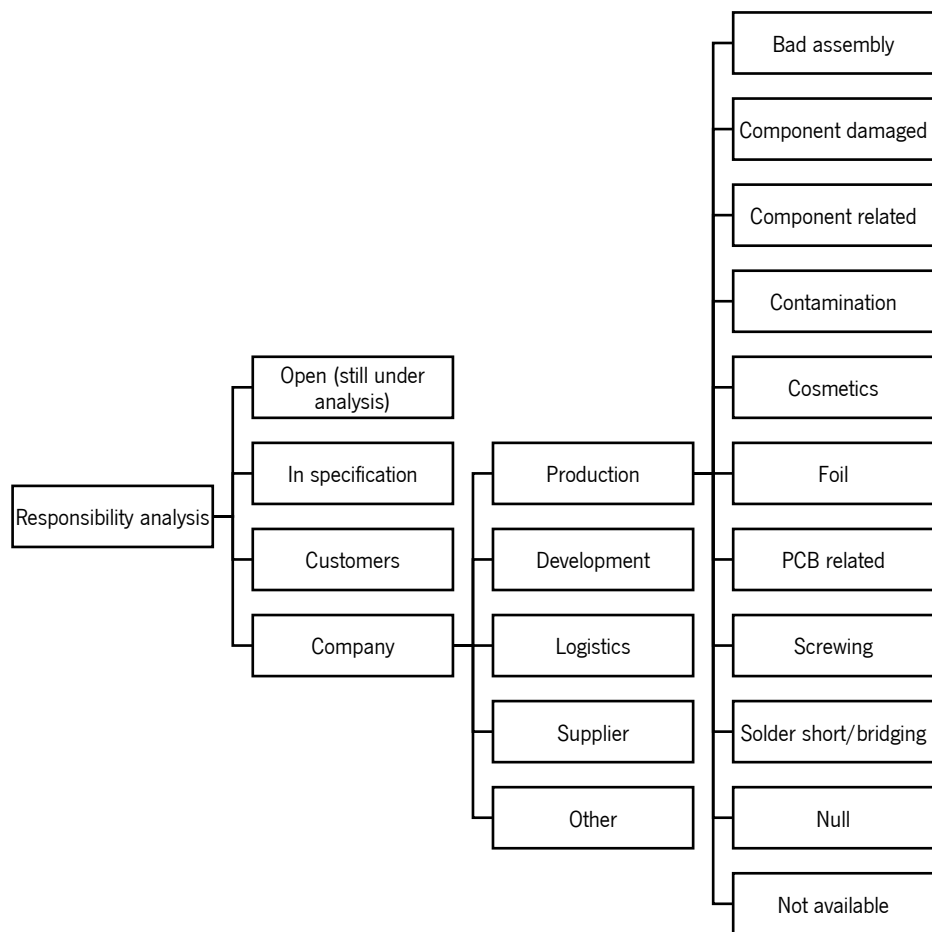


Figure 26 - Categorization of production related defects¹.

¹ Null: missing sort.

Not available: there is a defect but it has no associated category.

4.6 Key Performance Indicators

This section introduces three KPIs used in the Company. The first two (Section 4.6.1 and 4.6.2) are related to internal activities (tests/inspections and rejections/internal failure), while the third (Section 4.6.3) is related to external complaints (external failures).

4.6.1 First Pass Yield (FPY)

First-pass-yield (FPY) describes the proportion of good devices after the first production run, *i.e.*, devices without any defect logged against it, and, accordingly, without associated rework or re-inspection activities. In other words, good devices are error-free parts, that never failed in the process. Once a device fails at any kind of station, it can never again contribute to the number of good devices.

The FPY during a timeframe is defined as the ratio of the number of good devices built in this period to the total number of devices built in this period. It is expressed as a percentage rather than a ratio. Therefore, the ratio is multiplied by the number 100 to get the percentage values for FPY, as shown in the relation of Equation 1.

$$FPY (\%) = \frac{\sum \text{Good devices}}{\sum \text{Produced devices}} \times 100 \quad (1)$$

For example, if 100 devices are produced and tested within the production process in one month, and 96 of them pass all the testing on the first try, the FPY is 96%. The remaining four failed, were reworked, and tested again, in one or more points.

It is possible to evaluate the FPY on different levels (*e.g.*: plant, business unit, product family, production line, WS, TS) to extract useful information. By comparison among production lines, *e.g.*, the higher the FPY, the better the performance of the line. Since rework and re-inspection represent costs, the higher the FPY, the higher the profitability from a qualitative standpoint.

FPY was defined as the official KPI to be followed from 2017 onwards. Previously, another KPI was used, the Total Fall Off Rate (TFOR). TFOR was used as a production line performance indicator since 2011 in all four subsidiary plants, including the Company. TFOR was measured in parts per million and did represent the number of failed tests per plant/line/station/product.

For example, considering a final assembly line with 12 stations, producing 1000 devices per shift, TFOR and FPY are calculated as follows.

TFOR

1000 devices x 12 stations = 12000 tests

60 fails => TFOR = 5000ppm

10 fails => TFOR = 833ppm

FPY

1000 devices per shift

60 devices fail => FPY =94%

10 fails => FPY = 99%

In other words, while TFOR used to focus on overall pass/fail, the FPY focuses on the line output.

4.6.2 Internal Reject Rate (IRR)

Internal Reject Rate (IRR) describes the number of reworked devices for every million produced devices. As referred to back in the previous Section 4.1.1, the parts classified as defective at any WS or Testing Station are transported to a technical analysis station/repair station, which is offline. Parts classified as non-defectives return to the production process and represent false defects given by the measurement system.

IRR is defined by the proportion of repaired devices to the total number of devices, and this ratio is multiplied by the number 10^6 to get the ppm (parts per million) values for IRR, as shown in the relation of Equation 2.

$$IRR (ppm) = \frac{\sum \text{Repaired devices}}{\sum \text{Produced devices}} \times 10^6 \quad (2)$$

As referred to in Section 4, there is a technician in the repair station who enters the information about the defective parts into a system. The defect type is manually labeled according to a directory, before the reworking or scrapping of the part.

As FPY, it is possible to evaluate the IRR on different levels (*e.g.*: plant, business unit, product family, production line, WS, TS) to extract useful information. By comparison among production lines, *e.g.*, the higher the IRR, the worst the performance of the line. Since rework and re-inspection represent costs, the higher the IRR, the lower the profitability from a qualitative standpoint.

4.6.3 Incidents per Billion (IPB)

Incidents per Billion (IPB) describes the number of incidents for every billion produced devices. “Incident” refers to a 0 mileage claim notification, regardless of the amount claimed: there may be an incident with only one part claimed, as there may be an incident with several parts claimed. This ratio is multiplied by the number 10^9 to get the billion proportion. As the IPB is computed yearly, for any year Y, it is given by the relation of Equation 3.

$$IPB = \frac{\sum \text{Claim notifications in Year Y}}{\sum \text{Produced quantity in Year Y}} 10^9 \quad (3)$$

The performance indicator related to 0 mileage complaints used by Company was recently changed due to the need for having an annual closing. Until 2020, the KPI adopted in IPB place was the “0 mileage defective Parts per Million”. "Parts" refers to the quantity of claimed products, distinct from the IPB word "Incident", which refers to a claim notification regardless of the amount claimed. Another difference lies in the unit of measurement, PPM has the million proportion, while IPB has the billion.

There is also a divergence related to the formula calculation for these KPIs. The PPM formula considers the Production Date, while the IPB considers the Notification Date. This implies that the IPB can have an absolute annual closing because when the year is over it is already known how many parts were produced and how many notifications there were, so both the numerator and the denominator of its formula are already defined. PPM, on the other hand, does not allow this annual closing at the end of the year, because only the denominator of its formula is known at this point, while the numerator can keep increasing until there are no more complaints, which can vary depending, for example, on the warranty time defined in the contracts.

To exemplify this formula difference, Table 16 orders product claims according to the notification/reporting and production date to provide a hypothetical example with made-up data for confidentiality reasons. To generate this stair-step table, all the failures reported from the beginning of the production year to the end of the notification year are summed up and given in absolute terms of the total number produced during the relevant period.

Table 16 – Complaints by notification year *vs.* by production year.

		← Notification Date				
		2018	2019	2020	2021	Total
Production Date	2016	6	1			7
	2017	136	4	1		141
	2018	722	176	8		906
	2019		960	260	3	1223
	2020			939	165	1104
	Total	864	1141	1208	253	85

It illustrates a situation in which among the products produced in 2018, 722 were claimed in the same year of production, another 176 products were claimed in 2019, and another 8 in 2020. Assuming that each notification (incident) refers to a unique claimed part and 12 million products were produced in 2018, the values for PPM by the end of 2018, 2019, and 2020 would be the following:

$$PPM_{2018}^{2018} = \frac{722}{12000000} 10^6 = 60.17 \text{ incidents per million}$$

$$PPM_{2018}^{2019} = \frac{722+176}{12000000} 10^6 = 74.83 \text{ incidents per million}$$

$$PPM_{2018}^{2020} = \frac{722+176+8}{12000000} 10^6 = 75.50 \text{ incidents per million}$$

While the result for the IPB_{2018} would be already static by the end of 2018:

$$IPB = \frac{864}{12000000} 10^9 = 72000 \text{ incidents per billion}$$

It is noteworthy that the need for an annual closing is what triggered the Company to change the customer complaint KPI from PPM to IPB.

4.7 Quality Costs

The controlling department (CTG) is responsible for the Company's controlling process, the economic plan, and financial and accounting processes (Campos, 2020).

According to the CTG, the **internal failure costs** data is recorded together by cost center, date, manufacturing department, etc. As shown in the KPI three presented in Figure 27, it may also be computed by production lines and consists of the costs of rejection, rework, and replacement. Internal failure costs are tracked on a monthly basis.

The Company does not determine the totality of costs, but only the categories that it considers most relevant or that it can determine easily. For example, there are no calculated costs related to the **inspection, analysis, and re-inspection** activities in the Company.

The **external failure costs** include transport necessary to move the unit claimed from the customer (intermediate or final) to the Company; analysis carried out at the unit to verify the effect and defect; all costs associated with problem-solving to identify the root cause of the problem (team time, simulations, tests, laboratory analyses); guarantees; consequences for future business; among others. Since the consumption of these resources varies from case to case, one would expect the price of some external failures to be higher than others. However, the Company estimates the average external failure cost for each customer complaint (either 0 mileage or field) at 5000€.

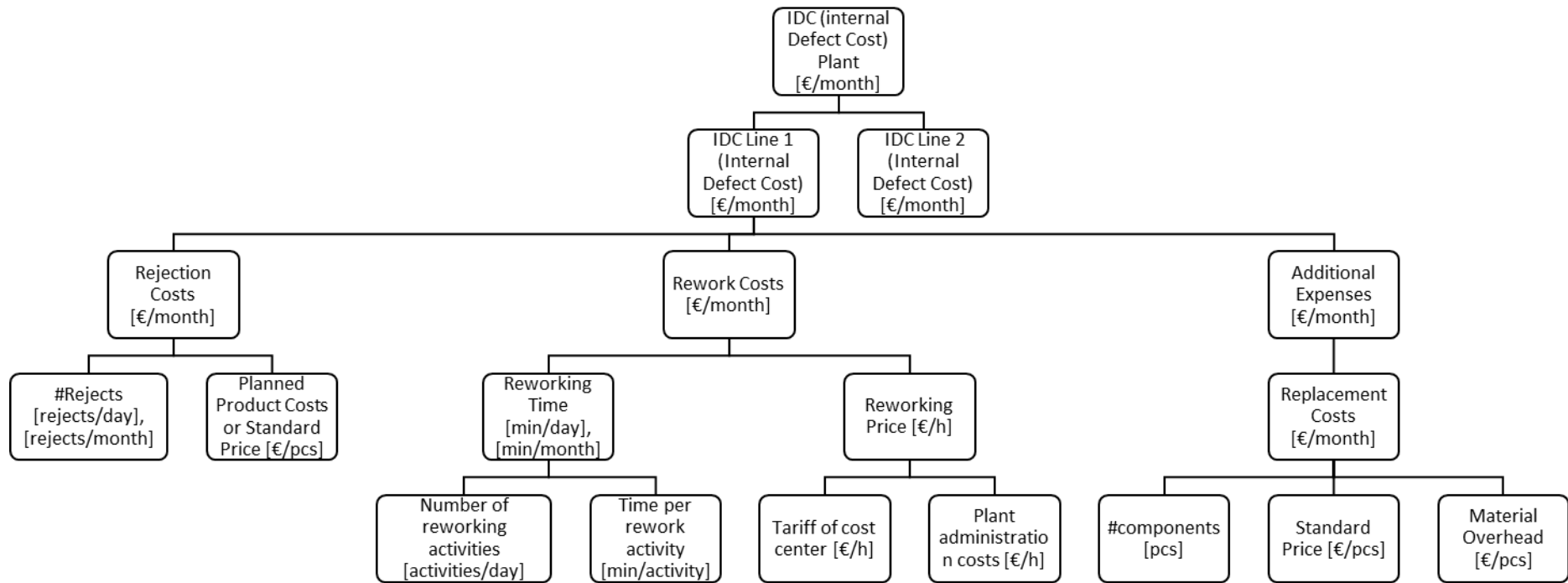


Figure 27 – Company's KPI Tree for Internal Failure Costs.

4.8 Performance Workshop

Performance workshops (PW) are events with cross-functional teams, consisting of individuals responsible for various departments and functions in the organization, that aim to analyze production lines after QG4, *i.e.*, in the Production phase. The PWs usually take eight days: the two first days are for the workshop itself; the five following days are dedicated to implementing “quick wins” to be closed during the PW, and on the eighth and final day a close-up meeting is carried out to present the results and end the PW. Figure 28 illustrates the workshop timeline along with the used tools.

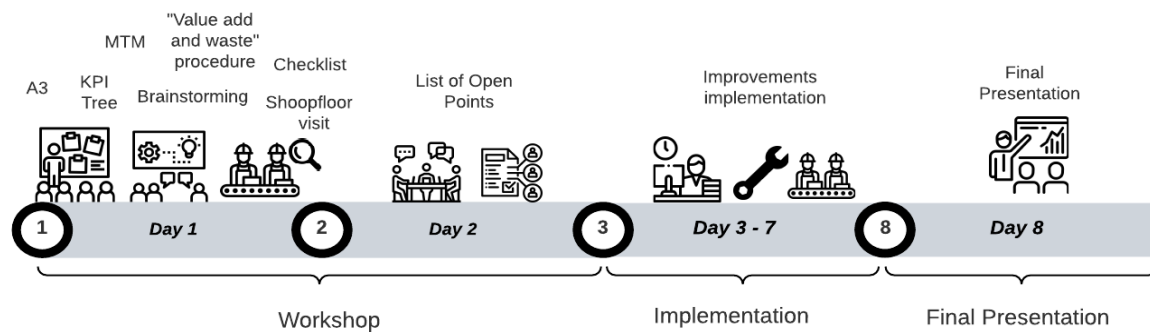


Figure 28 – Performance Workshop Overview.

The workshop agenda for the first two days is outlined in Figure 29.

	Topic	Duration
Day 1	Schedule	00:30
	Presentation of the Workshop Systematic	
	Product and Line presentation	01:00
	A3 Contracting Report presentation	
	“Value-added/waste” analysis procedure presentation	
	Application of “value-added/ waste” analysis on assembly workstations and Open Points List (OPL) creation	01:45
	Application of “value add/ waste” analysis on testing workstations and OPL setting	01:30
	Review of OPL	01:00
Day 2	Preparation for the “go-to Gemba”	00:30
	Alignment of activities for Day 2 Questions	00:30
	Process Analysis at Gemba	02:00
	Presentation of process analysis by participants	
	OPL setting down with actions derived from process analysis	00:30
	Layout analysis and identification of potential improvements	00:30
	OPL screening to define points to close at the workshop	01:00
	Potential gains calculation and its identification in line balancing	01:30
	Planning of next activities	00:15
	Questions and Feedback	00:15

Figure 29 – Workshop Agenda.

As indicated, there are various stages in this event. It starts with the Moderator presenting the workshop's procedure, along with the Contracting Document (Figure 29), where the objective and the

target of the PW are stated. Then, the product and production line to be analyzed during the PW are presented by the Industrial Engineer responsible for it.

Besides the Moderator and the Industrial Engineer, the team is composed of around ten stakeholders, such as product engineers, assembly managers, testing engineers, and quality engineers. Usually, half of the participants have not previously participated in a PW, while the other half have participated in one or more events. The Contracting Document (Figure 30) has important information and is considered an A3 report, so named because it is written on A3-sized paper. A3 reports become the everyday tool through which managers analyze how to move from the current situation to a future state. Additionally, they constitute the mechanism that extends responsibility to all the people involved (Pérez-Pucheta *et al.*, 2019).

CONTRACTING WORKSHOP			
Problem description and initial situation Current productivity: Cycle time:		Contracting finalized: (Sponsor) Contracting released:	at: dd/mm/yy at: dd/mm/yy dd/mm/yy to dd/mm/yy
Limitation of the area of investigation: Area: Project x Content: Increase output according to customer requirement Line/Working cell: Line/product identification		Sponsor: Manager name	Project leader: Project leader name
		Steering Committee: Project team	Moderator: Moderator name
Targets within the Workshop:		Targets after the Workshop:	
Quantitative Increase productivity x% Target: T pcs/op.h	Qualitative Line balancing Standard implementation and stabilization	Quantitative Increase productivity y% Target: T _{after} pcs/op.h	Qualitative Line balancing Standard implementation and stabilization
Particular Agreements: (e.g.: Capacity agreed with the customer corresponds to a cycle time of x seconds. The current production corresponds to an average cycle time of y seconds)		Implementation Implementation planned until: dd/mm/yy Availability Project Leader: x% Review with Steering committee: dd/mm/yy	
Workshop participants: 100% released from other duties			
Name		Function	
Participant 1		Industrial Engineer	
Participant 2		Quality Engineer	
...		...	

Figure 30 – Contracting Report template used for the PW.

Among all the information, it sets the objective of the workshops, which is related to productivity improvement. The productivity indicator is expressed by the following Equation (10):

$$\text{Productivity} = \frac{\text{Production quantity}}{\text{Number of direct operators} \times \text{Working hours}} \quad [\text{pcs/mhr}] \quad (10)$$

The Contracting Document used within the PW is always based on this productivity indicator, considering both the human factor (working hours) and the production quantity. Other CI events, such as the Ration Project Planning (Leite, 2013; Machado, 2021), analyze also costs.

The productivity improvement objective can be reached either by increasing the production output with the same operators or by maintaining the production output with fewer operators. The target to be reached through the PW is derived from a Line Balancing analysis, a production strategy that involves balancing operator and machine time to match the *production rate* to the rate at which parts or products must be produced to meet customer demand, *i.e.*, *takt time*. For a given production line, if the production time is exactly equal to the takt time, then the line is perfectly balanced. Otherwise, resources should be reallocated or rearranged to remove bottlenecks or excess capacity, which usually happen as a result of the PWs. In other words, the quantities of workers and machines assigned to each task in the line are rebalanced to meet the optimal production rate.

In the PWs, the KPI tree is used for target analysis. According to company guidelines, the KPI tree is a tool that must be used in all CI projects across the company. In addition to helping to understand the relationships between indicators through a visual map, KPI trees are created with embedded formulas to calculate the indicators and to derive the project target down to monitoring the KPI level. Specifically, in the PW case, that implies finding out which indicators eventually influence productivity. This is done by simulations based on the change of the cycle time indicators of the workstations.

After the presentation of the line balancing analysis and of the contracting document, there is a brief presentation of the Company's procedure called "value add and waste", according to which activities within the production line are considered either as 1) value-adding activities, 2) evident waste activities, or 3) concealed waste activities. The first group comprises those activities through which a product acquires an added value, *e.g.*, screwing. The second group comprises the activities that are unnecessary to increase product value and should be minimized, but can never be completely eliminated, *e.g.*, refilling of reservoirs. The third group comprises the activities that do not bring an increase in value, and although required under given circumstances, should be entirely eliminated., *e.g.*, double handling.

The value-adding and waste procedure also considers in its premises the Company's ergonomic standards for the range of distances. Short-range distance is set for usual tasks, *e.g.*, assembling parts, while long-range distance is set for occasional tasks, *e.g.*, reaching a material. If the short- and long-range movements exceed the respective limits of 30 cm and 50 cm, they are considered wastes.

In a brainstorming session, the PWs participants look to this procedure as a diagnostic tool to identify wastes per workstation and to define measurements to overcome them, *i.e.*, to reduce the cycle time and consequently improve productivity. For doing so, the cycle time is estimated through Methods-Time Measurement (MTM), a method for motion time study based on the predetermined times of five basic movements: to reach, to grasp, to move, to position, and to release (Almeida and Ferreira, 2009; Fantoni

et al., 2021; Tavares Pinhão, 2015). It is used in the field of workplace design and improvement (Fantoni *et al.*, 2021) and can be complemented along with chronometer analysis (Almeida and Ferreira, 2009).

The brainstorming session leads to the development of actions within an Open Points List, where tasks and deadlines are defined by the group for each improvement suggestion, along with the nomination of the participant responsible for follow-up and ensuring each one of these activities is executed. This is done within a project management tool. At the end of the first workshop day, an alignment of activities for the following day is carried out, preparing for the visit to the factory floor, the so-called “Go to *Gemba*”.

On the second day of the workshop, the team visits the shop floor to observe the production line. Tasks and activities are simulated by the same personnel who perform them in their normal daily work, and they eventually point out key deficiencies, sources of difficulties, and alternative solutions. In the meantime, each PW participant is responsible for measuring the cycles of a given line operator through a stopwatch. On the sheet where these measurements are noted, it is suggested to measure 10 cycles to check process stability and compliance with Standard Work.

In addition to the cycle time measurements, the PW participants also analyze the wastes of the process using a checklist to take notes. The list comprises sections where they write observations related to Waiting, Inventory, Transport, Motion, Over-processing, Overproduction, Defects, and a section for other wastes eventually observed. During the waste analysis, the participants can use a measuring tape to verify distances, *e.g.*, the ones apparently above the ergonomic limits.

After the “Go to *Gemba*” activity, the PW team reconvenes, and each participant can point out the identified shortcomings. The ideas provided by each team member are then collected. These individual thoughts are documented and reviewed by the team. This process leads to the elimination of duplicate suggestions while also allowing the expansion of original ideas when needed. The group discussion is related to the solution ideas, proposed plans, and corrective actions, all of which were documented in the List of Open Points.

During the following five days after the workshop, each participant has time to implement the proposed actions. At the final meeting, on the eighth day, the moderator of the PW briefly presents the general results to the top manager of the production department and the PW participants. The contracted target is shown in contrast to what has been achieved in terms of increased productivity, together with examples of actions taken. The plan for implementing the actions that it was not possible to fully implement during the PW is also presented, with their potential estimated productivity gains. Such actions are considered “future proposals”, whose implementation and verification of effective gain are then under the responsibility of the industrial engineering team.

5 Analysis and Discussion of Results

This chapter presents the analysis and discussion of the results of the case study analysis in relation to KPIs reviewing and improvement (Section 5.1), KPIs relationships (Section 5.2), designing and improvement of inspection and quality control strategies (Section 5.3), and the modeling of inspection strategies to minimize quality costs. (Section 5.4).

5.1 Revision and Improvement of Current KPIs

Qualitative analysis of the KPIs

The KPIs IRR, FPY, PPM, and IPB are presented in Table 17 based on eleven attributes (Neely *et al.*, 1997) to explore what constitutes a well-designed KPI. Table 17 was filled out according to the data reported in the Company's information system, *i.e.*, wiki page, dashboards, and old reports. Most of the information was available, except the "objective" and "who acts on the data" items. That is why these fields were filled with a question mark (?) in Table 17.

Table 17 – Main attributes of the analyzed KPIs.

Title	TFOR (Total Fall Off Rate)	FPY (First Pass Yield)	IRR (Internal Reject Rate)	PPM (Parts per Million)	IPB (Incidents per Billion)
Objective	?	Represent all error-free complete devices in the processes	Represent the rejection rate in the processes	?	?
Scope	Used to be applied in all product classes	Focus only on “complete devices” (<i>i.e.</i> , some stations are out of scope)	9 product classes	7 out of 9 product classes	7 out of 9 product classes
Target	Used to be defined by a top-down approach	Defined by a top-down approach, considering the result achieved in the previous year increased by 10% of the improvement margin. <i>E.g.</i> , if in the previous year the FPY resulted in 80%, there is a margin of improvement of 20% (to reach 100%). Therefore, the new target would be $80\% + (20)10\% = 82\%$	Defined by a top-down approach	Used to be defined yearly by a top-down approach (usually 10 percent less than the previous year)	Defined yearly by a top-down approach
Formula	$TFOR (ppm) = \frac{\sum Test\ fails}{\sum Total\ tests}$	$FPY (\%) = \frac{\sum Good\ devices}{\sum Total\ devices}$ (by production date)	$IRR (ppm\%) = \frac{\sum Repaired\ devices}{\sum Produced\ devices}$	$PPM (ppm) = \frac{\sum Produced\ items\ in\ Year\ Y\ that\ failed}{\sum Produced\ quantity\ in\ Year\ Y} \cdot 10^6$ (by production date)	$IPB = \frac{\sum Failure\ notifications\ in\ Year\ Y}{\sum Produced\ quantity\ in\ Year\ Y} \cdot 10^9$ (by notification date)
Frequency of measurement	Updated in “real-time” in a dashboard	Shared monthly in an excel file located in a folder, whose path is described on the wiki page Updated in “real-time” in the dashboard Ad hoc	Monthly	Updated in “real-time” in a dashboard	Shared monthly in an excel file located in a folder, whose path is described on the wiki page Updated in “real-time” in a dashboard, with an annual closing

Title	TFOR (Total Fall Off Rate)	FPY (First Pass Yield)	IRR (Internal Reject Rate)	PPM (Parts per Million)	IPB (Incidents per Billion)
Source of data	SAP	SAP	Company internal software program	SAP	SAP
Who measures?	Automatically	Automatically	Analysis technicians on repair stations	Automatically	Automatically
Who acts on the data?	?	?	?	?	?
Notes and comments	Replaced by the FPY	Implemented in 2017		Replaced by the IPB	Implemented in 2021replacing PPM
Frequency of review	Top-down approach	Top-down approach	Top-down approach	Top-down approach	Top-down approach

Table 18 shows the synthesis of the major results obtained through the current KPIs analysis based on documental research and semi-structured interviews with Company's employees. The first column shows the relevant questions used to assess the KPIs, while the other columns present the results for each KPI. The KPIs TFOR and PPM were excluded of this analysis because they are no longer in use in the Company, *i.e.*, following the KPI lifecycle, they were reviewed and replaced by FPY and IPB, respectively.

Table 18 – Synthesis of the analysis of the current performance measures.

	FPY	IRR	IPB
Are the measures clear?	Yes	Yes	No
Are the measures practical?	Yes	Yes	No
Are the measures easy to understand?	Yes	Yes	No
Are data collection and analysis worth the cost?	Yes	Yes	Yes
Are the objectives of the measure aligned with the objectives?	Yes	Yes	?
Is it possible to act based on the data?	Yes	Yes	No
Are the scales and units appropriate?	Yes	Yes	No
Is there any possibility of ambiguity in the interpretation of the results?	No	No	No
Can the data be analyzed quickly enough so that actions can be taken?	Yes	Yes	No
Is the measure consistent no matter when it is performed?	Yes	No	?
Is the frequency of measurements adequate?	Yes	Yes	Yes
Can the data be promptly communicated and easily understood?	Yes	Yes	No
Is the frequency of the review of targets adequate?	Yes	Yes	Yes

This analysis suggests that the performance measure FPY should be maintained without changes. It is in accordance with both the characteristics reported in the literature for a good performance measure and with the objectives of the Company, although there is a suggestion to improve it presented at the end of this section. The performance measure IRR is also aligned with the objectives of the Company, but there is an issue related to the consistency of this KPI. The performance measure IPB is the one with more divergences on what constitutes a well-designed KPI. The following sections present some considerations and further analyses of these KPIs.

5.1.1 First Pass Yield

FPY is a good measure of the effectiveness of a process and the elimination of waste from that process. First-pass yield can also be a good measure of the success of CI activities. Very often CI initiatives are focused on the reduction of waste and inefficiency, which can be hidden from analysis if FPY is not measured. A waterfall chart, such as the one presented in Figure 31, is frequently used to break down the FPY performance in the Company. Therefore, specific analyses are made for each one of the parcels contributing to the low FPY performance, and corrective actions are taken to overcome them.

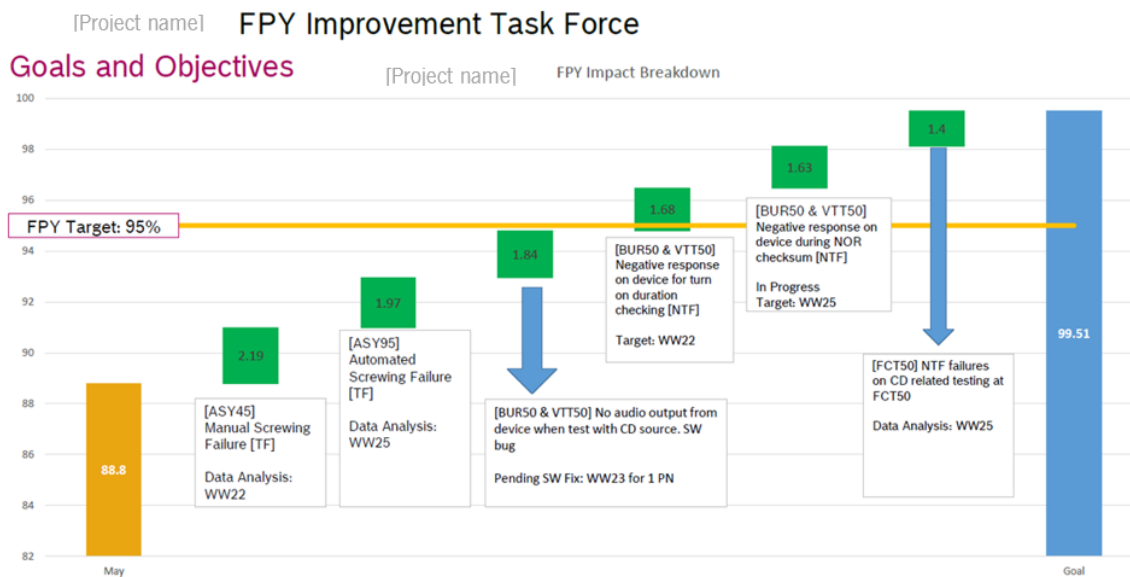


Figure 31 – Example of FPY use in a CI task force.

The FPY improvement task forces are congruent with the ones presented in the literature, *e.g.*, using six-sigma project formats and the DMAIC methodology (Gijo *et al.*, 2014; Gijo and Scaria, 2014). During the improvement task forces of FPY, the involved team needs to be aware that some measures might be of interest to other products, projects, and plants as well.

FPY was defined as the official KPI to be followed from 2017 onwards. Previously, another KPI was used, the Total Fall Off Rate (TFOR). TFOR was used as a production line performance indicator since 2011 in all four subsidiary plants, including the Company. TFOR was measured in parts per million (ppm) and did represent the number of failed tests per plant/line/station/product.

During the ramp-up phase of the Industrialization Process (Section 4.2), monitoring test performance using TFOR was difficult until steady-state production was reached. This is because during ramp up there are debug activities, which used to cause significantly higher TFOR, while newly adopted assembly processes used to lead to significantly lower TFOR results. As a result of this inconsistency, a new KPI was necessary allowing ramp-up monitoring, and it was decided that FPY would be implemented.

As FPY is measured in % and represents the number of error-free parts per plant/line/station/product, it is suitable for both ramp-up and steady-state production. Figure 32 represents the Industrialization Process phases indicating the monitoring stages and the transition from TFOR to FPY.

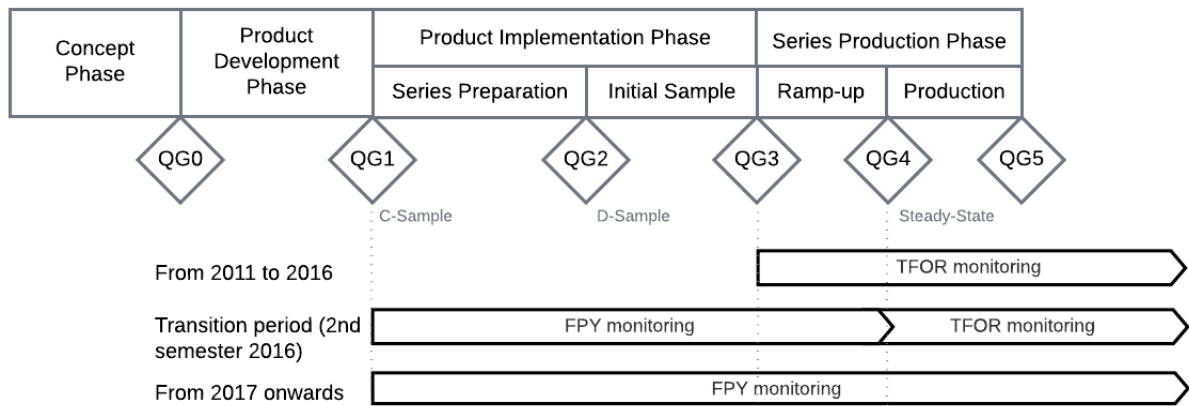


Figure 32 – TFOR to FPY.

Considering the limitations of the TFOR, the importance of the revision phase in the KPIs life cycle became evident. Back in 2016, a team carried out several meetings addressing the TFOR evolution and identifying the above-mentioned limitations. The objectives were to find an agreement on a common approach for a new KPI inside the Company. The replacement of the TFOR with the FPY was a very challenging project. This initiative was taken by the Company, which had to articulate and disseminate the new KPI with the other plants through presentations, meetings, emails, and other modes of communication. The target definition was very difficult, particularly during the transition period. Nevertheless, the switch from the TFOR investigation into FPY brought a clear picture to measure the performance of the line before steady-state production, as early finding and fixing of errors give a good indication of what would be faced in the line during steady-state production.

As referred to in Section 4, many components/sub-assemblies that compose a complete device are built in-house. It was defined that the FPY would not comprise all the sub-assembly processes. Therefore, the FPY is calculated based on data from the Final Assembly only, while data from the sub-assemblies are not contemplated/are out of scope. For example, if a unit does not fail at any point in the Final Assembly line, it is computed as a good device for the calculation of the FPY, even if it has a PCBA that has been reworked due to a quality defect arising in the PCBA insertion process. The history of a product begins with the production of its components. It is relevant under which conditions a product is produced, or to which stresses the product and its components have been exposed. The FPY overlooks the "history of the components".

5.1.2 Internal Reject Rate

Through informal interviews with those responsible for carrying out the IRR records (*i.e.*, the technicians in the repair stations who enter the information about the defective parts into a system) and through direct observation of this process, it was possible to perceive a discrepancy existing in the IRR because of poorly executed records. The observed causes of bad registrations are:

- Lack of knowledge of the existing codes for the registration of defects and presumption that the code to be used would be the “S-case” (S-case = improper rejection by the inspection/test system). S-cases are not to be considered in the indicator: it relies on the subjective judgment of the repair personnel.
- Easiness in registering defects as “s-case”.
- Difficulty in choosing the appropriate defect code due to the lack of technical knowledge regarding the product and product pieces.
- Records are badly executed on purpose to reduce the IRR of production lines (*i.e.*, S-case is not counted).

In sum, it was verified that sometimes the analysts go the easier way, registering wrong due to a lack of knowledge or intended manipulation. As stated by Cerqueira (2021), in January and February 2021, the sum of internal incidences related to poorly assembled foils in the Company was 78 cases. After standardizing the data collection method and raising the awareness of the ones responsible for the records, the IRR of the lines of one client were 1231 incidents of poorly assembled foils recorded in March, and 53 at another client. This corresponds to an increase of approximately 1600% in the IRR.

This factor of human error leading to typos and missing information when dealing with defective products is also described by Sokolov *et al.* (2021), who reported a case where the scrap cost was calculated based on documents filled out by the production operators (Sokolov *et al.*, 2021).

5.1.3 Incidents per Billion

The scope of both PPM and IPB includes seven out of nine product classes. The target, defined by a top-down approach for all production facilities worldwide, requires the achievement of a result 10 percent better compared to the previous year. The source of data is an ERP system software (SAP), and all the KPIs are automatically measured and displayed in a data visualization tool. The indicator reviews are done in a top-down approach (in the last revision the PPM was replaced by the IPB).

Since many product classes have an external complaint rate of around 100 incidents per million, calling it IPB (incidents per billion) may complicate the interpretation of the magnitude of the unit of measurement. In other words, it is simpler to understand the first sentence than the second:

- 1) 100 claims for every 1 million pieces produced.
- 2) 100,000 claims for every 1 billion pieces produced.

The most important feature of a KPI is to be derived from a strategy with an explicit and clear purpose (Kaplan and Norton, 2007; Neely *et al.*, 1997, 2005). Van Camp and Braet (2016) emphasize the need to explicitly state the contribution of every single metric to the strategy since their misalignment could push progress in various untargeted directions. KPIs not aligned with the Supply Chain strategy and without clear objectives may result in conflicts and inefficiencies (Kazemkhanlou and Ahadi, 2011). Based on interviews with workers and managers and after consulting existing information in the company's wiki page that reports on KPIs, it was apparent a lack of a clear objective, which is the main problem with both the previous (PPM) and the current (IPB) customer complaint KPIs. Therefore, assuming certain purposes, this section presents three situations that could lead to wrong conclusions and generate misleading policy messages from IPB, which are summarized below and detailed afterward.

Situation 1: If the objective is to control the production process, the indicators are not useful because they are lagging indicators.

Situation 2: If the objective is to quantify the failure rate claimed to plan improvement efforts in weak areas, the current indicator is not useful: since IPB is calculated considering the number of notifications, one single notification can contain numerous claimed parts. This leads to misinterpretation of the indicator as it hides valuable information for understanding problems.

Situation 3: If the objective is benchmarking, the indicators are not useful. Both the previous and the current KPI aggregate product classes by giving them equal weight. This invites simplistic conclusions as some products with different complexity levels fall under the same measure and the indicator is not capable of identifying which class failed.

Situation 1:

Generally, items produced on a particular date are sold on different dates. The interval from the month of production to the month of purchase is known as the “sales lag”. When claims are reported to the company, there are frequently substantial delays between the time that a claim

occurs and the time it is entered into the warranty database used for analysis. This delay period affects recent counts of claims and is known as the “notification delay” or “reporting lag”. Figure 33 presents the complaint handling process timeline.

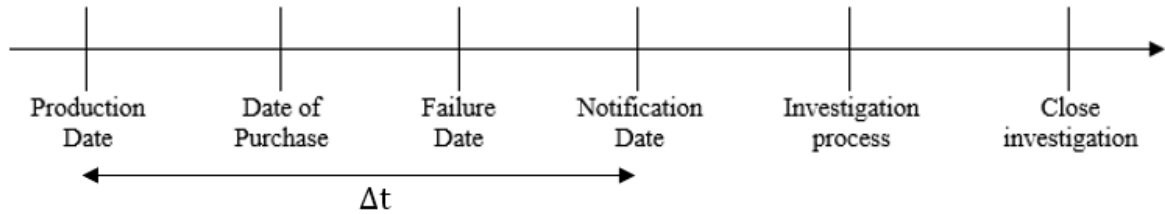


Figure 33 – Complaint handling process timeline.

Considering all the complaint data of the Company from January 2016 to March 2021, a total of 3364 complaints were recorded. Figure 34 is a histogram that presents the frequency of days between the Production Date and the Notification Date (Δt), showing that about 50% of the notifications happen eight weeks after the Production Date.

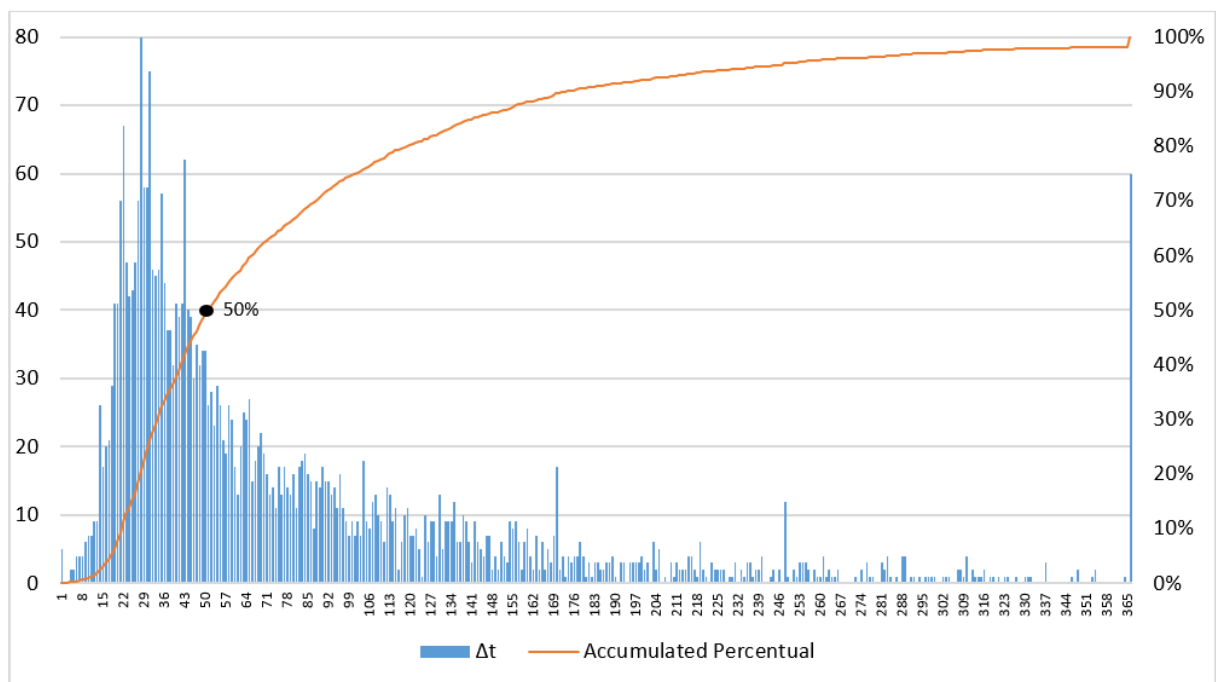


Figure 34 – Days between Production Date and Notification Date (Δt).

As shown in the histogram presented in Figure 34, both failures and notifications can be out of time. This implies that the number of complaints received in a given year may not indicate the current quality because of this lagged effect. The KPI must provide timely and accurate feedback (Defeo, 2016), which in this case can be understood as the ability of the system to feed customer claims back to production facilities in the form of quality controls (Sanchez-Marquez *et al.*, 2020).

However, both PPM and IPB are lagging indicators. In the manufacturing phase, if the process is changing, it is more likely that the detection of changes will happen earlier through leading internal indicators than by lagging external indicators (Mitra, 2016). A lagging indicator is mostly used for review purposes in the long term, and, therefore, their focus is not to offer the opportunity for control during the production process or to measure operational performance, but to measure performance at a corporate level (Carina Sofia de Andrade Marinho, 2018). The existing 8D process can trigger a prompter recalibration of internal quality control to ensure the system continues predicting, reacting, and preventing future customer complaints.

Situation 2:

A possible cause of misinterpretation of the indicator is due to its calculation by notifications (incidents) instead of by claimed parts, as this can hide valuable information for understanding problems. For example, considering that in one year (Year 3 in Figure 35) one notification is reported with several claimed products, the IPB would not show this issue, while if the indicator were calculated by PPM, this situation would be evident.

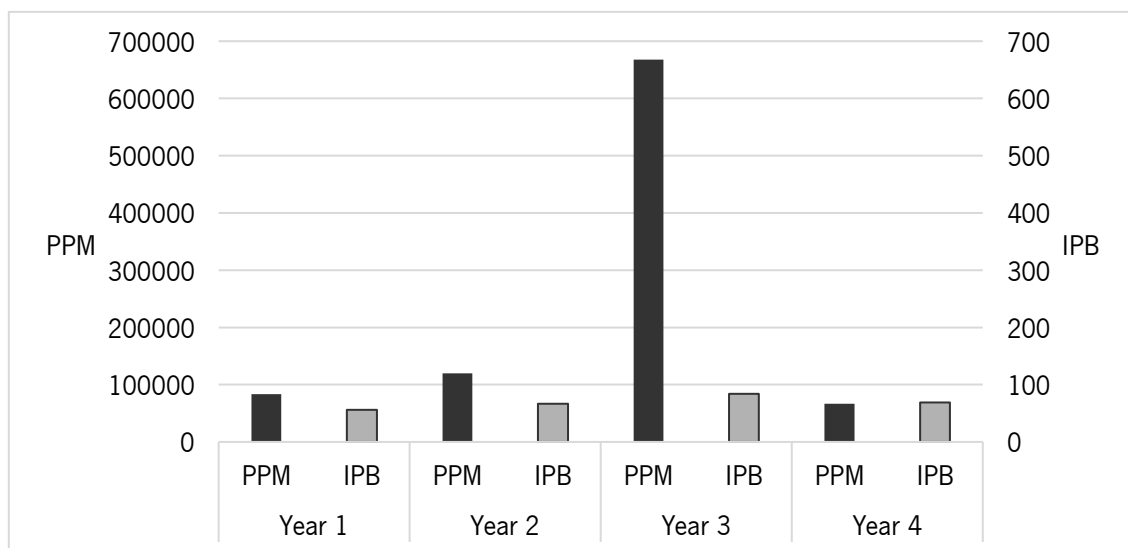


Figure 35 – PPM vs. IPB.

Situation 3:

The way PPM and IPB indicators are defined gives equal weight to all product classes, however, they are different in their complexities. Although it is desirable that all product classes are impeccable regarding quality, they should not be treated in the same way: different strategies may be necessary to achieve the same quality level. For instance, two of the Product Classes are Chassis Sensors and Instrument Clusters, as shown in Figure 36. A Chassis Sensor is a very robust product

that rarely fails and is produced in large volumes in the Company. On the other hand, an Instrument Cluster is produced in a lesser quantity and is, comparatively, a very complex product with more critical variables to be controlled. Therefore, its probability of failure is much higher. Aggregating these different Product Classes in the same indicator can generate misleading policy messages (*i.e.*, making it looks like a company's performance is better or worse than what it is).



Figure 36 – (a) Chassis Sensor; (b) Instrument Cluster.

5.1.4 Improvement Suggestions

Based on the presented qualitative analysis, it is possible to suggest improvements for the specific evaluated KPIs and the Company's PMS in general.

5.1.4.1 Specific KPI

Improvement suggestions for the specific evaluated KPIs are summarized in Table 19 and discussed below.

Table 19 – Synthesis of the suggestions for the analyzed KPIs.

KPI	Proposition/suggested change	Procedures necessary for the implementation
FPY	Maintain a historical record of defective parts in the assembled product log as a means to allow a more effective investigation of defective products by tracking the roots and propagation of failures.	Involving the IT area for the creation of a product log that shows the previous production status of all main components.
IRR	Improve the reliability of the current data acquisition system.	Providing technical training, as well as raising awareness on the importance of correct registrations into the system through information campaigns.
IPB	Make the purpose of IPB (and any other KPI) clear and explicit on the company's information system page. Define targets for each product class.	Creating a "KPI attributes list" as a company guideline to be used for all the KPIs.

FPY: As explained in section 5.1.1, the main issue of this KPI is the absence of a historical record of defective parts in the assembled product. The suggested improvement refers to keeping this information in the assembled product log as a means to allow a more effective investigation of defective products. This can be done by involving the IT area in the creation of a product log that shows the previous production status of all main components to track the roots and propagation of failures. The main implementation challenge would be related to data management issues.

IRR: The IRR lacks consistency because of deficiencies in the current data acquisition system. This could be solved by providing technical training, as well as raising awareness of the importance of correct registrations in the system through information campaigns. Issues should be logged into the system so that correct data can be generated, and proper mitigation steps can be taken. Only in the presence of the right data, causality can be attributed correctly and conclusively to various observations.

IPB: For the IPB, the lack of a clear objective was an obstacle to well-defined policies as exemplified in Section 5.1.3. Literature states that KPIs must be derived from strategy with an explicit purpose, otherwise, they will not be understood as relevant. Thus, it is important to make the purpose of IPB (and every other KPI) clear on the Company's information system page.

There may be several purposes for the customer complaint indicator (IPB), for example: (1) Quantify complaint rate by OEMs to assess customer satisfaction; (2) Quantify complaint rate warranty decisions to assess supplier quality; (3) Quantify complaint rate according to product class to identify fault peaks, to find out the weak areas and to plan endeavors for their improvement. According to the established objective, one or more stakeholders will be responsible to act based on the data. This way, the problem of lacking the “who acts on the data” field would be solved for this KPI.

About the scope and the target, although a composite indicator for all the product classes may facilitate the interpretation if compared to a battery of many separate indicators, it is believed that an individual indicator with an individual target should be defined for each product class. Then, instead of aggregating all product classes with the same weight (equal to 1), it is suggested to aggregate them with different weights, considering, for example, product complexity and costs. The weighted composite indicator would better summarize the complex multi-dimensional realities to support decision-makers, by reducing the visible size of a set of indicators without dropping the underlying information base (Joint Research Centre-European Commission, 2008). For this, it is

necessary to construct a weighting system and review it periodically as a part of the target and objective setting for the future.

5.1.4.2 Performance Measurement System

In addition to the specific KPI issues discussed above, it was also identified that the PMS as a whole could benefit from further changes. In sum, the general recommendations of Table 20 are suggested in this regard.

Table 20 – Synthesis of the suggestions for the PMS in general.

Regarding the dashboards	Regarding the KPI targets	Regarding the review phase of the KPIs lifecycle
Provide user-friendly dashboards with graphical representation and visualization of KPIs. Enable greater transparency by providing access to the dashboards in a horizontal reporting approach. Display a summarized and updated "KPI attributes list" along with the dashboard.	Setting realistic minimum KPI targets considering the complexity of the product, station, or situation in the case. KPI targets need alignment at the beginning of the projects, and the way these targets are defined must be approved by management and clearly described in the KPI attributes lists. Targets for FPY should increase over time toward steady-state production.	To install a team for larger KPI reviewing projects, especially when running in more than 1 plant at the same time. To take a "fresh look" and think both individually and in group sessions (with the established team) about new possible KPIs. Report directly from the wiki pages instead of creating extra PowerPoint presentations, avoiding asymmetric information distribution.

The first suggested change relates to the graphical representation and visualization of KPIs. Visualization of the results should receive proper attention, given that visualization can influence (or help to enhance) interpretability (Joint Research Centre-European Commission, 2008). The study of KPIs and their metrics lends itself to Shneiderman's visualization mantra, "overview first, zoom and filter, then details-on-demand" (Shneiderman, 1996). Therefore, rather than just representing the indicators as a static quality figure with its target, it is important to make available visualization technique that communicates more information. Through an analytic dashboard, it is possible to enable the users to explore the indicator as they wish for emphasizing a particular set of information, for example:

IRR: filtering the reject rate by product class to identify fault peaks to find out the weak areas and to plan endeavors for their improvement.

FPY: filtering according to TS of the same category to identify divergences. Add a temporal grouping tool to keep track of changes over time.

IPB: filtering the complaints by OEMs to assess customer satisfaction; filtering according to warranty decisions to assess supplier quality.

One of the main challenges associated with this change is the fact that it takes time to implement and fine-tune a dashboard, especially in a large and complex organization. Additionally, the PMS could benefit from visualizing KPIs relationships through node networks or matrix-based tools, as discussed by Brundage *et al.* (2017). These relationships among evaluated KPIs are discussed in Section 5.2.

Another suggested change is related to the need for greater transparency by providing improved access, extended visibility, traceability, and disintermediation for KPIs. The main drawback of this change is related to the license to use the dashboards, which specify prices to additional users, limiting broader data sharing. However, it is essential to make the organization's data easily accessible to new participants/segments (whilst also guaranteeing protection to intellectual property in sharing of company related information), as this eliminates the need of intermediation to extract and email data.

In conjunction with the reachable dashboards, it is also suggested to involve the IT area and place on the Company's internal information system an updated "KPI attributes" table, along with the responsible for the KPI in case of more information is needed by the KPI user. It is important to describe the meaning, presentation, data sources, and technical requirements in order to get a solid foundation for further analysis.

To manage a KPI review in a context of a global network of four plants, with specific locations and cultures, is very challenging. One challenge refers to the different understanding of general quality targets on the project level, in different plants, and in the Quality Management and Methods (QMM) department. For instance, with the FPY starting in four plants at the same time, it became very difficult to have a mutual understanding of issues and countermeasures among all plants.

Each site in the network has an assigned strategic role according to the specific location factors, *e.g.*, qualification level of employees, specialization regarding the market, final product, or realized processes. Defining a mutual target system for all the plants is not always realistic.

As already stated regarding disaggregating the IPB targets by the product classes, all targets must be designed and drilled down according to the capabilities of individual sites, product classes, and situations, with individual optimization measures being set depending on the respective target system. In other words, depending on the operational context, there is a different scope for action that can be pursued, and the goal setting somehow guides these efforts: too high/unrealistic targets can demotivate, while too low can restrain the excel opportunity.

Considering the limitations of the KPIs analyzed, the importance of the revision phase in the KPIs life cycle becomes evident, as well as the need for redesigned KPIs. Reflecting on the case study experiences, we stress that it is important to take a “fresh look” and think individually and in group sessions about new KPIs. Particularly, the replacement of the TFOR by the FPY was a very challenging project as presented in Section 6.1.1. This initiative was taken by the Company, which had to articulate and disseminate the new KPI with the other plants.

Considering the lessons learned in the overall reviewing process, it is suggested to install a team for larger KPI reviewing projects, especially when running in more than one plant at the same time. In addition, it is beneficial to report directly from the wiki pages to management and users and not create extra PowerPoint presentations, as this represents double work and carries the possibilities of two different views and asymmetric information distribution.

While the initiative to replace the TFOR with the FPY was taken by the Company itself, the replacement of the PPM by the IPB was required by the global parent company. Perhaps the parent company sees the IPB as a means through which they can benchmark the subsidiary's performance regarding customer complaints. This internal benchmarking is supposed to entail the aspiration to improve upon, or at least match a peer plant, reinforcing competitive globalization. However, some interviewees reported that as the definition of IPB has become taken as given, the rules stipulated by the parent company for measuring the complaint indicator gave little scope for variations across different local units.

Apparently, the Company gives more strategic value and importance to adopted KPIs “rooted” in their own manufacturing strategies, designed on a trial-and-error basis, such as the FPY. Accordingly, it could interpret, redefine, and customize given KPIs and hence author their own KPIs versions, although this can generate somehow redundant KPIs.

Nonetheless, it is also recognized the several challenges that accompany any organizational change. In particular, this work has shown the difficulty and complexity in designing/reviewing and updating the KPIs regarding the following aspects:

- Technical: Complexities are related to changes in information technology to implement the changes in procedures for computing the KPIs, *e.g.*, regarding data quality, technology, and expertise.
- Goals and objectives of an organization: Having a business need, a clear link to business objectives, and a reasonable establishment of targets.

- Organizational factors: The establishment of KPI requirements in a multinational company may be very difficult, whether in a top-down or horizontal approach.

5.2 Identification and Quantification of Relationships between KPIs

5.2.1 Internal and External KPI Intertwining

After evaluating three existing KPIs in detail and proposing changes to each particular KPI and the overall PMS, this section is concerned with determining if there is any type of quantitative correlation between the FPY, IRR, and IPB.

To analyze and establish potential relationships between internal tests (which are related to IRR and FPY) and customer complaints (related to IPB), it is necessary to deal with an imbalanced dataset. Daily, millions of tests are generated in the Company. The amounts of passed and failed products within internal inspections are highly disproportionate, as only a small proportion of the products are failures. The number of customer complaints is even more imbalanced.

An example that illustrates this imbalance is displayed in Figure 37. For a sample dataset encompassing all the production of 2021 and 2022 of the product presented in Section 5.4 (a total of 3109317 units), 133349 failed at some internal inspection and were therefore repaired, while 2975968 units passed all tests and internal inspections the first time or were considered as improper rejections of the testing stations (*i.e.*, s-cases).

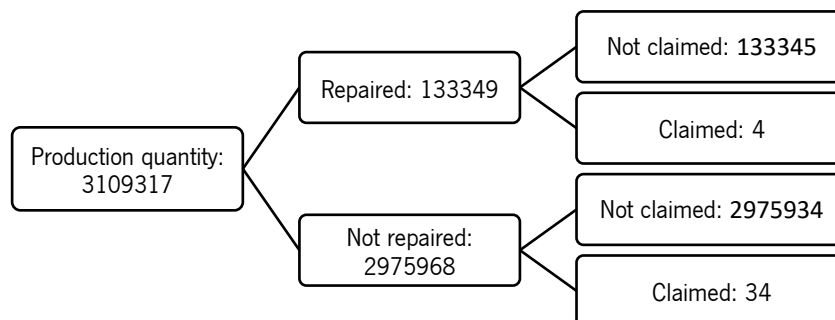


Figure 37 – Imbalanced dataset.

To enable an appreciation of the difference in proportions between the groups (repaired and not repaired), the chart of Figure 38 provides a visual breakdown between the claimed and not claimed product quantities for each group. As illustrated, of the 133349 units that were repaired, 4 were claimed by customers, 0.0030%; while of the 2975934 units of the not repaired products, 34 were eventually claimed by customers or 0.0011%.

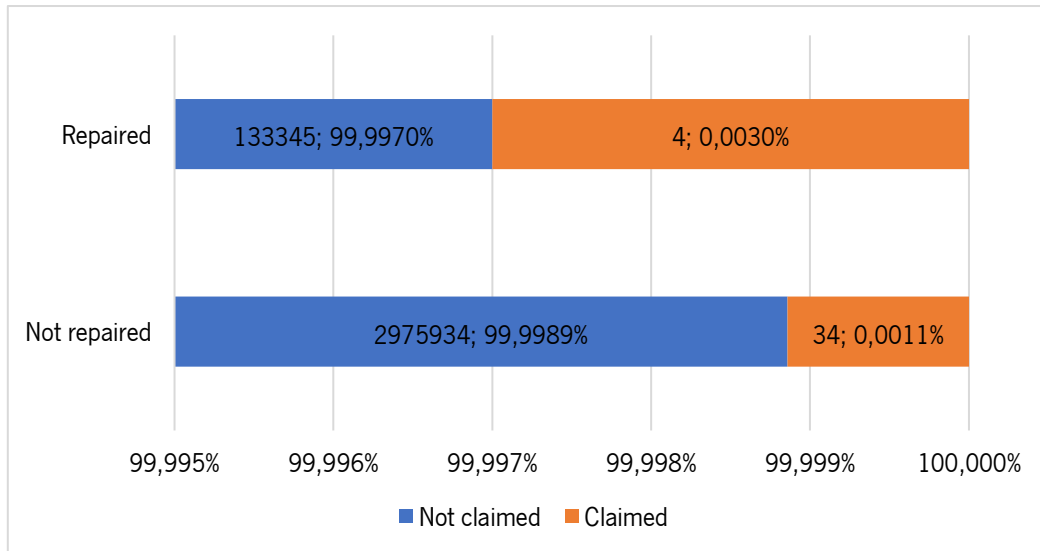


Figure 38 – Internal inspection x external claim.

In order to compare the proportions from the different (independent) populations of repaired and not repaired products, the Fisher's Exact Test for Count Data was used. In other words, it was investigated whether there is a significant difference in the proportion of these two groups with the incidence of claims by considering the hypotheses:

$$H_0: p_1 = p_2 \text{ versus } H_1: p_1 > p_2$$

Where:

- H_0 : There is no association between repairing a product and the incidence of claims. They are independent variables.
- H_1 : The proportion of claims in repaired products is higher than the proportion of claims in not repaired products.
- p_1 denotes the population proportion of repaired products that were claimed.
- p_2 denotes the population proportion of not repaired products that were claimed.

The Fisher's Exact Test for Count Data resulted in a p-value of 0.07867, which is less than the significance level of 0.10. Therefore, as the results are statistically significant, H_0 can be rejected. Consequently, there is evidence that the repaired products are associated with a higher incidence of customer complaints.

In addition, the odds ratio is significantly higher than 1, *i.e.*, $p_1/p_2 > 1$. The fact that p_1 is about 2.6 times greater than p_2 means that the odds of a repaired product being claimed is 2.6 times the odds of a not repaired one being claimed.

Further on this subject of relationships between internal and external defects, a project was carried out in the Company to interlink the IRR and the IPB-related data, assuming that higher internal repair activities imply higher customer complaints. Considering customer complaints as a quality measure reflecting the number of complete units rejected by external customers, customer complaints can be faced as an “external reject rate”. In other words, by linking it with the IRR, this project enabled the investigation of the correlation between internal and external rejects. The main result of this project is the dashboard in Figure 39, where the horizontal axes present defect categories, the upper chart presents the number of external defects (claimed quantity), and the lower chart presents the number of internal defects (repair quantity). The process behind the development of this dashboard is described afterward.

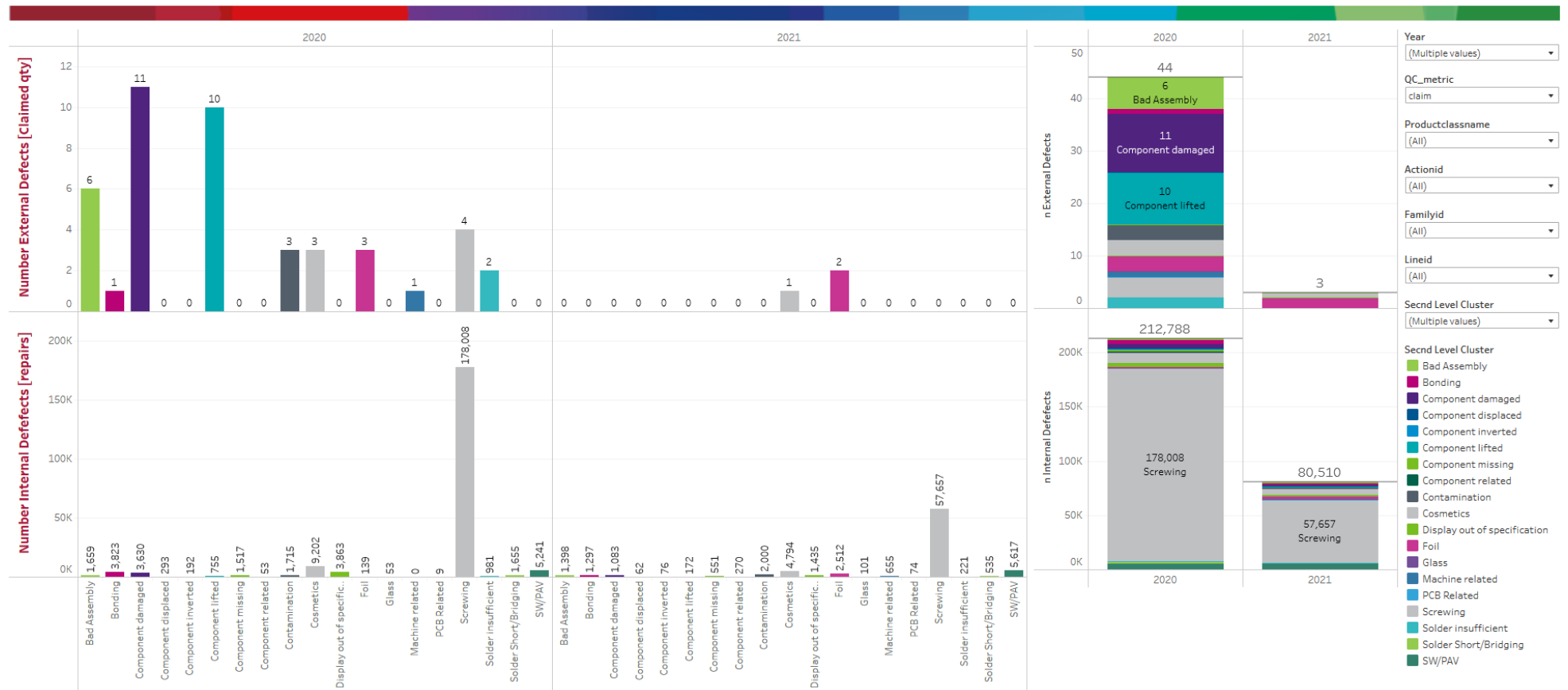


Figure 39 – Company dashboard intertwining internal and external defects.

5.2.1.1 Discussion

Figure 39 shows that there is not a visually clear correlation between internal repairs and external complaints. The results are very widespread and do not lead to any apparent conclusion. Concerns related to the components of the dashboard (defect categories, internal repairs, and external complaints) are discussed next.

Horizontal axes: Defect categories

After internal discussion within the QMM department, the team responsible for this project decided to use the same defect directory used during production (*i.e.*, repair activities) to assign the encountered complaint defect types. When the software used by the Analysis Technicians at the repair stations was analyzed, the defect codes were around 200 and were not standardized. Therefore, a multidisciplinary team listed the main defects of the factory – the so-called second-level cluster emerged.

With this directory, data is acquired in a more structured way. Nevertheless, since it still requires the technical analyst to manually label, it is both time-consuming and labor-intensive. To get the necessary data for the upper chart of this dashboard, it was necessary to classify the defect type of customer complaints according to the directory. This implied new tasks for the Customer Quality team within the data management for complaint process-related topics, including documentation changes. Therefore, the project involved human resources planning and delegating roles to the staff needed. A responsibility assignment matrix was established along with the process flowchart.

Additionally, it was necessary to carry on follow-up meetings to clear up the matters and impediments to classifying the defects, supplying feedback, and coordinating the changes to keep the dashboard updated. For example, there were customer complaints documents with defects classified according to the previous/old repository, and it was necessary to scrutinize each of these complaints to recode according to the new repository.

Lower chart: Internal defects (repairs)

Repair activities consist of correcting non-conforming items, including all consequent efforts such as disassembly, rework, replacement, reassembly, *etc.*, by following methods and procedures that will deliver the highest level of conformance. The conformance depends on how closely the repaired device will be to the original specification before repair, *i.e.*, it depends on the variation between the first pass yielded and the repaired devices.

If the assumption of making a repair to correct a defect is met, a correlation between internal repair with external defects data would not be expected. Indeed, other factors can contribute. For example,

- I) the more and the tighter the inspections, the higher the probability of detecting a defect, which can increase the scrap rate.
- II) the more operations and sub-processes, the higher the opportunity for repair or scrap.
- III) as the data collection related to repair is done by operators, there might have a human error associated, which can lead to misleading data.

Sokolov *et al.* (2021) analyzed how internal scrap costs can directly correlate to externally received customer complaints, and their results have shown no significant correlation between scrap costs and customer complaints. Sanchez-Marquez *et al.* (2020) also tested relationships between internal and external KPIs, and the most powerful relationship that appear is that of warranties (external defects) with the internal metrics First Time Trough (equivalent to FPY), End of Line First Time Trough.

Tuominen (2012) proposes a cost assessment for inspection strategies which requires defects and consequence costs. The author exemplifies five defect types along with their causes, three of which are related to reworks on assembly line (Tuominen, 2012).

Although a higher level of conformance in repair procedures alone does not guarantee maximum product reliability, high conformance is a good philosophy to follow during the repair to obtain the best possible outcome - when combined with a high operator skill level and an efficient operation.

Upper chart: External defects (complaints)

The appearance of external defects is not constrained only by the inspection of quality characteristics during a given manufacturing process. That is, even though a part passes through all the testing and inspection activities within a production process, defects may appear afterward. Examples of whys are:

- I) poor product design.
- II) wrong characteristics identification in the planning phase.
- III) pitfalls during product operations (improper handling during logistical delivery operations, material contamination, product packaging, and product storage).

For example, Cerqueira (2021) points out some fragilities related to the inspection of foils in the Company. Most of the foils defects are not revealed at the time of production, even though they already exist, for two different reasons: 1) the tests are carried out more simply than the one customer has access to, therefore the defect does not appear, or else; 2) because the defect is intermittent at the time of production/inspection.

Some failures are latent or functional problems that cannot be detected in regular internal inspection, but only in product audits (Sanchez-Marquez *et al.*, 2020). Indeed, if the problem is intermittent, occasionally the defect might only appear during customer use, under certain operating conditions.

Besides, external defects rely on customer perception. While some types of defects are critical because of the serious consequences they can cause, there may be other product characteristics that even though not fulfilling the original specification, can be overlooked if the consequences are insignificant (Tuominen, 2012).

Moreover, failures are nondeterministic events, and the combination of a large number of identical products and a small number of product defects often results in a situation where a product with certain attributes fails, whereas several products with (almost) identical attributes exhibit no problem (Detzner and Eigner, 2021).

General conclusions

The results did show a relation between the IRR and the IPB. However, the strong class imbalance, in conjunction with a high-dimensional feature space and nondeterministic occurrence of failures, makes it particularly challenging to find a cause-and-effect relationship between the internal and external KPIs. Nevertheless, the Company dashboard showing the relationship between these KPIs is still beneficial.

In a complex product, several different modes of failure, with completely different root causes, are possible. The documentation of the information in a structured repository of failure patterns/defect types enables a holistic and comprehensive analysis of the complaint information, *i.e.*, important insights and background information on different defect types.

This conceptual complaint information serves as a basis for the improvement of products and processes, *e.g.*, by identifying and prioritizing problems/defects by categories to help establish improvement activities more effectively (the highest-scoring defect will likely have the biggest payoff once fixed), *i.e.*, a kind of prioritization to apply these resources in a target-oriented way. In this regard, organizing the data within the dashboard in a Pareto order considering the ratio proportion would facilitate the visualization. In addition, the focus can be directed by forming teams that specifically look at each defect category. This dedicated effort should foster improvements rather than using generic approach to all categories.

In addition, the initiative to develop the dashboard shown in Figure 39 required organizational factors that, according to Saihi *et al.* (2023) are essential for quality management in the context of Industry 4.0, *i.e.*, it was necessary to build departmental bridges and seek consistent and coordinated goals, a sufficient

flow of information was sought through management and between colleagues and the clear work processes and definition of responsibility (Saihi *et al.*, 2023).

5.2.2 Capability Studies and Manufacturing

There is a dashboard within the Testing department where by selecting product families, the production line is highlighted with the produced quantities. Selecting a line, a series of data can be observed interactively, such as process times (test and assembly) per TS, rejection quantities, bottleneck analysis, and station FPY. Although there is a high quantity of data available, it does not have enough detail to link complaints with the production process at the critical to quality characteristics/variable level.

The total number of features is much larger than the number of non-conforming products. As many features are available, several of these features show a correlation by coincidence alone. It is often not discernible from the data which feature truly has a causal relationship and which feature is merely dependent. In fact, the spurious correlations outnumber the meaningful ones when the number of dimensions is high.

Indeed, the existence of a large amount of available data, smart algorithms, and computational power does not mean there will be a straightforward solution to finding cause-and-effect relationships. This is especially true in manufacturing, where systems are complex and dynamic, with many sources of variation. In other words, the application of predictive models in the industry is not straightforward. Indeed, among the challenges and barriers that impede achieving the full advantage of Industry 4.0 to quality management, Saihi *et al.* (2023) points out the lack of processing capacity and effective management of the massive amounts of data and their conversion into useful insights.

Since data plays a pivotal role in this regard, managing the data pipeline effectively, and aligning data curation efforts with the goals and requirements is the key differentiator. Some challenge lies in how to convert business requirements from product managers into KPIs and data requirements for data scientists, and how to continuously improve the applications in terms of accuracy and fairness.

The interdependencies of quality testing activities can be used to harmonize inspection processes. By analyzing the character of the relationships, it is possible to harmonize certain test activities to reduce the total test effort. For example, if individual components are qualified and tested separately in the early stages of production, it is possible to reduce inspection time for the final function of the assembled product. On the other hand, if the final assembled product is tested only in the last step and its functioning is fine, this implies that certain requirements needed in the previous steps were met, even if they were not tested. To exemplify the last case, a Testing Engineer of the Company reported a case where there

were several pins inserted in a PCB, connected one by one by means of soldering. Each one of these solders used to be individually checked for short circuits. With the more robust manufacturing process and new technologies, functional tests emerged further down the production line that verified the absence of short circuits more economically. That is to say that the testing system is constantly in evolution. Paraphrasing the Testing Engineer of the Company: “Old test systems are different from current ones, and current ones are different from tests to be done in the future”. Still, no studies were presented supporting these alleged savings, and it is not known what was considered in the analysis.

At best, eliminating costly quality testing activities performed at the production stage is possible, shifting the inspection focus to earlier or even later stages of the product lifecycle. However, optimizing and aligning interrelated quality testing activities throughout the product lifecycle requires a deep understanding of the interconnectedness of quality inspections. Effective alignment of quality testing activities relies heavily on existing expertise.

5.3 Identification of Practices for the Planning and Improvement of Inspection

5.3.1 Inspection Planning in practice

The main objective of Section 4.2 was to give an overview of the phases of the industrialization process of the Company. This overview is important to understand the IP process (Section 4.3) since the latter depends on activities that take place during the Industrialization Process phases. Since each individual decision within the IP affects decision situations in its following stages, the overall decision situation can be characterized as a multi-stage decision problem (Basse *et al.*, 2015). With this systemic view, it can be noticed that the IP is a very complex process that evolves many operational alternatives, constraints, and cost factors, which according to Mandrolí *et al.* (2006) interact intricately and make the inspection solution far from trivial. Any solid inspection strategy will have to consider the needs of various stakeholders and make reasonable trade-offs between its objectives.

Nevertheless, it is also relevant to contrast the Company’s practices against other companies’ practices and the literature as means to identify points for improvement. Therefore, in this Section, the practices related to the IP documentation and IP costs are outlined.

Particularly, the QG system shown in Figure 14 (page 65) is commonly adopted during product and process development (Gomes *et al.*, 2022). As presented in Section 4.2, samples go from A to D in the Company. Other companies also name product samples/prototypes following an alphabetical order, *e.g.*, Tahera *et al.* (2015).

The Company IP follows somehow the arrangements proposed within the literature review (Table 9, page 39). However, the inspection strategy is somewhat conditioned by the classification of characteristics A, B, and C, and the FMEA plays an important role in this classification (although the classification of the characteristics into A, B, or C (Section 4.3.1) also follows the alphabetical order, it is important to notice that there is no relationship with the names of the samples).

5.3.1.1 IP-related Documents

For similar products, there are standard control measures already defined within the standard PFMEA. Generic FMEAs contain both historical and potential failure modes, causes, controls, and so on. Their purpose is to support a learning organization to generate specific tailored FMEAs in the future (Carlson, 2012). Carvalho (2019) reports a cost-benefit analysis of a remanufacturing line that was being planned in the Company to recover a display, reducing waste. For this new line, it was necessary to define technical solutions, workstations, and work instructions, and because the standard PFMEA had several pieces of information in these regards, it was a key element in this process.

Back in 2011, Ribeiro's (2011) work aimed at improving the standard PFMEA of the company. When analyzing an adjacent file/database containing all the production processes of the Company, Ribeiro (2011) eliminated 24 out of 81 processes since they were no longer part of the product's manufacturing processes, *i.e.*, around 30% of the initial content of the file was eliminated. Moreover, he suggested updating this file according to additional implemented control measures in the processes after lessons learned from customer complaints (Ribeiro, 2011).

Indeed, field failure data must be brought into generic product and process FMEA regularly, as well as any other discovered failure modes/causes not adequately addressed in it. Customer-related incidents must be prevented by improvements in the production processes. Accordingly, product and process FMEA must improve test plans and process controls to accurately detect all possible failures and their causes. The analysis of external defects must draw attention to the associated "IP relevance", with a consequent IP review, and alignment with the related documents (Haghi *et al.*, 2018; Hellebrandt *et al.*, 2018; Linder *et al.*, 2016; Ruessmann *et al.*, 2020).

The product and process FMEA helps map the road to CI and by assessing and documenting the risks of failure. After started, they become living documents and are never complete. As dynamic tools of improvement, they will use feedback to improve the product and the process. However, the fact that Ribeiro (2011) encountered so many outdated processes (more than 10 years ago) in the system that

subsidizes the development of the PFMEA casts doubt on the consistency of the control plans in the Company at the time.

5.3.1.2 IP-related Costs

Within the overall documentation provided regarding the IP process in the Company, there is no indication about whether the quality costs are taken into account. When questioning a Testing Engineer about it, he answered that in the industrialization process, some teams think about costs, estimate them, and present a layout proposal in the industrialization decision.

The layout establishment is usually based on flexible production schemes, *i.e.*, systems that can change the type of product and not lead to a high impact on costs. Therefore, multi-purpose machines are used in the production process, referred to by the acronyms MAE and EWAK, which came from the German language: *Maschinen und Einrichtungen* (MAE) means Machinery and Equipment, and *Erst Sonderwerkzeug Anschaffungs Kosten* (EWAK) means Initial Costs for Special Tools. MAE are transversal to several projects, *i.e.*, the same MAE can be used in multiple production lines, while EWAK, on the other hand, are special tools, *i.e.*, specific to each product. Figure 40 illustrates examples of an MAE and an EWAK, with the EWAK located within the MAE.

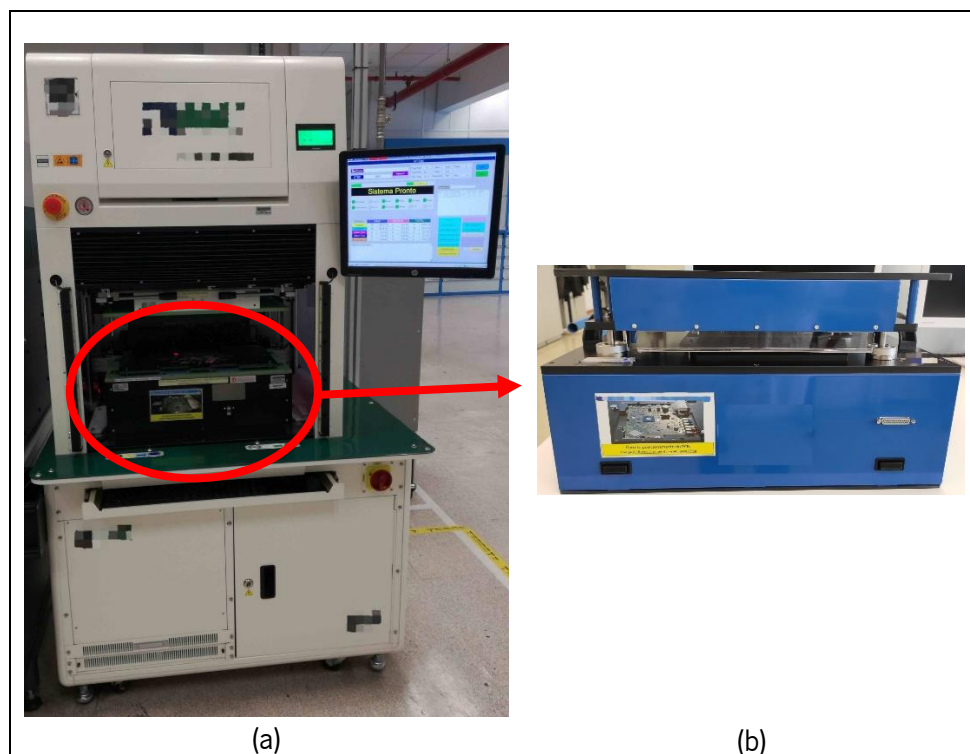


Figure 40 – (a) MAE; (b) EWAK.

A work was carried out by Gómez (2013) in a subsidiary of the same group of the Company, but in the business unit of Body Electronics rather than Car Multimedia. Gómez's (2013) work is related to production line planning activities, aiming at standardizing a Final Assembly Line. One of the line processes analyzed in his work is the Single Pin Insertion, consisting in inserting pins in PCB without soldering. A cost comparison was made regarding two options to inspect this process: optical control versus manual gauging. The variables considered in the comparison were energy consumption, the initial investment in MAE and in EWAK, cycle time, "hours of maintenance done by operators" and "percentage of process engineer". The analysis resulted in the gauging becoming around two times cheaper than optical control. However, quality-related variables are overlooked. Specifically, Gómez (2013) analysis did not consider internal and external failure quality costs nor quality parameters during the layout proposal activities.

Tuominen's (2012) work, on the other hand, shows that it is possible and beneficial to consider many CoQ-related factors to compare different inspection strategies. In the exemplified case, Tuominen (2012) compares sampling inspection using a coordinate measuring machine (CMM) and 100% inspection using a modern optical measuring system, concluding that a correct inspection strategy for quality control may lead to a significant increase in the profit margin of the business.

The cited analysis by Gómez (2013) suggests that other branches of the same group of the Company also do not consider quality components with the full potential they could when assembling test and inspection systems on production lines. This potential is further explored and modelled in Section 5.4, while the next Section 5.3.2 explores the observed practices related to Inspection Improvement in the Company.

5.3.2 Inspection Improvement: Observed Practices

Literature states that inspection processes in manufacturing systems are often considered as inflexible static output resulting from the initial planning process during product and process development (Kukulies *et al.*, 2016) and there is a lack of revision of inspection activities as part of quality control (Filz *et al.*, 2021). In order to evaluate the truth of these statements within the Company's practices, this section is related to the CI event called Performance Workshop (PW) (referred to in Section 4.8) and how it impacted the IP.

The PW follows the conventional practices for a CI activity, *i.e.*, information management, KPI analysis, mapping, diagnosis, root causes, countermeasures, implementation, follow-up, and standardization (Peças *et al.*, 2021). As the focus is related to the IP changes triggered by the PW rather

than the PW itself, only the following activities will be discussed: KPI analysis (Section 5.3.2.1), mapping (line balancing before and after the PW, Section 5.3.2.2), and countermeasures (Section 5.3.2.3). More information and an overview of the main results of eight PWs that were carried out at the Company may be retrieved in the work published by Reis *et al.* (2023).

The production line focused on this event comprises a total of 14 automatic workstations that produce an Infotainment System. The manufacturing line has a mixed structure of manual assembly, WS, and TS, which is very similar to the one presented in Section 4.4. There are a total of seven operators in the line.

5.3.2.1 KPI Analysis

The rate at which the Company should produce the product to meet the total demand, *i.e.*, the takt time, triggered the PW target: to increase productivity by 5.13%, as detailed in Table 21. After analyzing the KPIs, it was concluded that three workstations had a cycle time greater than necessary; all three referred to manual workstations: operators 5, 6 and 7.

Table 21 – KPI analysis to identify the necessary improvements.

	Before PW	Target	Percentage difference
Productivity (piece/operator hour)	11.7	12.3	5.13%
Output (piece/month)	47126	49640	5.33%
Output (piece/day)	11782	12410	5.33%
Line Takt (second/piece)	39.5	37.5	-5.06%
Operator 5 (second/piece)	38.7	37.5	-3.10%
Operator 6 (second/piece)	39.5	37.5	-5.06%
Operator 7 (second/piece)	39.5	37.5	-5.06%

5.3.2.2 Line balancing before and after implementation

The graph in Figure 41 shows the line balancing before and after the PW. Initially, the longest cycle time for the line (*i.e.*, the bottleneck) was for operators 6 and 7, both with a cycle time of 39.5 seconds, which decreased by 4.5 seconds due to the PW. The cycle time of operator 5 was reduced as well, and overall, the new line cycle time became 37.5 seconds as established by the initial target.

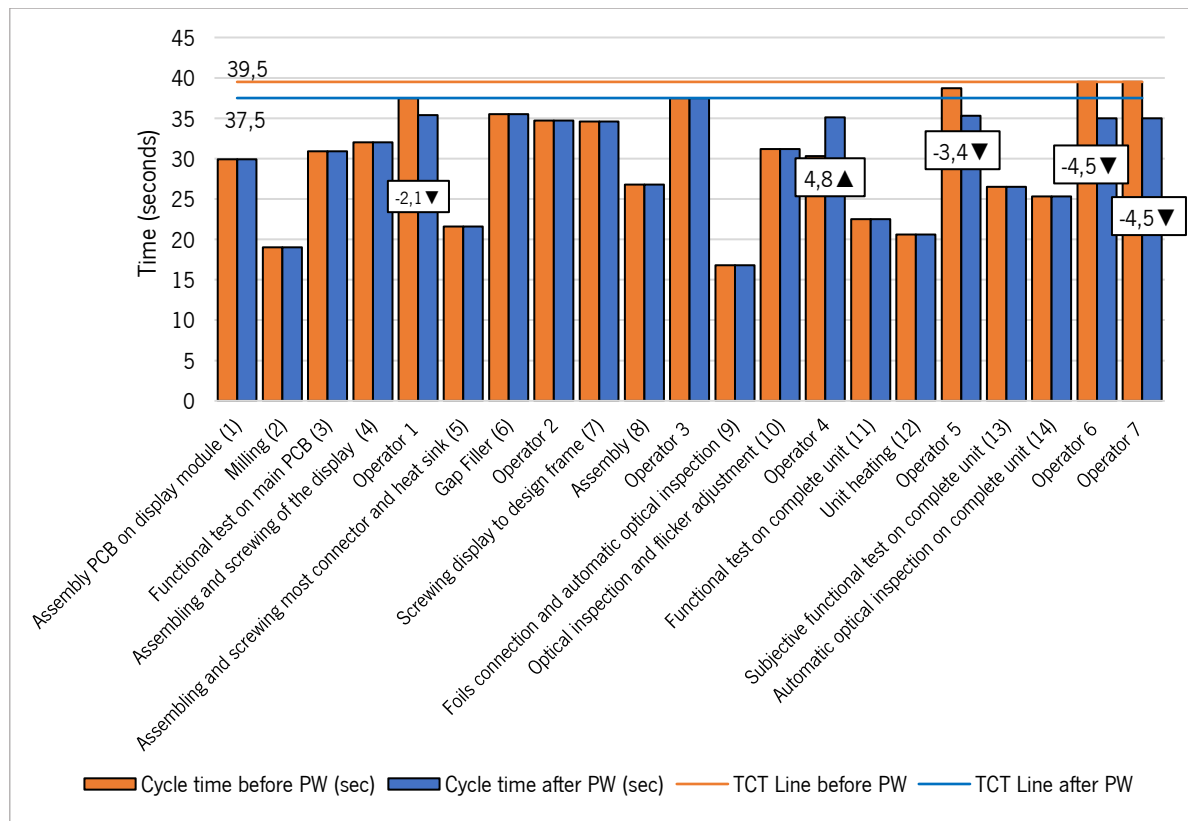


Figure 41 – Line balancing before and after PW.

Some workstations are composed of automatic equipment, for both functional tests and optical inspections. During the placement of parts from one station to another, operators also perform assembly tasks and visual quality controls.

5.3.2.3 Countermeasures (workshop ideas)

During the PW event, knowledge was created through the exchange and dissemination of ideas (*i.e.*, tacit knowledge) in a process of socialization. Knowledge externalization occurred as the suggested improvement solutions, resulting from the materialization of shared tacit knowledge, were documented in the Open Points List. In this list, when setting up deadlines and ownerships for ongoing monitoring and adjustments for the proposed actions, not just suggestions were raised, but also confrontation and negotiation processes occurred. These discussions and negotiations are based on the fact that some actions require more time for analysis, while others were simpler and can even be done right away.

Table 22 presents the improvement suggestions made during the workshop related to automatic and visual inspections, along with some comments on their impact on cycle time.

Table 22 – Suggested changes in automatic inspections and visual inspections.

Workstation	Improvement suggestion	Comment/Impact on cycle time
<i>Changes in Automatic Inspections</i>		
3. Functional test on main PCB	Reduce cycle time so as not to increase a unit of equipment	The improvement of test routines was possible due to the evolution in the maturity of the unit's software. The improvement reduced 10 seconds per part in cycle time.
11. Functional test on complete units	Reduce cycle time so as not to increase a unit of equipment	The improvement reduced 3.5 seconds per part in cycle time.
12. Subjective functional test on complete units	Check why the equipment is slower than the rest	Machine 12 uses different automation hardware, which explains the verified differences. The machine's automation routines were revised, resulting in a reduction of 3 seconds per part in cycle time.
13. AOI on complete units	Increase inspection capability	The improvement reduced 5.7 seconds per part in cycle time.
<i>Changes in Visual Inspections</i>		
4. Assembly display and screwing	Dismiss the check for the presence of springs on the Support Plate	The improvement reduced 0.7 seconds per part in cycle time.
12. Subjective Functional test on complete unit	Check what is needed in visual control	The verifications of pins, connectors, loudspeakers, and cables were removed because the AOI objectively guarantees these points. The verification of the felt was removed because it is not described at PFMEA. These changes reduced 1.9 seconds per part in cycle time.
Packing and labeling (offline)	Dismiss the "shaking unit" task and the visual control of the customer tag	The visual control of the customer label continues because the AOI on the complete unit (13) does not check the label quality, just its presence and location. The "shaking unit" task dismissal resulted in a reduction of 0.7 seconds per part in cycle time.

5.3.2.4 Discussion

Some improvements are not in the inspection category but impact the productivity of the inspection-related workstation. For example, a suggestion related to motion waste: "remove material from PCB range to improve PCB load/unload in the Functional Test Equipment". This suggestion was given in the workshop and with follow up it was verified that there was a gain in the Overall Equipment Effectiveness of the Inspection Station (3).

Moreover, test cost is impacted by the cost of test equipment and the amount of time each part spends on that equipment. Reducing the testing time can have significant cost savings by avoiding the necessity of providing more test equipment to cope with volumes. For example, if the time required to perform a test is 150 seconds and the cycle time for the production line is 30 seconds, then either five TS are necessary to achieve the cycle time, or it is necessary to reduce the testing time from 120 seconds.

When there is more than one piece of equipment (TS) to cope with the volume and cycle time, some may be faster or more precise than others, as happen in the case reported in Table 22, “machine 12 uses different automation hardware, which explains the verified differences” The machine's automation routines were revised, resulting in a reduction of 3 seconds per part in cycle time.”

Along the same lines, Castro’s (2017) work was focused on improving the productive capacity of a Milling Pool in the Company. For doing so, it was necessary to know several items: the operative times of each product or component in each workstation, the labor time involved in the manufacture of each item, the number of workstations, and their expected use. Thus, Castro (2017) attempted to establish a pattern for the duration of tests. He hypothesized the test duration would be proportional to the number of components analyzed per unit. By the comparison of 15 different units (with varying numbers of components being inspected) along with their test times, it was verified that there is not a linear relationship between these two variables, *e.g.*, while in a given unit it took an average of 5.93 seconds per component, other took only 0.12 seconds. An alternative hypothesis was put forward: there could be a correlation between test duration and the type of components tested. However, it was not possible to test this hypothesis because there was no information on the number of components of each type in each board model (Castro, 2017). According to this analysis, it was not possible to obtain a relationship between the test time and the number of components to be tested per board. Nevertheless, the testing time is directly related to cycle time, as shown in the line balancing in Figure 41, and it is important for testing cost control. This matter is further discussed in the next section (Section 6.3.3).

The Knowledge Management tools of Lessons Learned and Best Practices (Hellebrandt *et al.*, 2018) are part of the outputs of the PW. They encompass the systematic collection and consolidation of the PW suggestions and gains, *i.e.*, to accumulate knowledge and expertise from insights into problems faced during the manufacturing stage. The consideration of this documented practical knowledge is also incorporated into future projects, and the “best practices catalog” is used as input for new workshops in production lines. According to the literature, to realize firm-wide lean knowledge assimilation, it is necessary to document, standardize, and share Kaizen Events’ successful practices across all interested parties for potential utilization and implementation in day-to-day operations (Vlachos *et al.*, 2020).

As reported in Reis (2023), the ideas more frequently suggested in the PWs are the ones related to incremental and more feasible actions to put into place, for example, to place a box closer to the operator to decrease the movement time to reach a part. For more systemic suggestions, such as implementing changes in automatic assembly stations, more efforts are required, which usually encompasses several

departments, go through negotiation phases, and the cost-benefit analysis history for these changes shows that they generally do not pay off. Therefore, the team ends up not even suggesting improvements.

As a result of the changes related to the automatic testing process, the document that specifies all the tests that must be done on the product (*i.e.*, PAV) also changed. As a result of the subjective inspection modifications, some standard documents were also altered, namely the PFMEA, the Control Plan, and the Standard Work. As the Company is a subsidiary of a large international organization that operates across diverse business sectors and the product FMEA is elaborated in the headquarters in Germany, when there is a change proposal in the PAV, the request goes to Germany, involving several people and approvals. As it is an expensive process, the cost-benefit must be very high for it to happen. Indeed, the production volume by the end of the project is often the factor that determines whether the investment to change automatic stations will be worth it.

Thus, it is shown that these inspection changes involve interdisciplinary collaboration to manage all approvals and documents related to it and may also involve external stakeholders since the alteration of an inspection previously contracted with the client requires their approval. Therefore, this case study supports that the PW with representatives of stakeholders may facilitate and even accelerate the inspection improvement (Sousa and Nunes, 2021).

Although the checklist used in the shop floor visit contemplates all seven types of lean wastes, the categories of defects, transportation, and overproduction are not present in the data of these eight PW, probably because they do not directly impact productivity improvement, which is the main PW objective. The lack of actions related to the waste category defect in the PWs data is particularly consistent with the findings of Goshime, Kitaw and Jilcha (2019), who claimed that most managers who strive to implement lean in their respective companies are focusing on the minimization of wastes such as wastes of time, resources, labor and inventory control rather than focusing on the quality of products.

Doolen *et al.* (2008) report a kaizen event focused on a required inspection step, which was often a bottleneck constraining the overall capacity of the manufacturing operations. Because of the high capital cost of the inspection equipment, high maintenance costs for the equipment, and the need for a dedicated operator for each inspection station, organizational leaders identified this process as critical to the long-term success of the organization. The deliverables of the so-called Inspection Kaizen event included providing documentation of workflow changes and future work plans. This included the development of procedures for equipment and work cell setup (standard work), documentation of changes to existing procedures, and the development of training plans and training materials detailing the implementation of

recommended changes for all shifts. This corroborates the argument that changes in the IP must also change the related documents (Doolen *et al.*, 2008).

Considering the changes in inspections within Table 22 and the arrangements of the IP listed in Tables 9 and 10, the types of changes during the Manufacturing Stage caused by the PW were related to what characteristics to inspect (IP1), *e.g.*, “dismissing visual controls not defined in PFMEA”, and whereby (IP7), *e.g.*, “checking why one equipment was slower than the rest”.

The decision on how much to inspect (IP arrangement 4) to decide the acceptability of a batch can vary from a sample to 100% of inspection and is recurrent in ISM in the literature, *e.g.*, (Hamrol *et al.*, 2020; Sousa and Nunes, 2021), however, changes in the inspection extent did not appear as a suggestion in PW. When questioning whether they can be triggered by the PWs, the Testing Engineer answered that probably not, briefly explained the Company IP process (Section 5.3), and justified his response as follows. During this prototyping phase, the main quality characteristics of the parts are measured at an inspection rate of 100%. Once the process is stabilized, technologies are developed as integrated online operations. In steady-state production, critical quality characteristics (classified as A) continue to be measured at 100%, while less critical characteristics (classified as B or C) can eventually be controlled by samples. However, in reality, all the characteristics keep being measured at 100%.

In addition to unnecessarily measuring all features at a rate of 100%, sometimes extra features are measured unnecessarily. For example, if a product is shipped to a country with a polar climate, *i.e.*, sub-zero temperatures, there is additional testing during production to ensure that the product will perform well in these extreme weather conditions. This additional test is not required for products that will be used in countries with a tropical climate. Although in this example one can justify it by saying that it is a precautionary move, there are many other cases where if no one notices this type of deviation when reusing software test systems from similar products, many tests will be done unnecessarily, resulting in longer test time, that is, higher appraisal costs.

The inspection changes within the case study reported in this section were driven by a CI event that aimed to increase the productivity of a production line. Therefore, there is a possibility of implementing a CI event for new process development, applying the knowledge obtained in previous inspection changes to improve IP, or adopting an “Inspection Kaizen event” such as the one reported by Doolen *et al.* (2008), where the focus would be on IP improvement rather than on productivity increasing. Nevertheless, the fact that the Company has designed and regularly applies its own CI methodology in the production phase

attests to the recognition of the importance of CI practices, in project format, in the context of lean companies.

In addition to the contributions of this case study to the kaizen events literature, there are also contributions for practitioners in general, who can use the results to compare the design of their CI events with that of the case study, to identify areas where they seem to excel and possible areas for improvement. Though, since the applications of CI events are very practical, they should not be regarded as just analytical exercises.

5.3.3 Conceptual Framing: IP-PDCA

In this thesis, the topics concerning IP design were addressed in the literature review (Section 2.4.1) and further explored in the case study context (Section 4.3). In sum, it was seen that the IP is usually based on customer requirements and the optimal allocation of the Company's internal resources. Nevertheless, considering the implementation of feedback loops in business processes, the IP must be continually evaluated over time to be adapted according to both the new dynamic environment and the Company's CI activities. In other words, internal and external disturbances can eventually lead to the need to adapt or re-plan the IP. To summarize the performed qualitative analysis (Section 4.3.1 and 4.3.2) of IP and IP improvement, the next section (5.3.3.1) links it into a CI perspective based on the PDCA cycle. This framing generalizes findings and is expected to contribute to the literature on IP continuous improvement by helping enhance companies' practices towards inspection improvement. Accordingly, the IP-PDCA framing is presented along with the discussion of each component.

5.3.3.1 The IP-PDCA framing

The PDCA cycle concept was developed to encourage the use of small-scale improvements for continuous performance improvement while allowing for rapid assessment of improvement actions (Juran and Godfrey, 1998). Figure 42 is based on the PDCA cycle and represents a four-step model for carrying out changes in IP. The "Plan" quadrant represents the IP arrangements within the yellow gear, which is interactively aligned with the IP related documents. In the "Do" quadrant, there is a supply chain that consists of suppliers and manufacturers and the associated incoming inspection, process inspection (manufacturing and assembly), and outgoing inspection. At this phase, Inspections and Testing are implemented according to the IP. In the "Check" quadrant, change drivers that may cause IP adaptation are listed in an Ishikawa diagram. Finally, in the "Act" quadrant, several tools that help the company to

stabilize or even increase inspection performance are presented along with a wrench, suggesting that such tools serve to adjust the gears of the IP.

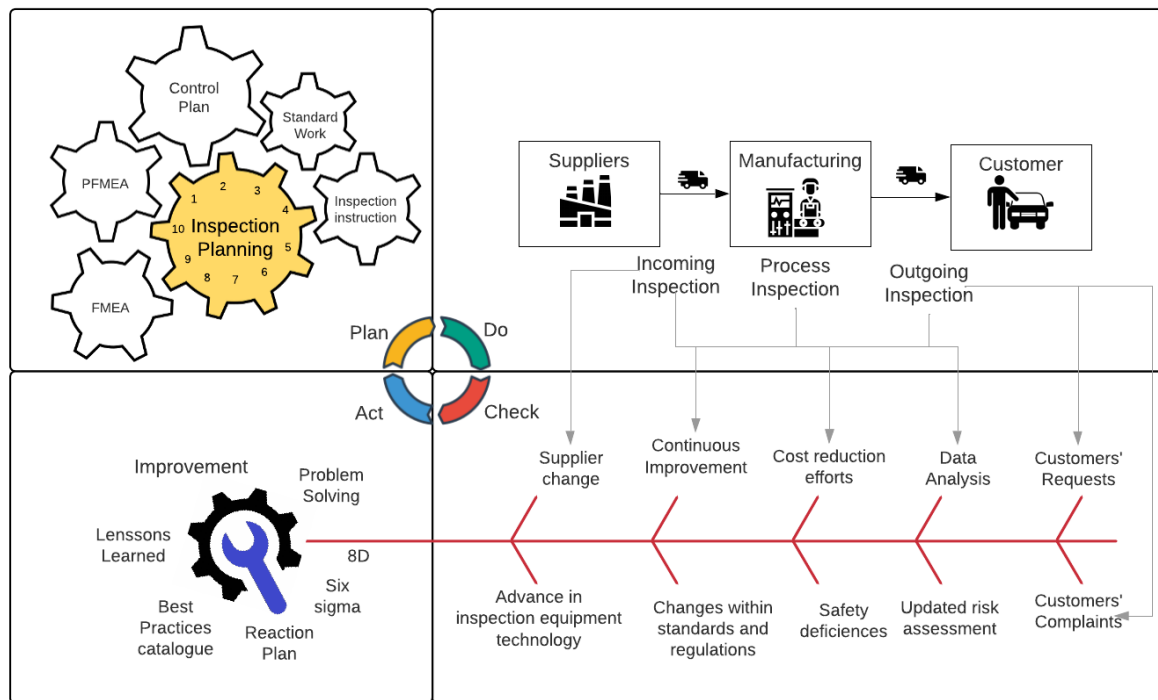


Figure 42 – Proposed framework: PDCA-IP.

Plan:

Whenever one of the ten IP arrangement changes, the IP must be adapted, and the related documents must change as well, *e.g.*, the control plan, product and process FMEA, production and inspection instructions, inspection plans, PAV, etc. In other words, they must be aligned iteratively, as represented in Figure 43 by the gear set containing all inspection-related documents integrated.

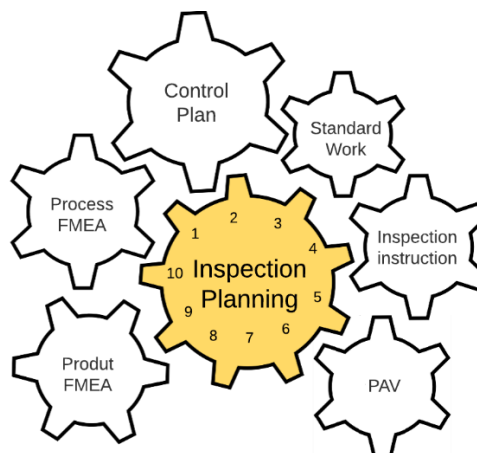


Figure 43 – Iterative alignment of the IP-related documents.

For example, the team must associate the risk assessment in the PFMEA in case the initial inspection strategy has been modified in the IP, to ensure the Control Plan is impacted by the results of the updated PFMEA. This interactive alignment is best accomplished by both well-written actions and by including a multidisciplinary IP team. Accordingly, any changes to the procedures for the inspection and testing activities should be noted by an ongoing document change system (*i.e.*, IP arrangement 10), with a clearly defined documentation trail back to the main or general procedure.

As the PAV is a document used specifically in the Company, while the framework is intended to be generic, the gear representing the PAV document is not in Figure 42 within the proposed PDCA-IP framework. Likewise, other companies might consider adding their documents which are not represented yet into the framework.

Do/Check:

Advanced manufacturing environments involve frequent changes in product design and process configuration as customer requirements change. The supply chain for such an environment would also have to be dynamic to accommodate these changes within the IP (Davrajh and Bright, 2013). In other words, some internal and external disturbances can eventually lead to the need to adapt or re-planning the IP. Examples are represented in the Ishikawa diagram in Figure 44, a.k.a. fishbone diagram, a tool for listing potential causes to create an effect under investigation. These change drivers are responsible for triggering the IP adaption process in ongoing series production. Hence, continuous or event-driven monitoring of inspection-related change drivers is required to recalibrate internal controls in a CI environment.

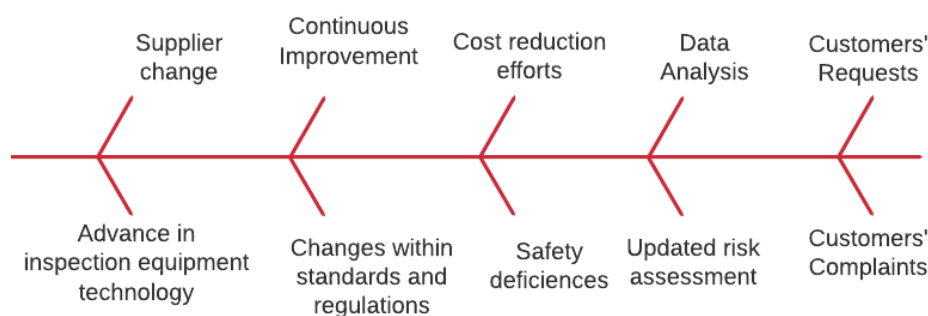


Figure 44 – Change drivers of IP.

Data analytics, for example, is a promising driver of change. Considering inspection-related performance indicators, such as customer complaints and defective units within a process, it is possible to monitor these variables and trigger the need for corrective action within the inspection process whenever one or more substantial changes occur (Sousa and Nunes, 2021). Although there is an

increasing availability of data from the manufacturing phase as well as data analytics tools, there is a lack of revision of inspection activities as part of quality control (Filz *et al.*, 2021). By considering quality inspections throughout the entire product lifecycle, interdependencies between inspection activities can be identified and turned into valuable information (Kukulies *et al.*, 2014). Indeed, Madrid *et al.* (2016) argued that inspection data is eventually used to improve production in progress, rather than reused to optimize product quality during design activities. They claim inspection data is not used at its full potential due to informational, technical, and organizational barriers (Madrid *et al.*, 2016).

Act:

The methodology of implementing continuous IP improvement can be varied in different organizations. Regardless of the methodology of the CI programs, every organization needs to use a proper combination and selection of quality tools, methodologies, and techniques in their implementation process. It is very important that they are properly selected according to the need and demands of the team and further applied correctly to the appropriate process and approach in the organization. Several tools that help the Company to stabilize or even increase inspection performance are presented along with a wrench in Figure 45, suggesting that such tools serve to adjust the gears of the IP.



Figure 45 – Company tools to improve IP.

For example, the 8D (D for disciplines) is a standard procedure commonly used by the automotive industry to identify the root cause of a failure and to handle fault complaints (VDA, 2017). When the 8D process is completed, a report is filled out to summarize how the root causes were determined and eliminated, and what was done to contain the problem to prevent the root cause from happening again (Blank, 2014; Riesenberger and Sousa, 2010). On the other hand, there are several methods, tools, and systems related to Knowledge Management, and the selection of the appropriate ones depends on the desired objective, resources as well as company-specific preferences (Hellebrandt *et al.*, 2018; Kukulies *et al.*, 2014). ECR is a well-established process for modifications of a technical artifact composed of five

steps: identification of potential change, development of alternative solutions, specification and decision on change, engineering implementation of change, and manufacturing implementation of change. It provides the opportunity to systematically adapt inspection procedures during the manufacturing stage (Kukulies *et al.*, 2014).

Taking the ECR as an example within the Act phase, any substantial change to the IP must be approved through an ECR, a process that involves significant human and financial expenditures. Engineering changes are only allowed if proven and imply an improvement in customer satisfaction, competitiveness, and/or product quality. Nonetheless, independent of the employed tool, the triggering of actions for IP adaption should always be centered on a cost-benefit analysis to evaluate whether efforts spent on planning and adapting ongoing quality inspection processes are justified. Accordingly, in addition to analyzing the impact of any changes in the IP on the production of defective units, it is necessary to analyze its impact on the quality costs to ensure that the actions correspond to increased financial gains, contributing to the company's competitiveness and sustainability.

5.3.3.2 Contributions

The proposed framework provides an organized and easy to understand management approach. Like most management systems, the IP-PDCA is designed to be malleable and adaptable to represent specific identified needs as a means to facilitate effective IP improvement. In this case study underlying the framework, Section 5.3.2 provided empirical evidence of how internal and external disturbances modified the inspection process during the manufacturing stage (*i.e.*, “Do”). The inspection changes within the PW were driven by a CI event that aimed to increase the productivity of a production line (*i.e.*, “Check”), resulting in changes (*i.e.*, “Act”) related to which quality characteristics to inspect (IP1) and whereby (IP7 - equipment decision), which had to be altered in the documentation (IP10) (*i.e.*, “Plan”).

As a conceptual and visual tool, the IP-PDCA proposes a synergistic dialogue between the results obtained in this section of the case study while placing a strong emphasis on their complementarities with respect to the initial theoretical domain of IP and IP improvement. In sum, the framework synthesizes findings and aims to accumulate a body of knowledge about similar phenomena in one image, thus bringing theory to a higher level. While Section 5.3 makes an important contribution in providing empirical evidence of inspection changes and their influencing factors in an organization, the next Section 5.4 proposes a model to analyze the CoQ for alternative inspection strategies.

5.4 Development of a Model to define the Inspection Strategy that minimizes Quality Costs

5.4.1 Conceptual Modeling

The situation diagrammed in Figure 46 is similar to the one presented back in page 79, Figure 24. However, while Figure 24 mapped a generic situation reflecting the current approach of the Company for handling defective parts, Figure 46 encompasses also the elements pertinent to the model being proposed in this Section regarding (1) the product inspection and the respective inspection errors (2) the analysis of the failed products, (3) operations for repairing/replacing the identified defective parts, (4) the reinspection of the s-cases and repaired products, and (5) the cost of passing a defective product to the next process.

Therefore, it specifies the TS in question (FCT50), along with several parameters and costs elements, as follows:

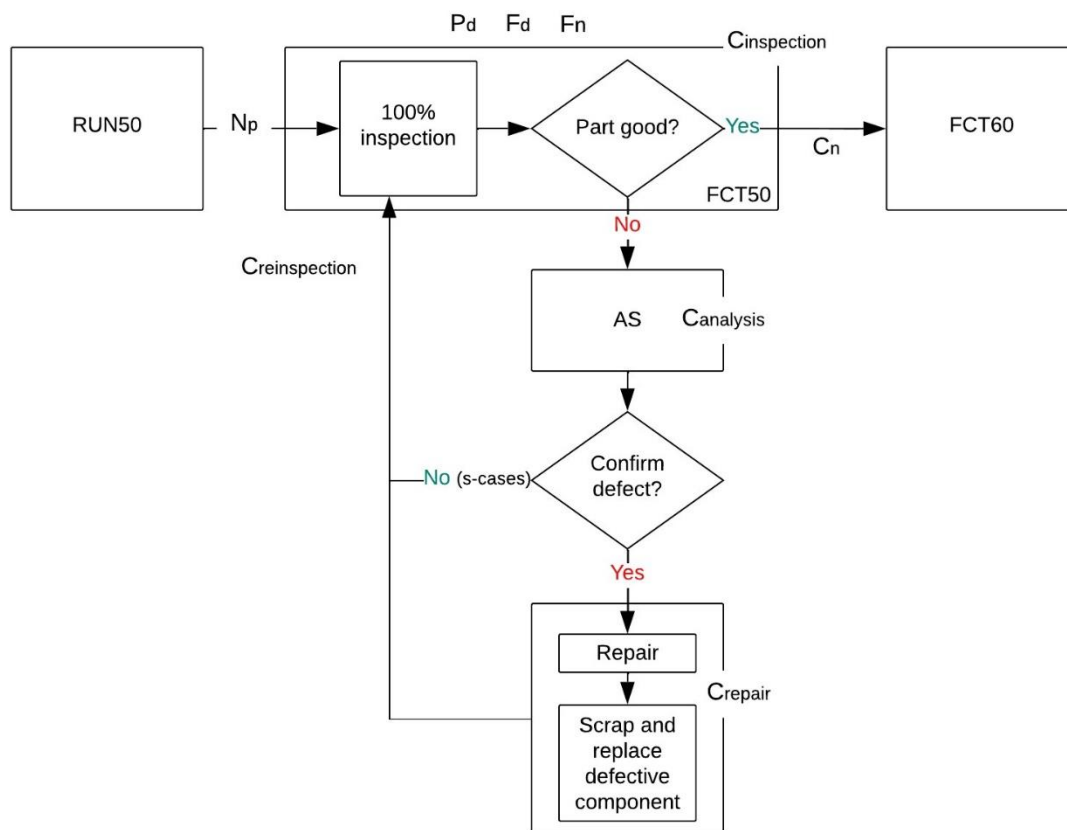


Figure 46 – Conceptual model of the current defect handling at FCT50 along with its costs and parameters.

- N_p : number of units passing through the FCT50
- P_d : proportion of defectives in FCT50
- F_d : false defectives (type I error)

- F_n : false compliant (type II error)
- $C_{inspection}$: unitary inspection cost (€/unit)
- $C_{analysis}$: unitary analysis cost (€/unit)
- C_{repair} : unitary repair cost (€/unit)
- $C_{reinspection}$: unitary reinspection cost (€/unit)
- C_n : unitary cost of passing a defective unit to the next process (€/unit)

5.4.2 Logical Modeling: Equations

This section presents the equations behind the calculus of the total CoQ per product unit. Based on the PAF approach, the total CoQ comprises the Failure-related costs (C_{repair} , $C_{analysis}$, $C_{reinspection}$, and C_n) and the Appraisal costs ($C_{inspection}$). The $C_{reinspection}$ is not computed within the category of Appraisal cost, as it is incurred due to Internal Failure.

The Total CoQ of using 100% inspection is expressed by Equation (9), while the Unitary CoQ is expressed by Equation (10):

$$\begin{aligned}
 Total\ CoQ_{100\%inspection} &= (C_{inspection} \cdot N_p) \\
 &+ [C_{analysis} \cdot N_p \cdot (P_d + F_d - F_d \cdot P_d - P_d \cdot F_n)] \\
 &+ C_{repair} \cdot N_p \cdot P_d (1 - F_n) \\
 &+ C_{reinspection} \cdot N_p \cdot (P_d + F_d - F_d \cdot P_d - P_d \cdot F_n) + C_n \cdot N_p \cdot P_d \cdot F_n]
 \end{aligned} \tag{9}$$

$$Unitary\ CoQ_{100\%inspection} = \frac{Total\ CoQ}{N_p} \tag{10}$$

Where:

- $N_p \cdot C_{inspection}$ is the overall cost of 100% inspection;
- $C_{analysis} \cdot N_p \cdot (P_d + F_d - F_d \cdot P_d - P_d \cdot F_n)$ is the overall cost of analysis;
- $C_{repair} \cdot N_p \cdot P_d (1 - F_n)$ is the overall cost of repair;
- $C_{reinspection} \cdot N_p \cdot (P_d + F_d - F_d \cdot P_d - P_d \cdot F_n)$ is the overall cost of reinspection; and
- $C_n \cdot N_p \cdot P_d \cdot F_n$ is the overall cost of passing defective units to the next station.

5.4.3 Data Modeling: Cost Elements and Parameters

Decision making regarding an economically optimum reaction plan requires many parameters and cost indicators to assess alternative options/solutions. Since the true accuracy of these elements depends on the underlying data, knowledge of how these elements are obtained can provide good indications of the precision that can be reasonably sought or expected. Therefore, Sections 5.4.3.1 and 5.4.3.2 present respectively how each cost element ($C_{inspection}$, $C_{analysis}$, C_{repair} , $C_{reinspection}$, and C_n) and parameter (N_p , P_d , F_d , and F_n), were estimated for the model.

5.4.3.1 Cost Elements

Inspection Cost

The inspection cost is accounted within the Appraisal category in the PAF approach to CoQ. The usual way of evaluating the automated test/inspection value is by calculating the return on Investment (ROI) on the necessary equipment (Yin, 2018). Regarding appraisal activities, a Testing Engineer of the Company states that the aim is to design a test chain that contributes to the best efficiency on cycle time, line balancing, and cost.

Figure 47 shows the breakdown of testing costs performed considering the data of a specific complete device, *i.e.*, it is an ABC study. The first column establishes the time (in seconds) necessary for testing the blocks of quality characteristics described in the second column (and for performing tasks associated with the testing, *i.e.*, load and connect a device). For example, the testing time of the block “light sensor calibration” is 2.9 seconds.

The first line of the table sets in yellow the total cost for the hardware and software used for automated testing, *e.g.*, cameras, MAE, and EWAK. Machine, tool license, and acquisition costs are counted in this item, *e.g.*, the EWAK cost results in 4040€. The fixed costs account for the equipment, while the variable costs account for the personnel costs. The inside of the table matrix indicates whether each equipment or operator (second row) is required to perform each test group (second column). When it is needed, it is indicated by 1 or 0.5 (light green cells), while when it is not needed, it is indicated by the number 0 (light yellow cells). It was necessary to get information within the Testing Department regarding the first items, while the costs estimate for operator activities were gathered along with the Accounting Department.

Therefore, it was possible to estimate the total testing cost per device for each group, considering fixed and variable costs, as designated in the last column, in which the last line sets the cost estimative for the testing of each product.

Station name		€ 41 391	€ 4 040	€ 32 967	€ 8 232	€ 7 220	€ 1 740	€ 3 000	€ 3 000	€ 1 500	€ 1 500	Station cost per test step			Operator cost per test step			
Test time	Functional Block tested	Base machine (MAE)	EWAK	Equipment 1	Equipment 2	Equipment 3	Equipment 4	Equipment 5	Equipment 6	Equipment 7	Equipment 8	Fixed	Fixed fraction	Estimated fixed cost per piece	Operator	Variable fraction	Estimated fixed cost per piece	Estimated total cost per piece
4	Load/unload	0	0	0	0	0	0	0	0	0	0	0,0	0,0%	- €	1	0,204155	0,02 €	0,02 €
7,5	Connect product	0	0	0	0	0	0	0	0	0	0	0,0	0,0%	- €	1	0,38279	0,04 €	0,04 €
15,4	MOST VI test	1	1	0	0	0	0	0	0	0	0	4497,8	4,3%	0,01 €	0	0	- €	0,01 €
2,9	Light sensor calibration	1	1	0	0	0	0	0	0	1	0	2347,0	2,2%	0,01 €	0	0	- €	0,01 €
6,625	brightness measurement symbols	1	1	1	0	0	0	0	0	0	0	7606,7	7,3%	0,02 €	0	0	- €	0,02 €
4,625	Symbol color + shape measurement	1	1	0	0	0	0	1	0	0	0	2277,3	2,2%	0,01 €	0	0	- €	0,01 €
1,062	Brightness measurement symbols B	1	1	1	0	0	0	0	0	0	0	1219,4	1,2%	0,00 €	0	0	- €	0,00 €
11,125	Temp bars brightness and color adjustment	1	1	0,5	0	0	0	0,5	0	0	0	9125,7	8,7%	0,03 €	0	0	- €	0,03 €
9,578	Fuel bars brightness and color adjustment	1	1	0,5	0	0	0	0,5	0	0	0	7856,7	7,5%	0,02 €	0	0	- €	0,02 €
10,125	Sound analysis	1	1	0	1	0	0	0	0	0	0	11189,2	10,7%	0,04 €	0	0	- €	0,04 €
17,032	Flicker adjustment	1	1	0	0	0	1	0	0	0	0	6714,5	6,4%	0,02 €	0	0	- €	0,02 €
21,421	White point adjustment	1	1	0	0	1	0	0	0	0	0	9355,4	8,9%	0,03 €	0	0	- €	0,03 €
7,829	Night illumination adjustment	1	1	0	0	1	0	0	0	0	0	3419,2	3,3%	0,01 €	0	0	- €	0,01 €
20,656	Gamma measurement	1	1	0	0	1	0	0	0	0	0	9021,3	8,6%	0,03 €	0	0	- €	0,03 €
20,469	Uniformity measurement	1	1	1	0	0	0	0	0	0	0	23502,2	22,5%	0,07 €	0	0	- €	0,07 €
3,343	Image contour test	1	1	0	0	0	0	0	1	0	0	3976,4	3,8%	0,01 €	0	0	- €	0,01 €
0,985	LVDS	1	1	0	0	0	0	0	0	0	0	287,7	0,3%	0,00 €	0	0	- €	0,00 €
2,375	Fan test	1	1	0	0	0	0	0	0	0	1	2193,7	2,1%	0,01 €	0	0	- €	0,01 €
1,093	Test end	0	0	0	0	0	0	0	0	0	0	0,0	0,0%	- €	1	0,055785	0,01 €	0,01 €
7	Automation out, fixed time	0	0	0	0	0	0	0	0	0	0	0,0	0,0%	- €	1	0,35727	0,04 €	0,04 €
175,143	Total Test time	155,55	155,55	38,5075	10,125	49,906	17,032	14,9765	3,343	2,9	2,375	104590,0	100%	0,33 €	19,593	1,0	0,10 €	0,43 €
													Estimation of the fixed testing cost per piece (accounting department)			Estimation of the variable testing cost per piece (accounting department)		Estimation of the total testing cost per piece (accounting department)
													0,33 €			0,10 €		0,43 €

Figure 47 – Breakdown of testing costs by blocks.

This analysis enabled the breakdown and visualization of costs by functional testing block. For example, data shows that the block “uniformity measurement” is the most expensive for this station (total estimated cost of 0.07€ per piece), therefore this block should be prioritized when establishing improvement activities to reduce costs. In other words, the breakdown allows improvement efforts to be targeted rather than a generic improvement approach to all categories (or no approach at all).

Therefore, it is possible to build a more reasonably budget plan by calculating the overall expected investment in terms of machines/equipment, *e.g.*, reducing the installed equipment, optimizing EWAK and MAE assignment, reusing equipment from other lines, and changing production layout to reduce operator walking distance.

Moreover, after the analysis of the data necessary for building Figure 47, it was concluded that there are various approaches to reducing test time, *i.e.*, removing delays, reducing internal repetitions/retries, eliminating doubled tests throughout the test chain, and reducing test coverage. This is because each group of quality characteristics described in the second column of the table comprises several quality characteristics. The list of characteristics comprises not only the ones originally specified in the PAV, but also the ones necessary for the operation of the testing software. Although these additional functions are not product characteristics *per se*, they are in the same list and include commands and configurations to execute the tests. For example, when a device is inside a TS, it has to be moved along the axes toward the exact position to be measured by the equipment (*e.g.*, cameras). The movement commands are dictated by the same software that commands the tests. Moreover, test algorithms are developed with a lag between tests. This buffer is provided in the testing algorithm between the command and the response of the product to be tested. Before the ramp-up, the times should be optimized, removing these delays, however, in some cases, there is a possibility of this optimization being overlooked.

Following the conceptual model of the current defect handling at FCT50 along with its costs and parameters presented in Figure 44, one can see that both the inspection and reinspection happen in the same equipment. Therefore, estimates for the cost of inspection ($C_{inspection}$) and reinspection ($C_{reinspection}$) were considered as the same. Basically, these costs were assessed by considering the sum of fixed and variable costs per piece. The fixed costs comprise the costs of the hardware and software used for automated testing, *e.g.*, machine, tool license, and acquisition costs, while the variable costs consider the operators. The estimated unitary $C_{inspection}$ and $C_{reinspection}$ costs resulted in 0.43€/unit. The uncertainty for both parameters was defined as triangular distribution ranging from 0.40 to 0.50 €/unit.

Repair Cost

The repair cost accounts for the Failure costs within the PAF approach to CoQ, specifically, Internal Failures, as it represents an activity related to the defects discovered before delivery of the product to the customer.

The cost of repair (C_{repair}) includes both the costs of the operator performing repairs and the cost of scrapping and replacing the eventual defective parts. The last was estimated considering the historical data regarding different defect types and their associated costs. The data on the types of defects found during the assembly processes is entered into the database by the production line managers. Therefore, it was necessary to contact the Manufacturing Department to obtain these data, which are presented in the dashboard in Figure 48. Accordingly, it was possible to calculate the weighted average for the repair cost, which resulted in 2€/unit. The uncertainty of this parameter was defined as triangular distribution ranging from 1.5 to 4€/unit.

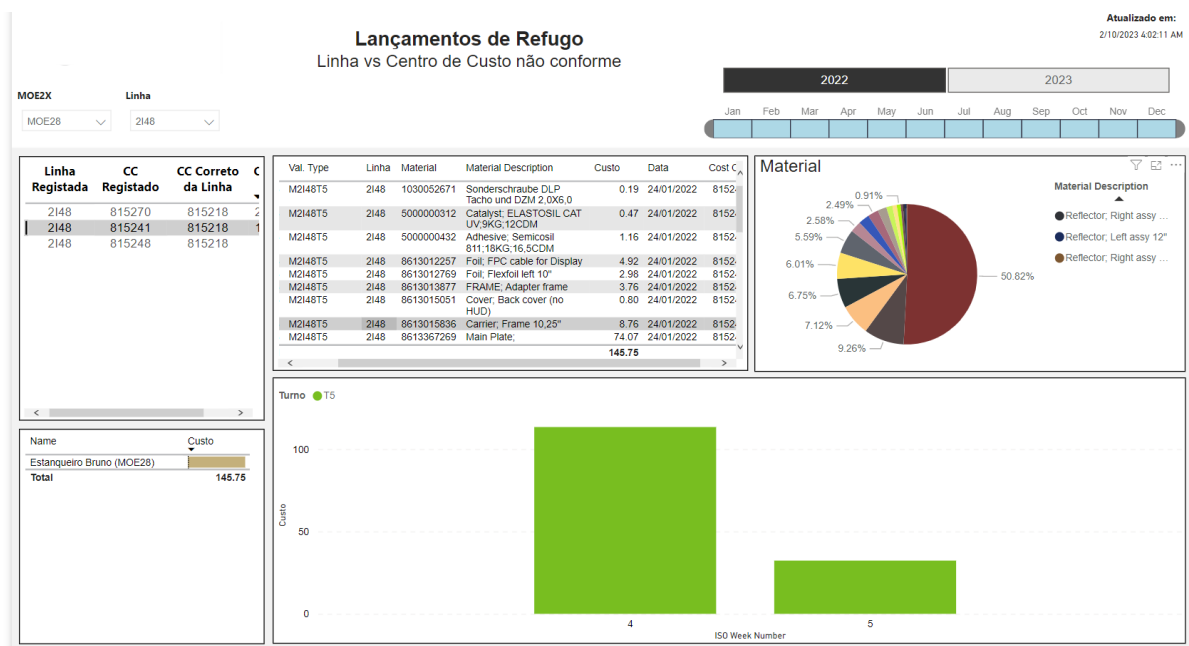


Figure 48 – Company dashboard showing scrapped parts and costs.

Analysis Cost

The assessment of the analysis cost ($C_{analysis}$) was also not yet been carried out by the Company. This data was estimated together with the Accounting Department, similarly to the analysis carried out for other operations that require human operators, resulting in 0.50 €/unit. The uncertainty of this parameter was defined as triangular distribution ranging from 0.35 to 0.75 €/unit.

Cost of passing defective units to the test station

The cost of passing a defective unit to the next station (C_n) was estimated purely based on expert opinion within the Company and Academia at 20€/unit. Given the high vagueness related to this parameter, this uncertainty was defined as triangular distribution ranging from 15 to 30 €/unit.

5.4.3.2 Parameters

The parameters are based on a database containing the results of tests carried out, *i.e.*, secondary data already available at the Company. The secondary data refers to the 310 producing days of the year 2020 in which 1328907 single units of the analyzed product (*i.e.*, an Infotainment System) were tested within the FCT50. The charts in Figures 49, 50, and 51 represent these data for N_p , P_d , and F_d , respectively. In all the three charts, the blue bars represent the real data within the histograms, while the red curves show fit comparisons of the data distributions performed in the software @RISK 8.1 from Palisade (<https://www.palisade.com/risk/>).

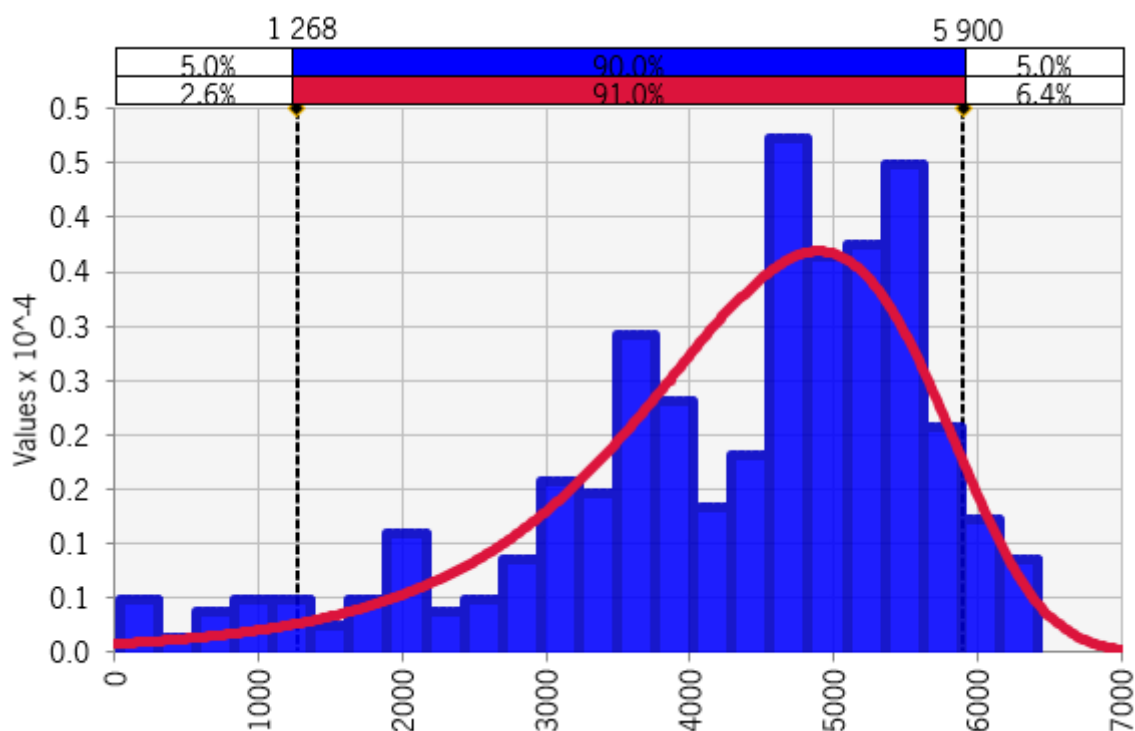


Figure 49 – Daily production quantity (N_p) histogram: Secondary data from 2020.

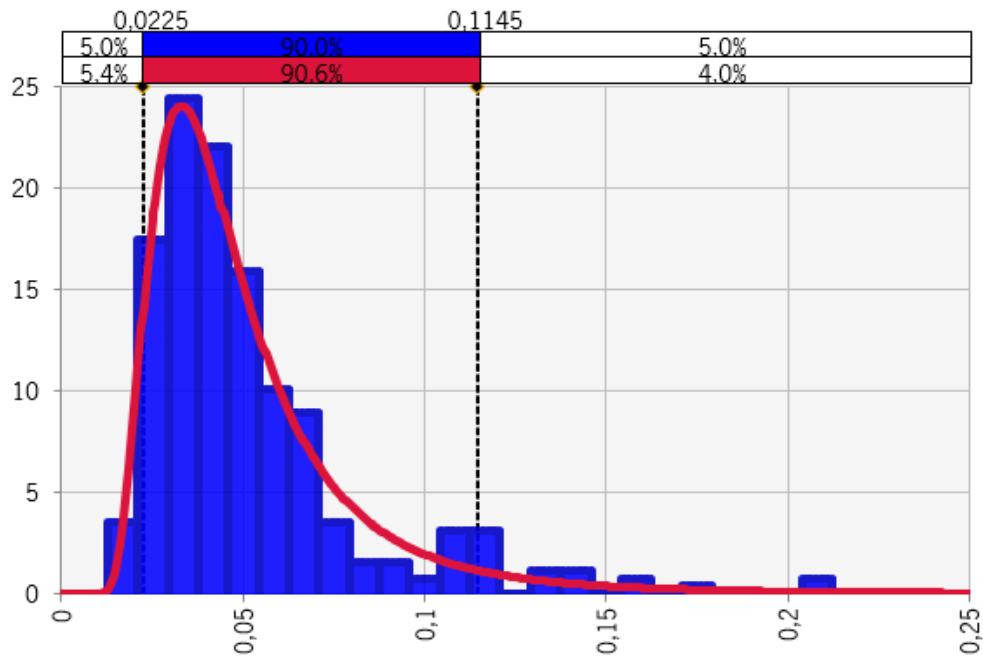


Figure 50 – Proportion defective (P_d): histogram: Secondary data from 2020.

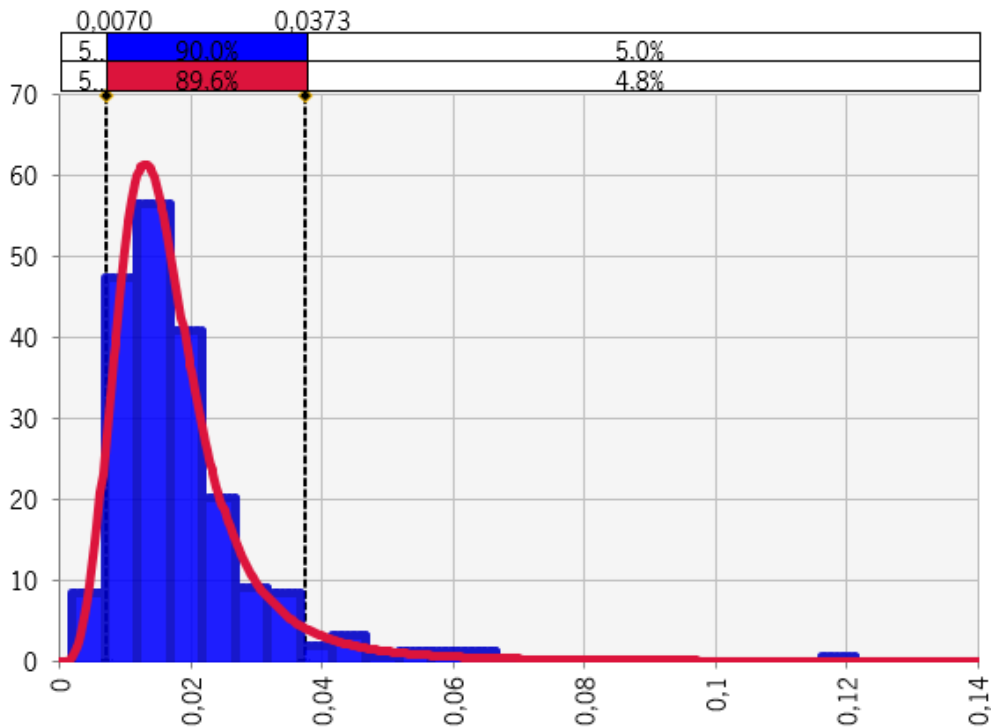


Figure 51 – False defectives (F_d): histogram: Secondary data from 2020.

Given these data, the N_p value considered in the simulation was 4314, and the P_d value was 5.1%, which are the realistic typical daily production quantity and proportion of defectives, respectively, according to the analysis performed at @Risk.

The estimated proportion of false defectives (F_d) (type-I error) was estimated based on the count of s-cases within the failed devices, *i.e.*, the cases which the analyst spotted improper rejections by the inspection/test system. The average of s-cases for the year 2020 in this station and this production line was 1.8%. As referred in Section 6.1.2 (about the IRR indicator), there is the human factor associated with registering s-cases, which implies an uncertainty associated with this estimation of F_d .

The Company usually defines product specifications tighter than initial customer specifications so that errors are forced on one side of the specification. The TS measures several quality characteristics, and whenever one of them happens to be outside the tight-imposed tolerance limits, the product will “fail” at the station. This can increase false defectives given by the measurement system, while reducing false compliant (type-II error). Nevertheless, the false non-defectives (F_n) were assumed as in Zaklouta and Roth (2012): type-I equal to the type-II error.

5.4.3.3 Data Modeling Overview

In order to quantify the CoQ of a given product (**Objective 4.1**), the list of model parameters (N_p , P_d , F_d , and F_n) and cost elements (C_{repair} , $C_{analysis}$, $C_{reinspection}$, and C_n) of the ISM is presented in Table 23. Many difficulties were faced in obtaining these values. Accordingly, some parameters and cost estimative are associated with more or less uncertainty. The definition, estimated value, and uncertainty intervals applied in Excel to perform analysis with the add-in @Risk are also presented in Table 23.

Table 23 – Model parameters and CoQ elements.

Abbreviation	Description	Value	Input at @Risk
N_p	number of units passing through the FCT50	4314	RiskExtvalueMin(4890,0049;997,4734)
P_d	estimated proportion of defective units	0.051	RiskPearson5(4,3076;0,1622;RiskShift(0,0024044))
F_d	estimated proportion of false defectives given by the measurement system	0.018	RiskLoglogistic(0,00069584;0,014803;3,314)
F_n	estimated proportion of false non-defectives given by the measurement system	0.018	RiskUniform(0,002;0,06;RiskStatic(0,018))
$C_{inspection}$	estimated average unitary inspection cost	0.43	RiskTriang(0,4;0,43;0,5;RiskStatic(0,43))
C_{repair}	estimated average cost of repairing a defective unit	2	RiskTriang(1,5;2;4;RiskStatic(2))
$C_{analysis}$	estimated average unitary analysis cost	0.5	RiskTriang(0,35;0,5;0,7155;RiskStatic(0,5))
$C_{reinspection}$	estimated average unitary reinspection cost	0.45	RiskTriang(0,4;0,43;0,5;RiskStatic(0,43))
C_n	estimated average cost of passing a defective unit to the next process	20	RiskTriang(15;20;30;RiskStatic(20))

5.4.4 Results and Discussion

This section presents the simulation results for the CoQ for two IS scenarios: 100% and no-inspection. It also presents the effects of a hypothetical investment in the manufacturing line to reduce the proportion of defective units (Pd) on the total CoQ per product unit. In addition, the behavior of these two IS scenarios is also analyzed from the perspective of historical data, *i.e.*, in a 2020 timeline.

5.4.4.1 100% inspection

As mentioned before, all product units that pass through FCT50 are tested (*i.e.*, 100% inspection), and there is a reinspection of the rejects after analysis and eventual rework. Even though this is the current inspection strategy at the TS, there is no indication of its total CoQ within the Company's reports and databases. Therefore, the developed model was used to calculate it through the equations and estimates and shown in Sections 5.4.2 and 5.4.3.

Accordingly, Figure 52 presents the histogram obtained from the Monte Carlo Simulation results, which resulted in a unitary total CoQ of 0.61€/unit for the current IS, which can be found between 0.535 and 0.911€/unit within a 90% confidence interval for the 100% IS. This value was absent from the Company's data for the TS since there are just overall estimates for the whole manufacturing line. However, it is reasonable according to specialists of the Company.

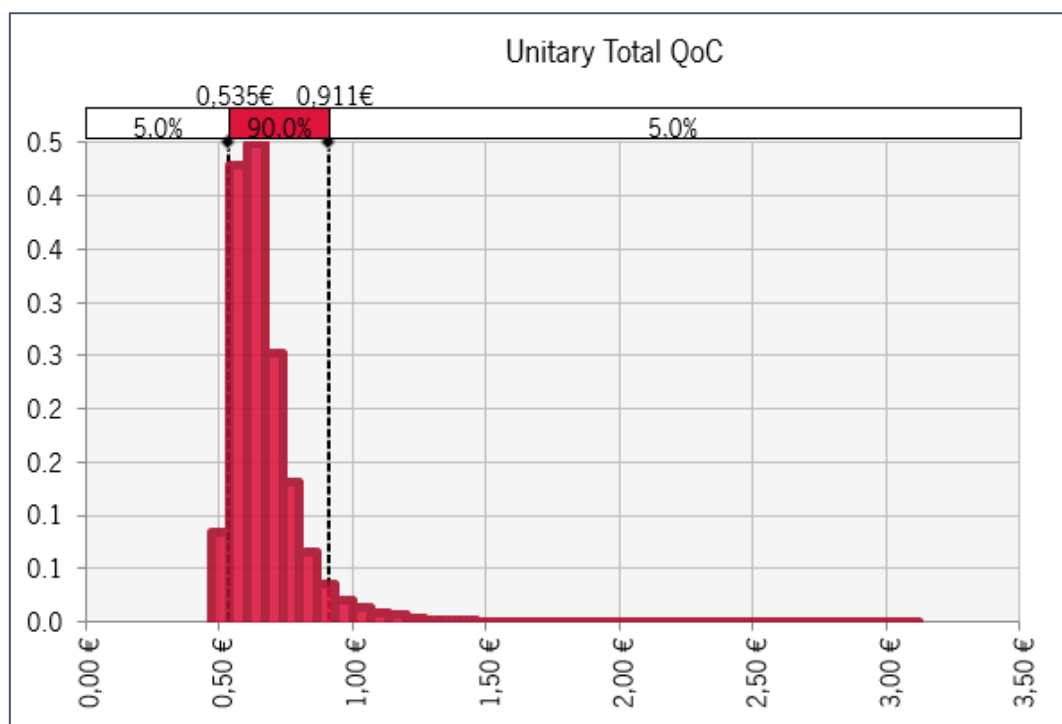


Figure 52 – Unitary total CoQ histogram with 90% confidence interval for the 100% inspection.
Source: Output from @RISK.

Figure 53 shows the tornado diagram that displays parameters with higher influence on the total CoQ. The P_d and C_{repair} have the highest impacts on the total CoQ. This also means that the objective function is more sensitive to the change of these costs than, *e.g.*, to the change in C_n .

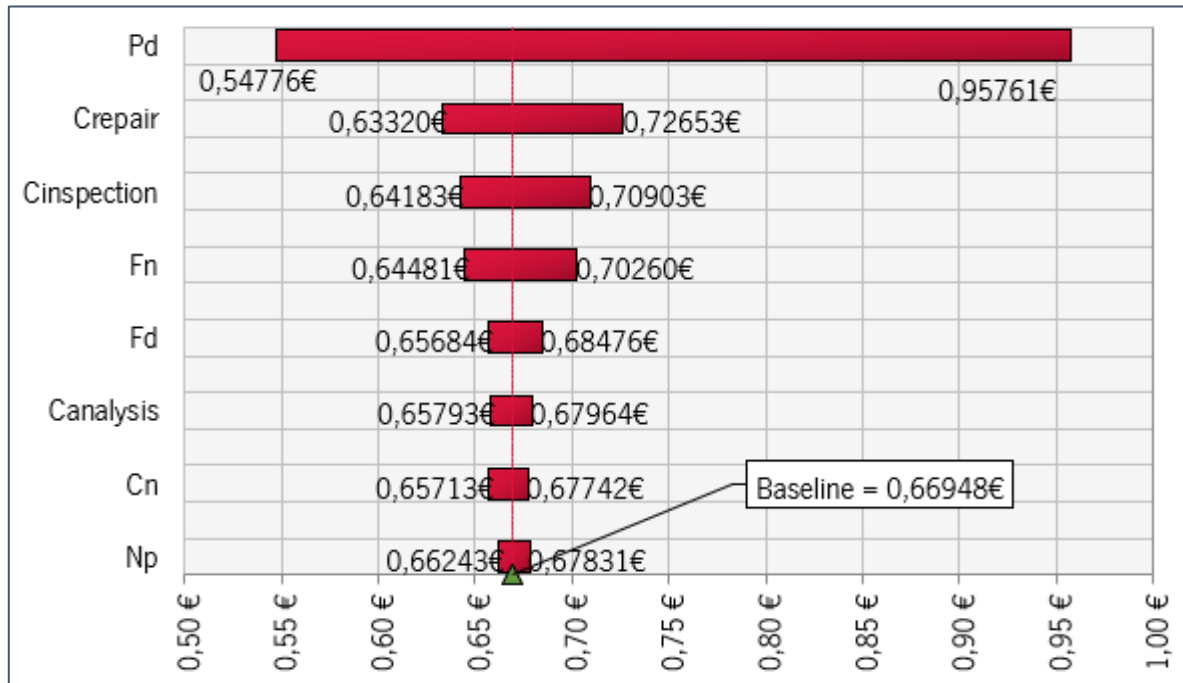


Figure 53 – Sensitivity analysis, ranking inputs variation effects on the unitary total CoQ. Source: Output from @Risk.

By acknowledging that changes in process values would result in different values in the total CoQ, and that P_d is the most impactful parameter on the CoQ, a scenario is presented supposing there was an investment in the production line to reduce the internal failure rate P_d . Therefore, assuming the improvement resulted in a reduction in the proportion of defectives from 5.1% to 1%, the unitary CoQ would perform as shown in Table 24. The data behind the CoQ calculation in this “what if” analysis are the same presented previously in Table 23, except for P_d , which was assumed as a fixed value at 5.1% and 1%. This is why the (min, max) for the 5.1% scenario is not the same result as the previous analysis (Figure 52).

Table 24 – Average Unitary total CoQ within a 90% confidence interval

Pd	Min (5%)	Average	Max (95%)
5.1%	0.60€/unit	0.61€/unit	0.74€/unit
1%	0.46€/unit	0.48€/unit	0.54€/unit

Even though the process is already highly robust at the Company, an inspection investment to reduce the proportion of defects from 5.1% to 1.0% could reduce the *Unitary CoQ_{100%inspection}* from 0.61 to 0.48€/unit. Such a reduction in the failure rate could be achieved, *e.g.*, through better machinery, better

supplied raw material, and training for the assembling operators. The investment in better equipment must be justified through an ROI considering acquisition and operational costs, the number of units being produced, among other factors.

Hsieh *et al.* (2010) have also analyzed changes in the defective rate due to quality investment, but in a supply chain context rather than in an inspection station, *i.e.*, investments at production sites and production processes of a supplier and a manufacturer. Foumani *et al.* (2020) analyzed inspection process with decreasing failure rate. Oppermann *et al.* (2003) considered the defect rate changes in a range of 5%, while Hamrol *et al.* (2020) considered 10%. Lim *et al.* (2015) and Shetwan *et al.* (2011) considered different internal failures may occur with specified probabilities at different stages in the overall process. Tuominen (2012) considered a fixed probability for each defect type. Sousa and Nunes (2019) and Zhu *et al.* (2016) considered changes regarding in control/out of control states, which may lead to different nonconforming product rates.

Based on these considerations within the literature, it is concluded that to calculate the costs of internal failure, one must take the stochastic character of the manufacturing system into account. Farooq *et al.* (2017) states one of the most important contributions from their work is that the failure rate was directly taken from Design of Experiments results rather assumed or simulated. This is also the case within the Pd considered in the model proposed, which was taken from the Company databases.

Nevertheless, although the values and fit distributions established in @Risk were very suitable, Figure 54 shows the analysis where the real distribution of the data was used to calculate the CoQ. The data were organized chronologically, *i.e.*, each point in the green line represents the unitary CoQ referring to a given day in 2020 in which there was production, with the specific Fd (purple line), and Pd (red line) values for that day.

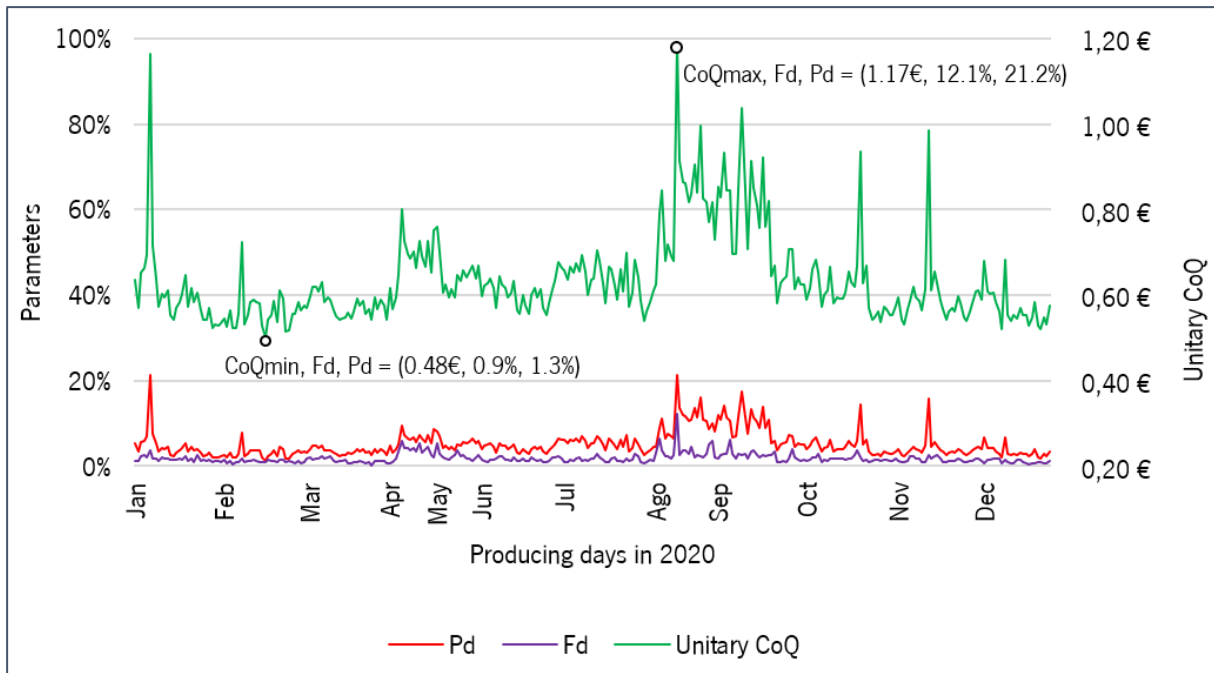


Figure 54 – Representation of the minimum and maximum CoQ in the year 2020 and respective Pd and Fd proportions.

The two points indicated in the chart represent the maximum and minimum unitary CoQ for the year 2020.

On 15 February 2020, 2528 units were produced (N_p), the Fd proportion calculated based on the s-cases was 0.9%, and the Pd was 1.3%. In this day, the Unitary CoQ reached its minimum for 2020, *i.e.*, 0.48 €/unit.

On 16 August 2020, on the other hand, when just 33 units were produced (N_p), the failure rate was 21.2%, and the Fd was 12.1%, the Unitary CoQ reached its yearly maximum, at 1.17 €/unit. Given the low N_p and high Pd for this day, it can be inferred that there was some problem during production, for example, a breakdown in the FCT50 machine, and it was decided to stop production, possibly for equipment maintenance.

5.4.4.2 No-inspection

If there is no inspection, it is expected that more defective units would be handed over to the next process compared to the current situation of 100% inspection. In this scenario, the relevant parameters are related to the expected cost of defective units delivered to the next process. The Total CoQ of no-inspection is expressed by Equation (11), while the Unitary CoQ of no-inspection is expressed by Equation (12).

$$Total\ CoQ_{no-inspection} = [C_n \cdot N_p \cdot P_d] \quad (11)$$

$$Unitary\ CoQ_{no-inspection} = \frac{Total\ CoQ_{no-inspection}}{N_p} \quad (12)$$

Where:

- $C_n \cdot N_p \cdot P_d$ is the overall cost of passing defective units to the next station.

Considering the C_n as 20 €/unit, and P_d as 5.1%, the $Unitary\ CoQ_{no-inspection}$ results in 1.02€/unit.

For the no-inspection scenario, a higher average unitary total CoQ was obtained compared to the 100% inspection scenario. Other works that found a similar result when comparing 100% to no-inspection include Sousa and Nunes (2021) and Hamrol *et al.* (2020).

In terms of the unitary CoQ, this does not seem so impactful, but given the Company's 2020 production, the $Total\ CoQ_{100\%inspection}$ results in around 837 200 € while the $Total\ CoQ_{no-inspection}$ is 1 338 920 €.

However, it is important to note that this result ($Unitary\ CoQ_{100\%inspection} < Unitary\ CoQ_{no-inspection}$) is not valid for any failure rate. To better explore the breakeven point that interchange this relationship, Figure 55 presents a scatter plot chart for $Unitary\ CoQ_{100\%inspection}$ and $Unitary\ CoQ_{no-inspection}$, in blue and red, respectively.

The CoQ was calculated for each point according to the company's secondary data, as an alternative of considering the values and fit distributions established in @Risk. Accordingly, instead of considering fixed values for N_p , P_d , and F_n , the real daily instances of these parameters were considered in the calculation of CoQ for both scenarios in this chart.

The linear trend lines, automatically generated in Excel, show for both inspection strategies a constant increase in CoQ as P_d increases, while the R^2 values indicate excellent fits of the estimated trend-line values to the actual data.

The most important aspect shown by the graph is indeed the breakeven point in the P_d proportion at which the $Unitary\ CoQ_{100\%inspection}$ equal the $Unitary\ CoQ_{no-inspection}$, *i.e.*, around (2.8%, 0.55€). In conclusion, for a proportion of defects greater than around 2.8%, inspection is worthwhile. Considering the company's historical data in 2020, it happens in just 40 out of the 310 days, *i.e.*, 13%.

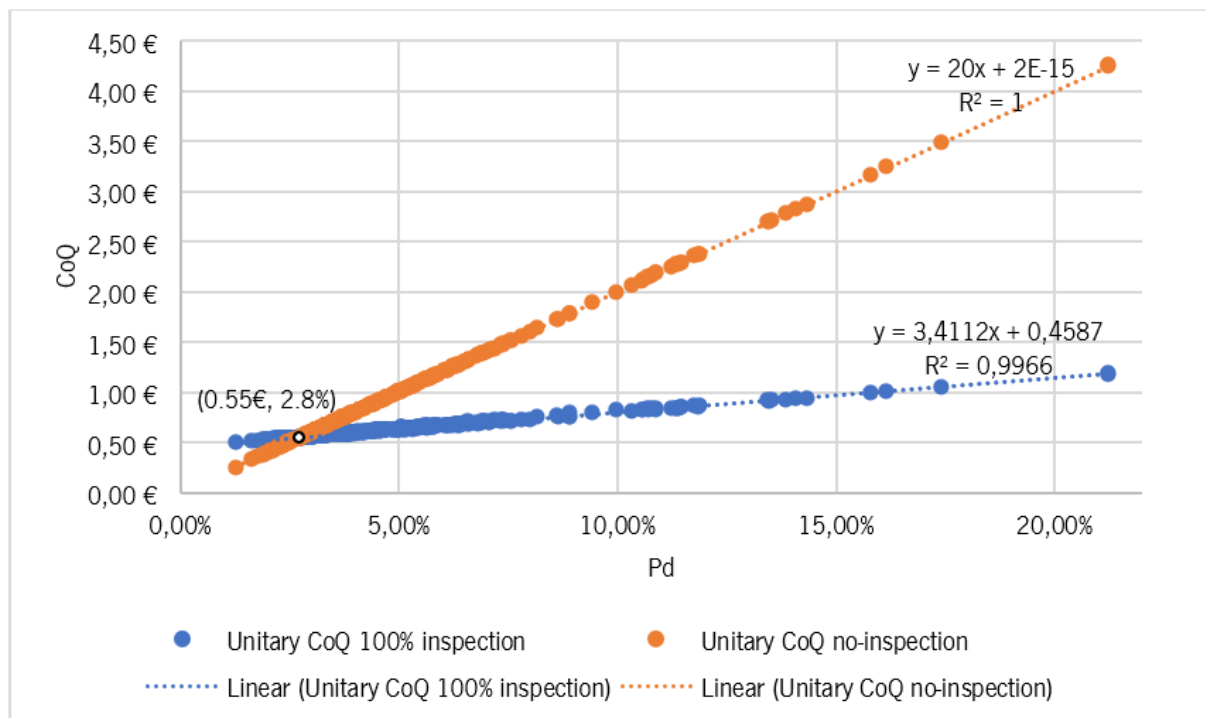


Figure 55 – Breakeven point between two IS: 100% inspection and no-inspection.

By supposing the same alternative scenario of an investment in the production line to reduce P_d from 5.1% to 1%, the $Unitary\ COQ_{no-inspection}$ would reduce from 1.02€/unit to 0.20€/unit, respectively (reduction of around 80%), while in 100% inspection scenario the $Unitary\ COQ_{100\%inspection}$ would reduce from 0.61€/unit to 0.48€/unit (reduction of around 22%).

Figure 55 shows that the Pd reduction is much more impactful in the CoQ for the scenario without inspection than for the one with inspection. In other words, whereas it is obvious that it is better to have a process with fewer defects, this is especially important for achieving a lower CoQ when one does not want to include inspection stations.

Although this hypothetical scenario of no-inspection is interesting, it is important to state that some quality characteristics must be mandatorily inspected during the production process, *e.g.*, those related to safety, legislation or even customer requirements, therefore, it is assumed that these characteristics would be inspected in another TS in this supposed situation of not inspecting in FCT50.

Even for characteristics that are inspected at the initiative of the Company rather than by external requirement, the complete absence of control is probably not the best solution, especially in cases of processes that are not as robust. Considering the context of the automotive electronics industry, inspection followed by analysis and repair activities helps to explain why some type of quality problem occurs, which is as a useful information for product and process improvement. By working on these tasks, analyzing defects and performing root cause investigations, quality engineers gain valuable information.

However, when the product is “functionally robust” and/or the process is “manufacturing method robust” (See 4.3.1), it is plausible to assume that some characteristics can only be controlled during the pre-production phase, where product samples are manufactured, instead of being inspected at 100% during the mass production phase.

5.4.4.3 Discussion

The choice of the most appropriate inspection strategy for assessing the quality of certain product characteristics is a non-trivial problem. The variety of products that can be produced with the existing technologies makes it difficult to standardize and adopt a unique inspection procedure (Verna *et al.*, 2022). Moreover, there may be several eligible and suitable alternatives for the considered production amongst all the different possible inspections (Verna *et al.*, 2022). Zaklouta (2011) points out that manufacturing process improvement often coincides with a need to change inspection strategy choice, thereby indicating that manufacturing process and inspection strategy selection should not be performed independently of each other. Therefore, a collaborative inspection planning, integrating both the inspection plan and the production plan, is critical to improve profit (Shiokawa and Ishii, 2019).

In manufacturing, where systems are complex and dynamic, there are many sources of variation. To develop a useful and sustainable ISM, it is necessary to keep its parameters up-to-date, which requires investments consisting in the deployment, provisioning, operation and management of CoQ data, mainly with regard to the appraisal and failure categories. As data plays a key role in this regard, managing the data pipeline effectively and aligning data curation efforts with goals and requirements is the key differentiator.

Therefore, as the necessary data can be stored in different departments, as in the case reported in this thesis, it is necessary to maintain an open and cross-functional communication, for example, between the design, manufacturing, quality, testing and accounting teams, building bridges and reaching consistent and coordinated goals. Indeed, the expertise of several departments needs to be brought in before a comprehensive model for assessing and addressing the CoQ for ISM is achieved. Additionally, it is important to consider their requirements to design a well-suited model, given their leverage and influence on the development and use of a model. A structure like the one proposed by Yang *et al.* (2021) to improve the representation and sharing of knowledge can be used to deal with the different demands needed in ISMs.

Considering the context of Industry 4.0, the existence of a large amount of data available, intelligent algorithms and computational power does not mean that there will be a direct solution to optimize

inspections. In this sense, economic analysis studies or detailed impacts on the CoQ are necessary to justify the necessary investments in the processes (Saihi *et al.*, 2023). While data overwhelming and the lack of integration and sharing may difficult the modelling of inspection strategies, smart manufacturing environments also create opportunities for enhanced data management, as well as real-time monitoring and quality control. These aspects are likely to contribute to higher quality outputs once translated into costs, as in the proposed ISM.

In terms of solution technique (Section 2.4.3.2 in the Theoretical Background Section), Mohammadi *et al.* (2015) points out that most of the real-world problems related to ISM have large sizes. To model an inspection strategy using *optimization* solution requires either more assumptions and simplifications about the inputs or more computing power to deal with all the different variables to calculate the optimized result when compared to *simulation* solution techniques. In addition, a single “best” *optimized* result can inhibit the operability and interpretability of the ISM and its consequent added value for decision making, which is expected to require a lot of information to assess the relevance of several alternatives. Indeed, to find out what the most adequate inspection strategy, the possible solutions to be compared should be proposed by the planners themselves, or at least by bringing in their background knowledge. Even after modeling them and getting the total CoQ of each one, the final decision must consider other factors other than just the cost, such as the risk attitude of the decision-maker and the possibility of including risks that are monetarily non-tangible, *e.g.*, threat of image loss through less costly errors (Basse *et al.*, 2015; Schmitt *et al.*, 2014).

Therefore, the total CoQ of the current policy can be used as the benchmark to be compared against, and then the cost performance of the other alternative inspection strategy can be tested with “what-if” analyses, through which it is possible to explore the performance of the simulated systems by tweaking the initial conditions. While this study only compares the no-inspection scenario with the current 100% inspection (with reinspection of rejects), explored dimensions of inspection strategies may also include scenarios such as reinspection of accepts (Zaklouta and Roth, 2012), sampling inspection, and comparison between inspection equipment options (Tuominen, 2012).

Moreover, a similar study can be modeled considering the interdependencies of quality testing activities to harmonize inspection processes. By analyzing the character of the relationships, it is possible to harmonize certain test activities to reduce the total test effort. At best, it is possible to eliminate costly quality testing activities carried out at the production stage, shifting the inspection focus to earlier or even later stages of the product life cycle (Kukulies *et al.*, 2014). In such a context, for each “check point”,

one can estimate the cost of inspection, the probabilities of the various possible internal failure outcomes, and the associated costs of correcting these failures (Lim *et al.*, 2015). It is underscored that this analysis entails a deep understanding of the interconnectedness of quality inspections.

5.4.5 Model Validation

Building a model involves being simultaneously engaged in its validation. The model validation process followed what was proposed by Landry, Malouin, and Oral (1983): conceptual validation, logical validation, experimental validation, operational validation, and data validation. To ensure the usefulness dimension of validity, an active participation of the main actors in the modeling-validating process and the consideration of the problem context in which this is carried out are emphasized (Landry *et al.*, 1983). Face validation took place with quality specialists inside the Company and in the Academia, with the reasonableness of the model being asserted. Accordingly, each dimension validity was assessed by both groups in terms of satisfaction degree, ranging from one (null satisfaction) to five (full satisfaction). The overall results are presented in Table 25 and explained afterwards.

Table 25 – Assessment of satisfaction regarding the model validity.

Type of validity	Degree of satisfaction				
	1	2	3	4	5
Conceptual validity					x
Logical validity					x
Data validity			x		
Experimental validity					x
Operational validity		x			

Conceptual validation wonders if one is looking at the problem situation from the appropriate perspective. Here the problem situation has to be adequately reflected, that is, in a way that encompasses the elements and relationships judged pertinent by those actors who deal with the problem situation (Landry *et al.*, 1983). The low level of conceptual validity is one of the major reproaches that are often made to operation research models (Landry *et al.*, 1983). It was indeed very challenging to translate business requirements and demands into model parameters and data requirements. The conceptual model is valid as it is based on the current defect handling at FCT50, as described in Section 6.4. A testing engineer, a quality engineer, and the head of the related production line checked the conceptual model and fully validated it.

Logical validation is concerned with the capacity of the formal model to describe correctly and accurately the problem situation as defined in the conceptual model. It implies verifying whether any pertinent variable or relationship has been omitted from the formal model, evaluating its internal

coherence (Landry *et al.*, 1983). It is important to mention that a high level of logical validity does not imply a high level of conceptual validity, nor vice versa. In relation to this, all pertinent variables were included in the model. A quality engineer from the Company and two Professors from the university checked for the validity of each equation, attesting the logical validation.

Data validation is related to the sufficiency, accuracy, appropriateness, and availability of the data (Landry *et al.*, 1983). Difficulties related to collecting and processing the necessary data in the case study were mentioned in Sections 4.4.1 and 4.4.2. Moreover, in Table 8 (Discussion on indicators for quality cost assessment), on page 37 in the literature review (Chapter 2), general recommendations in this matter were outlined. Nevertheless, it is important to indicate specific aspects of model validity can be improved to better modeling. Namely, the model incorporates quality-related cost items that the current Company cost assessment neglects, *e.g.*, the cost of passing defective units to the next process, which was estimated based on expert knowledge in the proposed model. In addition, the costs of analyzing products classified as failed ($C_{analysis}$) and repairing the defective ones (C_{repair}) were less accurate estimates, as the Company has a very strict stance regarding data confidentiality, which made the cost assessment quite difficult and challenging. F_n , the proportion of false non-defectives given by the measurement system (type II error), was estimated based on expert knowledge in the proposed model. Estimation can be done with the use of databases holding the results of the MSA analysis, expert knowledge, or the results of specially conducted tests (Hamrol *et al.*, 2020).

Experimental validation is related to efficiency in obtaining the solution and sensitivity to changes in model parameter values (Landry *et al.*, 1983). The model's sensitivity to changes in certain parameters was tested right after the logical validation, at which point the parameters and costs uncertainty were also defined based on the company's historical data and estimates, as shown in Section 5.4.3.3 (Data modeling), while the results of the experiments are presented in Section 5.4.4 (Results and Discussion).

Finally, *Operational validation* is related to the quality and applicability of the solutions and with respect to the intended users and use of the formal model and with respect to the problem situation (Landry *et al.*, 1983). It indicates whether the model has the potential to justify the time, efforts, and the costs. Unfortunately, due to time constraints regarding the delivery date of this thesis, it has not yet been possible to apply the model at the Company. Nevertheless, its potential as a decision-making aid instrument was discussed with Quality Engineers, who considered it a “*very interesting tool*”. In this regard, it is sustained that the ISM proposed in this thesis allows flexible adaptation and transfers to

products with different features, after appropriately tailoring the model variables' estimates to suit the specific case, *i.e.*, the dynamical reality.

On the one hand, the proposed model integrates aspects that are usually not integrated, linking operational and quality-related issues with costs. Therefore, it is instrumental in communicating concepts and solutions between the teams involved in the inspection strategies definition, and the comprehension of the mechanisms involved when adding quality-related dimensions (parameters and costs). Moreover, the model simplicity opens ways to create an interactive setup that can involve all the stakeholders related to the inspection planning without overwhelming them.

On the other hand, there is the practical value in assisting them in the decision-making by calculating future values or behavior of some parameters in order to reduce quality costs. By modeling alternatives, the model allows challenging current production line schemes by proposing more fine-grained ones where the total CoQ is reduced. This comparison between alternatives can be useful, for example, for justifying the investment in more precise equipment (which typically implies higher $C_{inspection}$ and lower F_d) if the model shows the total CoQ pays it off.

Given the today's Company culture of Industry 4.0, in a future perspective for the model *operationality*, the model parameters could be gleaned automatically, *e.g.*, through machine sensors, and directly fed into a digital manufacturing database that would also hold the relevant quality costs. Therefore, it would be possible to build a digital twin of the inspection stations considering the CoQ, to better inform the process in real-time, and be used to dynamically control the process for optimal results.

6 Conclusions

By having explored 1) the review and update of quality-related KPIs and the relationships between some of them, 2) real practices for the planning and revision of inspection and control methods, and 3) inspection strategy modeling considering CoQ in the context a Company within the automotive electronics industry, this research contributes to several streams of Quality Management literature and has many practical implications for quality practitioners. The relevance of this thesis for the literature is summarized in Section 6.1, followed by a description of their practical significance in Section 6.2, the research limitations in Section 6.3, and, finally, some directions for future research in Section 6.4.

6.1 Theoretical Contributions

First, this study directly addresses recent calls for longitudinal research (Melnik *et al.*, 2014; Reis *et al.*, 2022) that theorizes the KPI review process. The suggested changes in the analyzed Company's KPIs considered characteristics that were already proposed and discussed in the literature reviewed, such as the aggregation and disaggregation of measures, redundancies in the KPIs, the assessment of performance measures, the establishment of targets, data availability, constant target updating for CI, and the test of relationship between KPIs. Moreover, the qualitative analysis of the Company's KPIs contributes to a better understanding of the processes and challenges of reviewing and updating KPIs in a real organizational environment.

Second, it extends the current conceptualization of IP in the literature by proposing a more fine-grained conceptualization wherein 10 IP arrangements are outlined. In addition, while most of the research so far on IP and inspection improvement is theoretical, *i.e.*, not uncovering how actual IP improvements unfold from a real perspective, this study provides an in-depth analysis of the practices regarding these topics within the case study. In addition, this thesis proposes a conceptual and visual tool, IP-PDCA, which synthesizes these findings while synergistically positioning them within the literature (Kukulies *et al.*, 2016).

Finally, it presents an ISM providing valuable insights into the behavior of the different components of the inspection strategies and their impact on the CoQ. While most of the research so far on ISM have been based on fictional data or not adjusted to historical data, the model was developed and conducted using real-life data related to a functional TS of an Infotainment System. Under these circumstances, the study also directly addresses recent calls for more research about CoQ assessment, which is pointed out

as under-researched with significant potential to be explored further (Dimitrantzou, Psomas, and Vouzas 2020; Psarommatis and May 2022).

6.2 Practical Relevance

From a managerial viewpoint, this thesis also acknowledges many contributions.

First, the research findings attempted to assist the business managers to better understand the current practices, issues, and challenges of KPIs data systems and their management within the context of measuring quality-related performance. It also highlights the relevance of well-designed and constantly monitored KPIs for the development of appropriate policies, robust decision-making, and the CI of an organization. In sum, by addressing the evolution of the KPIs, identifying limitations, and suggesting improvements, this thesis supports the relevant role of continuously reviewing existing measurement systems to keep pace with the competitive environment.

Second, regarding the exploratory research on the causes of modifications in IP arrangements, some managerial suggestions also emerged that, although not directly related to the thesis objectives, can be seen as a side effect. Namely, from the participation in the CI workshop, it was noticed that the suggestions given by the participants are not only catalysts for process improvement but are also associated with organizational learning. In this way, it is argued that some measures can be applied transversally in other projects or situations instead of locally optimized in production lines focused on the event. Regarding the IP itself, it was concluded that there are various approaches to reducing test time, *i.e.*, removing delays, reducing internal repetitions/retries, eliminating doubled tests throughout the test chain, and reducing test coverage. In addition, it was recognized that *flexibility* plays an explicit role in the design of the production system, with MAE and EWAK equipment being important in the final composition of the production lines, and *productivity* is the main driver of changes the IP. Meanwhile, the *quality* related data, particularly its costs, are not explored to the full potential they could be when assembling test and inspection systems in production lines. In other words, at the very least, the study raises important questions by pointing to the fact that the Company still does not have a decision-making structure to design or invest in new production lines considering all the potential referred to in the literature and offered by the CoQ approach.

In this sense, this work contributes by diagnosing this problematic area and proposing a model that helps to overcome it. Namely, the model incorporates quality-related cost items that the current Company cost assessment neglects, *i.e.*, the cost of analyzing defective units, and the cost of passing defective

units to the next process. In addition, it is highlighted that both the collaboration between departments and a well-designed and constantly monitored CoQ assessment are essential in this regard.

6.3 Limitations

The first limitation relates to objectives 1 and 2. Because of time constraints and the need to conduct in-depth and longitudinal analysis, a limited number of KPIs could be considered. Also, assumptions had to be made on occasions when data was not available, or it was not possible to obtain it. For example, although there was some documentation about the reviewing process of the KPI which changed from TFOR to FPY, most of the involved stakeholders were no longer available to provide details about it as the team had been disassembled. In addition, an even more comprehensive analysis would need to consider more KPIs and look at implementation longitudinally across all their lifecycle. In terms of testing relationships between KPIs, the results did show a relation between the IRR and the IPB, however, the association was found for a specific data sample of a specific product, therefore, it cannot be generalized. In addition, the strong class imbalance, in conjunction with a high-dimensional feature space and nondeterministic occurrence of failures, made it particularly challenging to find a cause-and-effect relationship between internal and external KPIs in general.

Regarding the proposed ISM model, it is underscored that the validity and generality of the cost assessment carried out and applied are limited to the specific industrial framework of the case study, as the input parameters are contextual. In addition, as many difficulties were faced in obtaining the costs necessary for the proposed model, it is highlighted the challenge behind getting access to cost-related data within the Company. Accordingly, some of the cost estimates are associated with more uncertainty and purely based on experts' knowledge.

Nevertheless, the findings also opened avenues for further research in either KPIs or PMS stream, IP, and inspection strategy modeling, as outlined next.

6.4 Suggestions for Further Research

Further research could address the limitations identified in the previous section and explore other KPIs. Regarding the KPIs relationships, it would be interesting to test the connection between the IRR, FPY, and IPB related data for other products. Moreover, further research is needed to find cause-and-effect relationships between KPIs considering the different stages of the product lifecycle, for example, prototyping, ramp-up, full production period, and post-sales.

It is also possible to extend and/or validate the generalization of the proposed IP arrangements and IP-PDCA framework across different applications and provide feedback for further improvements and adaptations to each context.

Regarding the ISM model, further investigation could also look at different inspection strategy scenarios. While this study only compares the no-inspection scenario with the current 100% inspection (with reinspection of rejects), explored dimensions of inspection strategies may also include scenarios such as reinspection of accepts (Zaklouta and Roth, 2012) and comparison between inspection equipment options (Tuominen, 2012). Additionally, future research is needed to expand the model for more complex process configurations, including more WS. Nevertheless, a similar study can be modeled considering the interdependencies of quality testing activities to harmonize inspection processes. By analyzing the character of the relationships, it is possible to harmonize certain test activities to reduce the total test effort. At best, it is possible to eliminate costly quality testing activities carried out at the production stage, shifting the inspection focus to earlier or even later stages of the product life cycle (Kukulies *et al.*, 2014).

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