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A Systems Engineering Methodology for Quality Improvement of Manufacturing Systems

by

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Abstract

Complex manufacturing systems are commonly found in different industrial sectors. These systems are typically composed by a high number of components with unknown connections and behaviors. The inherent complexity of these manufacturing systems as well as the inability to tackle exigent quality problems is critical for producers, as it has a direct impact on product quality and cost. Measuring, reducing and managing manufacturing system complexity will increase product quality and maintain or reduce the cost of the final product.

An international consumer goods industry, whose main product is a three-piece tin plate aerosol can, is facing a similar challenge to improve the quality of its products. Although the industry is producing aerosol cans with a quality already above the international rules and regulations, customers are always in the quest of even higher quality and defect free products. This situation accounts for high financial costs and dissatisfied clients, compromising in the long run the dominant position of this manufacturer worldwide. Solving this problem is a big challenge for this company, not only due to the high production rates of assembly lines, but also due to the low cost of the final product.

Several available and renowned quality improvement methodologies for the diagnosis and control of different manufacturing processes are usually at the basis of any quality improvement actions. This research proposes a new methodology by applying Systems Engineering approaches for quality improvement based on a real-industrial case. In fact, and according to the literature review, applications of System Engineering tools in quality improvement problems has not been attempted so far, being one of the research gaps that this work attempts to address.

In order to reduce system complexity and highlight critical manufacturing process points, a new tool – the Non Conformity Matrix (NCM) - is developed based on Design Structure Matrix (DSM) principles. A 10-step methodology to apply NCM to industrial problems is proposed. In order to evaluate NCM complexity, three DSM metrics are implemented. It is observed that the NCM and associated metrics can support effectively quality improvement of complex production systems, highlighting the existent relationships between non-conformities and product defects.

Simultaneously, engineering analysis together with quality improvement tools are applied in order to further identify the root cause of the problem. In order to investigate and validate the results from the NCM and quality improvement tools, Design of Experiments (DoE) was applied on the critical stages of the manufacturing process, with the goal to identify and control the significant factors. The methodology proposed in the thesis is complemented by detailed cost of quality models to assist a correct decision-making.

The attained results in the thesis could be seen under three concurrent perspectives: (1) optimization of the manufacturing process through discovering the right combination of process factors; (2) selection of an optimized inspection strategy; and (3) investigation of potential alternative technologies and detection systems. Finally, a general Systems Engineering methodology was developed with the potential of being applied to other manufacturing systems, opening up new avenues of research.

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Farooq, Arsalan, Nóvoa, Henriqueta, Araújo, António, Tavares, S.M.O 2014. "An application of Knowledge Management in Design Structure Matrix for a process improvement phase." Risk and Change Management in Complex Systems, Carl Hanser Verlag GmbH & Co. KG, pp. 287-296.

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Tavares, S.M.O., Farooq, Arsalan., Araújo, António., Nóvoa, Henriqueta., 2013. "Application of non-conformity matrix to predict system interactions in complex quality problems". Advances in Sustainable and Competitive Manufacturing Systems, Lecture Notes in Mechanical Engineering, pp. 839-850.

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Chapter 1 - Introduction

This chapter starts by defining the boundaries of the Microleaks project, analyzed throughout the thesis. Then, an introduction to the manufacturing process of an aerosol can, and a first description of the product and its specificities is described.

Based on the problem definition, research hypotheses and research questions are expressed. Furthermore, the research approach and methodology that addresses the problem of Microleaks is developed. At the end, a brief presentation about the MIT Portugal Program framework, the affiliated institutes and partners is provided. The overall structure of the thesis and of the research approach finalizes the chapter.

1.1. Problem description

An international consumer goods packaging industry Colep, whose main product is a three-piece tin plate aerosol can, is facing a strong challenge to improve the quality of its products. Although the industry is producing aerosol cans with a quality already above the international rules and regulations, customers are always in the quest of even higher quality and defect free products. This situation accounts for high financial costs and dissatisfied clients, compromising in the long run the dominant position of this manufacturer worldwide.

The complete aerosol can is made up of four parts: the aerosol container (or simply aerosol can), the valve, the actuator, and the cap as illustrated in Figure 1. The aerosol can (or container) is made either from two-piece extruded aluminum or three-piece tinplate steel. There is a wide range of volumes available for each two-piece and three-piece can, depending on the final product characteristics and the gas to be used. Between the terms aerosol container and aerosol can, in this thesis aerosol can will be the term used to represent the three-piece tinplate steel product.

The valve has the objective of keeping the can airtight, clean and regulates the flow of the product during use. The actuator is responsible for controlling the angle, amount and shape of the product spray. The cap functions as a seal, keeping the product contained

until it is used. It also has a decorative component, contributing to the product's appearance. For certain products, a cap can also act as an actuator (FEA 2015).

Figure 1: Components of an aerosol can (FEA).

The working principle of an aerosol can is illustrated in Figure 2. An aerosol can is a pressurized container, which contains essentially one fluid/gas that boils well below room temperature (called the propellant – represents 50% to 90% of the container volume) and a mixture (solvent(s) plus active ingredients dissolved or suspended) that boils at a much higher temperature called the product (e.g. insecticides).
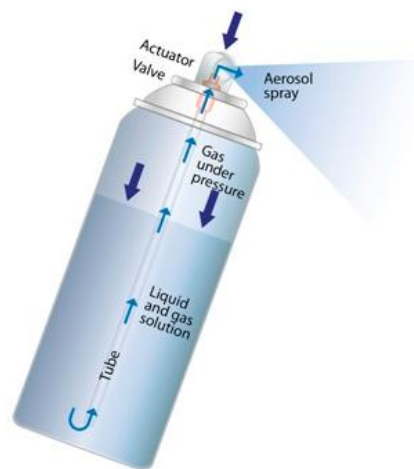
Figure 2: Working principle of an aerosol can (FEA).

Pressing the actuator activates the valve, opens a passage from the inside of the can to the outside. Consequently, the propellant exerts pressure on the active product and solvent

solution, forcing the liquid up through the dip tube and through the valve when opened. As a result, the product is expelled together with the propellant in the form of droplets, foam, paste or powder. The product that is expelled out is called aerosol spray or simply aerosol (FEA 2015).

The objective of this research thesis is focused in improving the final product quality in terms of leaks in an empty three-piece tinplate aerosol can. Therefore the study of the valve, actuator and cup are out of scope in this research. The empty aerosol can is a simple product composed mainly by three major parts, as shown in Figure 3: the top, the bottom and the body. A first fact of the problem definition is that the connections between these three parts and the lateral joining of the cylinder, highlighted with red lines in the figure, are the most important areas for reducing potential leaks.
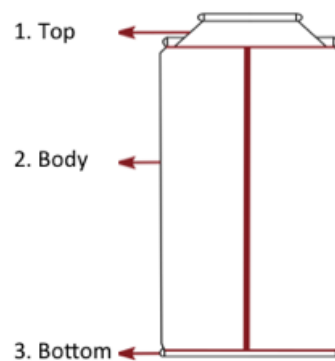
Figure 3: Basic components of an aerosol can

In order to accomplish the objective of reducing the leaks, along with the product description it is also important to understand and analyze the production process of aerosol cans. A brief process map is presented here and the detail analysis as well as key parameters related to the leaks at each process step are comprehensively discussed in Chapter 3.

The aerosol can passes successively by the following high-level production areas: primary cutting/slitting, varnishing & lithography, secondary cutting, stamping & assembly process, as briefly depicted in Figure 4. In the first step of primary cutting of the production process, the tinplate is unrolled from a large coil, straightened and cut into

smaller sheets. The top and the bottom of the aerosol can are made up from tinplate with the same thickness, while the aerosol body has a lower thickness.

In the varnishing and lithography process step, the visual attributes of the aerosol can are printed on the tin plate. Also, relevant types of varnish protection are applied to the aerosol body at this stage before it is cut. The top and the bottom are generally not lithographed.

In the secondary cutting, the lithographed and non-lithographed sheets are cut into rectangular tinplate. The non-lithographed rectangular tinplate is then stamped to form a top and bottom of an aerosol can. The aerosol body is not stamped – therefore, after lithography it passes directly to the assembly process.

In the assembly process, the lithographed rectangular tinplate is winded and welded forming a cylindrical shaped body. Later, the top and bottom are assembled with the cylindrical body via seaming joints (one seaming joint between top and body, and another seaming joint between bottom and body).

Incoming material   Primary cutting/slitting   Varnishing and Lithography

Secondary cutting   Stamping process   Assembly process

Three-piece aerosol can
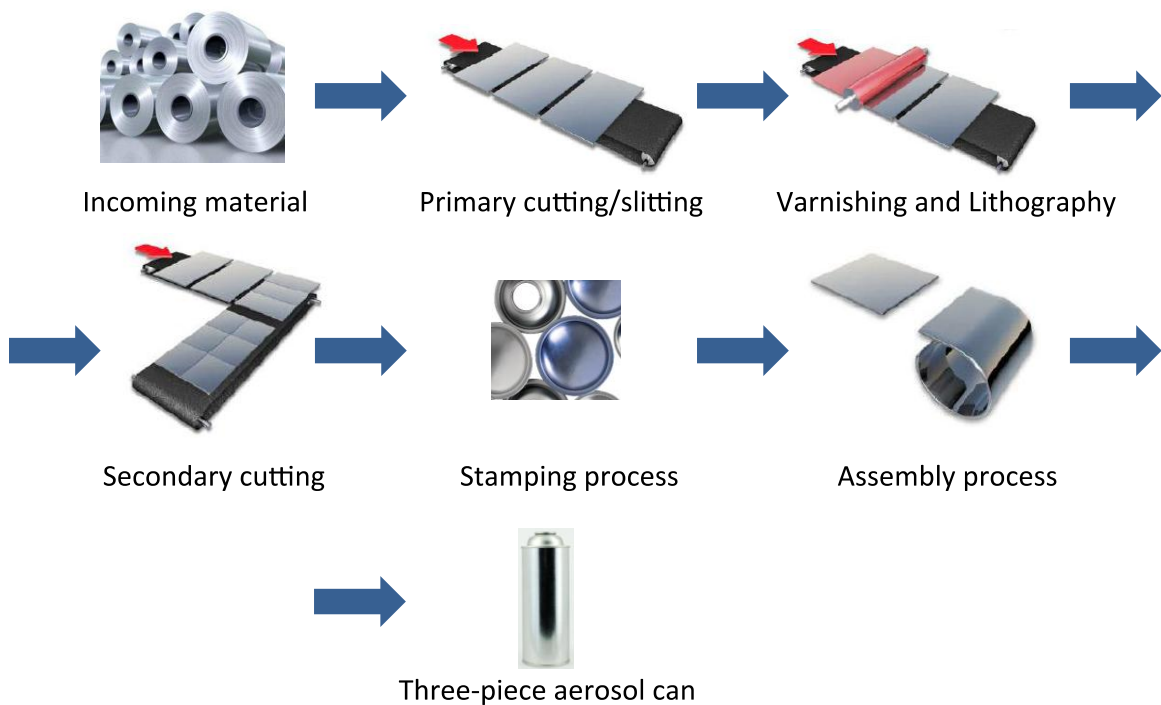
Figure 4: Production process of an aerosol can

A major challenge for the aerosol manufacturing industry is the production of hermetically closed vessels, i.e., the three parts of an aerosol can are perfectly assembled together without producing any leak. In practice, small leaks are always present in a 100% hermetically closed product. However, industries define the acceptable leak rate limits depending on the application of their products (gas or liquid). In the case of aerosol cans, solving this problem is a big challenge due to: (1) the high production rates of assembly lines (200-400 units/min), (2) the low cost of the final product (20-30 cents/aerosol can), and (3) all aerosol products contain gas molecules that vibrate and move freely at higher speeds than the liquid molecules.

In order to guarantee whether aerosol cans are 100% hermetically closed or acceptable for a specific application, leak testing of the aerosol cans is carried out after the assembly process. The type of leak testing performed at Colep is the automatic leak testing, which analyses 100% of the produced aerosols. The working principle of the automatic leak testing and other leak testing equipment´s used by the company are explained in detail in chapter 3.

The automatic leak testing machine has a limitation of detecting a leak rate of 2 ml/min; if there is a leak rate with a lower value than 2 ml/min, the aerosol can is accepted and shipped to the customer. The non-conformed cans shipped to the customer are detected by the customer, either at the filling stations, or in the warehouse in the form of wet boxes. This problem implies that the claims filed by the customers have huge costs of approximately €16000 - €17000 per quarter, plus the loss of goodwill and the even more important risk of losing company´s reputation. On average, non-conformed units detected by the customer have a leak rate lower than the value of 2 ml/min as shown in Figure 5. Due to the fact that customers are claiming mostly for very small leaks and this quality problem is of utmost importance to the company, the research project was named the Microleaks project.

As the Microleaks is not a new quality problem, being very resilient and hard to solve, the company has launched in the past quality improvement projects that used different improvement methodologies like, for example, 8D. During the 8D project, there were

several proposals presented to resolve the Microleaks project, however only one proposal was implemented because other proposals were either financially not feasible or unpractical. The proposal implemented, as a direct result of 8D project, is the manual waterbath leak testing after the automatic leak testing machine. The manual waterbath test is based on an acceptance sampling procedure because of the large difference between the production speed (200-400 cans/min) and the sampling speed (6 cans/min) of aerosol cans. Although the precision of this machine is 1×10^{-1} ml/min, a precision that would be sufficient to eliminate almost all defective cans, 100% testing of all the cans is impossible.
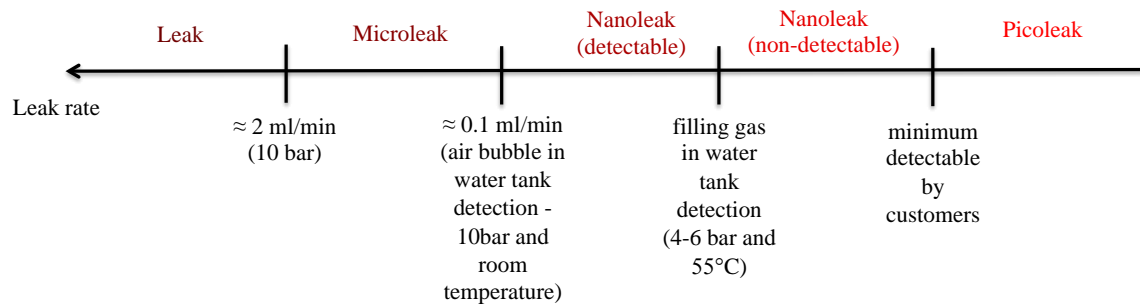
Figure 5: Classification of different leak rates at Colep (in ml/min)

Following manual waterbath implementation, the company uses the definition of Nano-Leaks, concerning leaks detected at the customer that are too small to be detected with the manual waterbath at room temperature. These Nano-Leaks are only detectable using waterbath tests through increasing the temperature as well as test duration, which raises the sensitivity of the waterbath tests. Figure 5 presents a visual representation of the relations between Leak / Microleaks / Nano-Leak (detectable or non-detectable) / Pico-leak definition.

The implementation of manual waterbath testing system was a containment action that only achieved minor improvements in the customer claims, being clearly unsuccessful in order to drastically improve the final product quality. The failure of these methodologies might be due to different reasons, such as acknowledging that the actual system might not be capable of producing high quality aerosol cans or simply due to a poor implementation of the improvement methodologies and/or the unavailability of a detailed implementation model. The industry has already understood the complexity of the Microleaks through

years of experience of dealing with it as well as the ever more exigent customer demand for defect (Microleaks) free cans. Therefore, this challenging Microleaks project was proposed to the MIT Portugal Program.

The project, that was developed hand in hand with the research presented in this dissertation, has the primary objective of improving the integrity of the aerosol cans, by strongly reducing the number of leaky cans, thus increasing the final quality of the aerosol cans delivered to the end customer. Furthermore, this is a universal problem within the aerosol cans market; by achieving this goal, Colep will be able to deliver higher quality aerosols to the market, reducing potential non quality costs, and gaining, in the end, a competitive advantage.

1.2.   Research hypothesis and questions

The Microleaks detected either in-house at Colep or at the customer facility are the consequences of non-conformities (NCs) generated along the manufacturing processes, as all manufacturing processes are not one hundred per cent reliable. A NC is a deviation from a specification (i.e. a standard or an expectation) and usually it is expected that significant part of the NCs produced are traced by the quality control system. So, in order to understand the problem of Microleaks, it is important to have a systematic analysis of all the NCs and their interactions and dependencies.

Furthermore, the leak detection systems currently installed in Colep don´t have the technical requirements needed to detect 100% of the Microleaks. Therefore, there is a need to develop better detection systems that can measure leaks with higher sensitivity. Nevertheless, any state-of-the-art detection systems proposed in the future need to be carefully assessed in terms of cost.

Moreover, the methodologies applied previously to eliminate Microleaks were not completely effective and successful. The complexity of the Microleaks, requires the use of more sophisticated methods and procedures, in order to drive a sustained variability reduction. Systems Engineering methodologies in this regard have been very successful in dealing with high complexity systems, covering subjects in lots of different fields, such as engineering, social and management sciences.

Based on this discussion and problem definition presented in section 1.1, the research is based on the following five fundamental hypotheses:

1. The non-conformities (NCs) generated along a manufacturing process can be determined with a high degree of reliability. The number of identified NCs is high enough so that the analysis of these NCs enables a good estimator of the final product quality;

2. Systems Engineering tool efficiently and effectively model the NCs generated in the production line, highlighting key areas of manufacturing processes that require special attention;

3. Systems engineering methodologies analyze manufacturing systems holistically, enabling a better elicitation of the problem;

4. Quality improvement methodologies analyze more deeply critical areas highlighted by Systems Engineering methodologies, thus improving the final product quality;

5. Cost of quality models allow analyzing the overall costs incurred for the prospective improvements, therefore making better decisions.

Based on these hypotheses, the research focuses on the following research questions:

1. How can Systems Engineering methodologies complemented with quality improvement methodologies be used to reduce the risk of product failure and improve the final product quality?

2. What Systems Engineering tools are better suited to solve quality improvement challenges and how engineers and managers apply them?

3. What are the detection systems best suited to detect in a cost efficient manner defective products at the target leak rate level?

4. How should cost of quality be modeled in order to estimate different quality improvement scenarios and assist optimum decision-making?

Based on the problem definition, hypotheses and research questions, subsequent section discusses the research approach and methodology developed.

1.3. Research approach and methodology

To address the problem of Microleaks, i.e. improving the integrity of aerosol cans, a Systems Engineering methodology for quality improvement of manufacturing systems is proposed. Systems Engineering considers business and technical needs of customers with the goal of providing a quality product meeting user needs. Quality improvement techniques fall under the umbrella of Systems Engineering approaches that identify root cause of the problem, fix the problem and perform verification and validation testing. Furthermore, this thesis is based on a comprehensive state-of-the-art across various disciplines covering quality improvement methodologies like Six Sigma and application of matrix-based Systems Engineering tool.

The quality improvement methodology applied for the problem of Microleaks is based on the DMAIC (Define Measure Analyze Improve Control) approach of Six Sigma. However, in the Define and Measure phase of DMAIC an innovative attempt is made to model the manufacturing system using a Systems Engineering matrix-based tool called Design Structure Matrix (DSM). More specifically, DSM is used to model the non-conformities generated along the manufacturing systems. In this thesis, a DSM is applied for a quality improvement problem for the first time, enabling an easier interpretation of the relations and interactions between the different system elements.

The key areas highlighted by DSM are further explored through understanding the physics of the problem by applying systems engineering methodologies holistically. This requires performing in-depth laboratory analysis of the aerosol cans e.g. microscopic, macroscopic and metallographic analysis.

Analyzing physics of the problem will provide a closer understanding towards determining the root cause of the problem. In order to have a thorough and systematic root cause analysis appropriate quality improvement tools enable improvement and optimization of the process. Moreover, the proposed methodology also allows developing

state-of-the-art detection systems that not only detects in-house defective products as well as support quality improvement tools for testing needs.

The Cost of Quality (COQ) model integrates the proposed approach, a model that is required to understand the overall costs incurred during waterbath sampling strategies, as well as the cost impact of the solution proposed. The solution includes process-based improvement and technological-based improvement where alternative technologies are compared in the COQ model for their feasibility, allowing better economical decisions.

Although the methodology developed was targeted to address a specific problem of Microleaks, a general framework was conceived in order to be applicable for other manufacturing systems.

1.4. MIT Portugal Program framework

MIT Portugal Program (MPP) is a unique post-graduate education network of intense and wide ranging collaboration between Portuguese Universities, research institutions, companies, and the Massachusetts Institute of Technology (MIT). MPP has been funded by the Portuguese Science Foundation (FCT) and the network offers a truly international education program serving as a model for the intersection of engineering education, research, innovation and entrepreneurship.

A total of 6 Portuguese universities, 28 Portuguese research centers and national laboratories, together with 25 MIT departments, and all 5 Schools within MIT are involved in this ongoing partnership. Seven Doctoral, Master's of Business Engineering and Master's of Science programs have been created in the areas of Bioengineering, Sustainable Energy and Transportation Systems, and Engineering Design and Advanced Manufacturing.

The Engineering Design and Advanced Manufacturing (EDAM) area offers a PhD program, Leaders for Technical Industries (LTI), and a Master's of Business Engineering, Technology Management Enterprise (TME). LTI program is anchored on multidisciplinary research problems, lying within a Systems Engineering framework. The LTI PhD research program considers that product and process innovation and current

complex decision-making must also take into account economics, management and social aspects. This perspective is clarified in the PhD Program Structure that the students must accomplish, where the courses are grouped into clusters, such as Design and Technology (three courses), Systems Engineering (three courses), Engineering Management (four courses), and Leadership. The collaboration with the MIT, where students are encouraged to undertake research activity, is a vital part of the PhD program.

The programs are designed to be in close connection with technically advanced industries. All LTI students complete an internship in an industrial environment where they develop business-integrated research. TME students are usually professionals from industry and they do their thesis research in a topic related to their professional activity at the company where they work.

1.5.   Industrial and academic partnership

The industrial and academic partners for this research project include: Faculty of Engineering University of Porto (FEUP); Massachussets Institute of Technology (MIT); Colep; Institute of Science and Innovation In Mechanical and Industrial Engineering (INEGI). A brief description is presented below:

Colep:

Colep is the main sponsor company of this research project. It is a RAR Group company and a leading global player in the consumer goods packaging and contract manufacturing industry. With a turnover of around 500 million euros, Colep employs 3,850 people in Portugal, Brazil, Germany, Mexico, Poland, Spain, United Arab Emirates and the United Kingdom. As part of "ACOA, the Alliance of Colep & One Asia", Colep offers customers a global supply network.

Colep has mainly three major sectors: Consumer products, Healthcare, and Packaging. Colep´s Packaging Division is one of the most important producers of tinplate aerosol and General Line packaging in Europe and the Iberian leader of tinplate General Line packaging. There are two production sites, one is based in Vale de Cambra, Portugal and the second is based in Kleszczów, Poland. The research project proposed by Colep is

based in Vale de Cambra (VDC) plant of packaging division in Portugal. The VDC plant has six assembly lines for aerosol can production and consists of several aerosol formats. A further detail about the aerosol formats is presented in chapter 3.

The LTI student has spent 18 months full-time in Colep-Portugal as an internee to understand and analyze the problem of Microleaks. During this internship, the LTI student built the process mapping, developed systems engineering methodology, performed root cause analysis, analyzed historical data, and performed experiments on the shop floor. Even after this internship, the LTI student was constantly involved with Colep and working with them and collecting data, performing confirmatory experiments, discussing details regarding Microleaks with the key suppliers and clients, and investigating detection systems.

INEGI:

INEGI is an interface Institution between University and Industry, oriented to the activities of Research and Development, Innovation and Technology Transfer. It was founded in 1986, among the Department of Mechanical Engineering and Industrial Management (DEMEGI) of the Faculty of Engineering of the University of Porto. Being a non-profit private association and recognized as being of public utility, INEGI is currently considered an active agent playing a significant role in the development of the Portuguese industry, and in the transformation of its competitive model.

INEGI has participated in this research project performing some of the laboratory work for analyzing the material properties of packaging products. The work included microscopic, macroscopic and metallographic analysis of aerosol cans.

FEUP:

FEUP is one of the faculties of the University of Porto participating in the MIT Portugal Program. The LTI student is a full time PhD student at FEUP enrolled in the department of Mechanical Engineering. FEUP offers PhD degrees in plenty of engineering fields and has several research labs. Design Studio is one of the labs in FEUP that is participating in EDAM focus area of MPP.

MIT:

MIT has five schools and all the schools are participating in the MPP. All MPP PhD students require performing an internship at MIT for a period ranging from 3-12 months. The LTI student has taken this opportunity and has spent 1 year as an internship at the Materials Systems Laboratory (MSL) in the Engineering Systems Division (ESD) of MIT. The main objectives of the stay were to develop novel framework of systems engineering methodologies for the quality improvement of manufacturing systems as well as develop cost of quality model.

1.6. Structure of the thesis

The overall structure of the thesis is illustrated in detail in Figure 6. First, the description of the industry problem in chapter 1 is explored. This is followed by research hypotheses and questions. As a result, the research approach and methodology that is based on Systems Engineering, quality management and engineering are devised.

Chapter 2 introduces the concepts of Systems Engineering, quality management, quality improvement methodologies and matrix-based methods. Extensive contributions over these concepts from various researchers and scientists are discussed.

A further detailed discussion is presented in chapter 3 over the Microleaks project, defining clearly the details of the problem, project scope, project team and working principle of the relevant equipment´s.

Chapter 4 discusses the process mapping of the entire manufacturing process, followed by the development of the novel non-conformity matrix tool, which is based on the principles of the Systems Engineering. The non-conformity matrix tool prompted the development of Systems Engineering methodology for quality improvement of manufacturing systems, which is based on the contributions discussed in chapter 2.

Chapter 5 is about optimization of the production process and the tool used is design of experiments. The three phases of the DoE are explained in detail in this chapter along with challenges faced during the implementation of the experiments on the shop floor.

The chapter ends by presenting the results and recommendations that can be implemented on the shop floor.

Chapter 1: Introduction
Industry problem description → Research hypothesis and questions → Research approach and methodology

Chapter 2: Literature Review
Systems Engineering → Quality management → Quality improvement methodologies → Application of matrix-based tool

Chapter 3: Microleaks project description
Project scope → Project team → Leaks, Microleaks and Nanoleaks → Working principle of equipment's

Chapter 4: Process analysis using matrix-based approach
Detailed process map → Development of novel Non-Conformity Matrix tool → Development of Systems Engineering methodology

Chapter 5: Design of Experiments as an optimization tool
Pre-experimental planning phase → Execution phase → Statistical analysis and recommendations

Chapter 6: Cost of Quality model
Prevention-Appraisal-Failure Model → Analyzing inspection strategies → Trimming technology → Leak detection systems

Chapter 7: Conclusions and recommendations
Summary of results → A General Systems Engineering methodology → Contributions and implications → Directions of future research

Figure 6: Thesis structure

Chapter 6 is about cost of quality model that explores not only quality as well as cost in order to optimize the solutions. The prevention-appraisal-failure model is discussed and inspections strategies are further explored. The outcome of possibilities from previous chapters is also analyzed in this chapter following the cost of quality approach.

The concluding chapter 7 presents first the summary of results followed by discussion on the general Systems Engineering methodology for quality improvement of manufacturing systems, which can be applied to other industries for the validation of the methodology. At the end, recommendations that were the result of the accomplishments during the thesis are provided. Furthermore, for future work, a brief work plan is presented that can be continued in the future for further improvement of the targets and methodology.

Chapter 2 - Literature Review

This chapter discusses the literature review from various contributions that are important for the development of the current thesis. First, Systems Engineering that identifies various processes is introduced. Then the focus of the research thesis along with clear identification of important pillars is elaborated.

The next section introduces quality management and because the focus of the thesis is on quality control and improvement, it is further explained in detail. An evolution of quality methods is revisited – particularly Deming´s philosophy of quality improvement that was considered important for this thesis is explained.

The next section discusses quality improvement methodologies and explains in detail Six Sigma´s DMAIC methodology because it is considered as important for the development of the methodology in the current thesis. A comparison is presented between the Six Sigma and other important quality improvement methodologies, like, for example, Total Quality Management, and Lean Manufacturing.

One of the pillars of the thesis is using matrix-based methods for modeling the manufacturing systems. A Design Structure Matrix that systematically models the entire manufacturing system is introduced. A brief explanation on the principles describing the steps in developing such a matrix is provided. This is followed by defining components modularity metrics that are used to measure system complexity for a matrix.

2.1. Systems Engineering

Systems Engineering has emerged as a new discipline focusing on complex engineering problems, integrating approaches based on engineering, management and social sciences. The new approach of Systems Engineering has at its core in the way problems are addressed as a whole, relating its social and technical aspects, as well as considering at the same time the dependent and independent variables. Furthermore, it considers both the business and technical needs of all customers with the goal of providing a quality product that meets the user needs (INCOSE 2006).

Systems engineering decomposes the system from the needs of a user as well as from the requirements of a system into System of Systems (SoS), subsystem, system elements or components. It identifies processes that define, implement, deliver, and sustain systems that fully comply product quality, satisfy customer and stakeholder needs. Therefore system engineering considers a system as a whole and leads rest of the processes including technical processes, project processes, enterprise processes, and agreement processes (INCOSE 2006). However, in this thesis only technical and enterprise processes are relevant and therefore discussed as shown in Figure 7.

Enterprise processes are the backbone of any organization and are used to direct, enable, control and support the overall system. INCOSE (2006) identified six enterprise processes: Environment management; Investment management; Quality management; System life cycle processes management; and Resource management. As this thesis is focused on quality control and improvement, only the role of quality management processes in systems engineering will be further discussed. As quality is defined as a primary driver for any project a quality management system is essential in every organization.
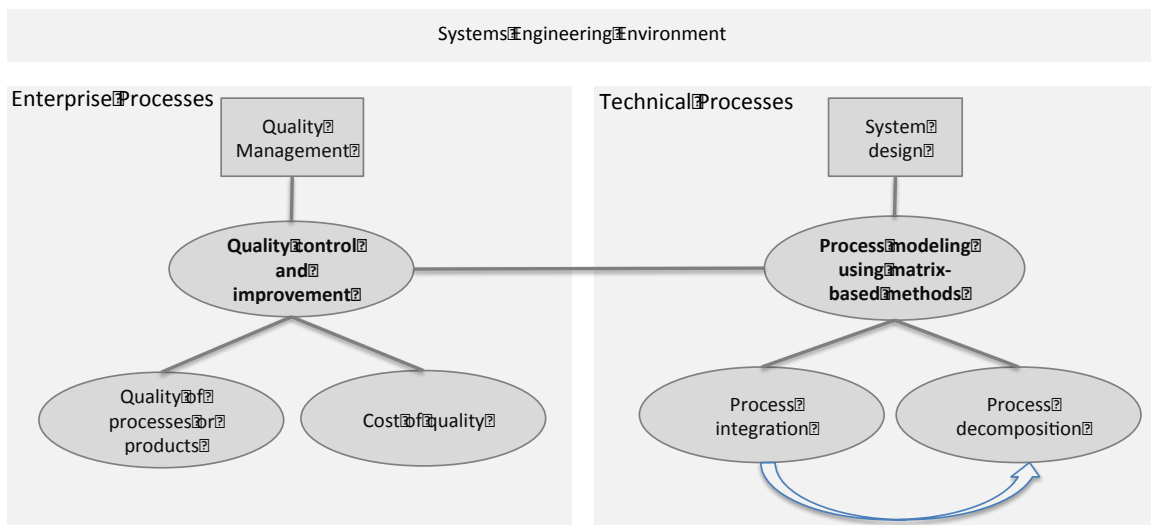
Figure 7: Focus of this research

Technical processes include stakeholder requirements, integration, verification, system design, and validation. However, in order to support the quality management system,

concepts and tools of system design are used in this thesis to model the architecture of a complete manufacturing system. This approach helps in the decomposition of the processes, and the posterior identification and integration of the key processes for improvement.

Figure 7 shows the focus of the research thesis, dependent on two main pillars: (1) quality control and improvement; and (2) process modeling using matrix-based methods. In this chapter each pillar is explained in detail and only the relevant work to the needs of this research is presented. First, evolution of quality methods is discussed, as well as the Deming´s philosophy of quality improvement. This discussion led to the development of the most well known quality improvement methodologies, i.e. Total Quality Management (TQM), Six Sigma, and Lean Six Sigma. Among these improvement methodologies, Six Sigma´s DMAIC is reviewed in depth because the methodology developed in the current research has been motivated from it. Furthermore, a comparison is presented among these quality improvement methodologies and the future of quality improvement. This discussion leads to the research gaps identified, particularly in what concerns modeling manufacturing systems using matrix-based methods. The matrix-based tool proposed and discussed in this thesis is a systems engineering tool called Design Structure Matrix.

2.2. Quality management

Improving quality for businesses is always a key concern. It is a desire that keeps business competitive, successful and financially stable. Business improvements require procedures to support the management of quality in a way that continuously gratifies customer demand. This is the continuous innovation task that leads to a goal-oriented improvement.

Customers can be an individual, a manufacturing industry, a retail store or a service organization. However, for each customer category quality has become, nowadays, the most significant decision factor to select a product or service. Therefore, quality of products and services requires to be looked primarily and foremost from a customer´s perspective. With the knowledge of customers feeling and expectations through

understanding business lifecycle, potential areas can be identified where significant value or improvement can be added from a customer´s perspective.

Over the years many practitioners and researchers have endorsed quality management as a new management theory in order to fulfill customer satisfaction. This fact can be seen under several perspectives, such as a paradigm shift for the industry, a revolutionary philosophy of management, or even a new thinking about the management of organization (Andersson, Eriksson, and Torstensson 2006). Moreover, it is consensual that for an effective and efficient management of quality, three components are involved: quality planning and design, quality assurance, and quality control and improvement (Montgomery 2010). These three components comprehend a modern quality management system, supporting each other in providing a high quality product. Quality planning and design is a strategic activity that implies, in the end, the design of a consensual strategic quality plan. This plan involves the identification of the all the internal and external customers of the organization and their needs, as well as the design of products or services that meet or exceed customer expectations. Quality assurance is the set of activities that ensures the quality level of products and services are properly maintained, as well as ensures an effective resolution of supplier and customer issues. Whereas, quality control and improvement ensures minimum variability in the process or product by following a certain set of methods or procedures (Montgomery 2010). As it was described in Chapter 1 that the focus of this thesis is product and process quality improvement, the following sections comprehensively discuss the quality control and improvement component of the quality management theory.

2.2.1. Quality Control and Improvement

Variability is a key source of poor quality that is controlled through a smarter implementation of statistical techniques and procedures. Many quality leaders have made significant contributions to the development of quality control and improvement methods over the years. A summarized timeline of the evolution of quality methods is presented below (Folaron 2003)(Montgomery 2009):

Table 1: A timeline for the evolution of quality methods

1920s	AT&T Bell Laboratories formally initiate a quality department, working on product quality, inspection and testing procedures.
1922	R. A. Fisher starts working on the use of statistical experimental design for the agriculture industry.
1924	W. A. Shewhart introduces the control chart concept in a Bell Laboratories technical memorandum, which is commonly recognized as the formal beginning of statistical quality control.
1928	H. F. Dodge and H. G. Romig at Bell Labs develop the acceptance sampling methodology.
1948	G. Taguchi develops robust parameter design for design of experiments.
	Toyota develops the Toyota Production System (lean manufacturing)
1950	K. Ishikawa introduces the cause-and-effect-diagram.
	The era of Deming´s philosophy of management begins in Japan
1951	Juran introduces the concept of cost of poor quality.
	J. M. Juran and F. M. Gryna's *Quality Control Handbook* is first published.
1960	G. E. P. Box and J. S. Hunter write fundamental papers on $2k-p$ factorial designs.
	K. Ishikawa first introduces the quality control circle in Japan.
1974	U.S. Department of Defense develops eight disciplines (8D) problem solving methodology.
1975-1978	Advent of the Total Quality Management (TQM) movement.
1980	Philip Crosby´s book on "Quality is Free" is published.
1980s	Electronics, Aerospace, Semiconductor, and automotive industries start to apply design of experiments.
1986	Deming´s fourteen key principles to managers for transforming business effectiveness in the book "out of crises" are published.
1987	Motorola's six-sigma initiative begins.
2000s	The work on Lean Six Sigma first appears in research papers.

Walter Shewhart, Edwards Deming, Joseph Juran and Genichi Taguchi are considered to be the guru of modern quality methods (Tari & Sabater 2004) (Montgomery 2009) (Schilling & Garvey 2008) (Black & Revere 2006). W. Shewhart, while working at Bell Telephone Laboratories initiated the concept of statistical control chart, which is today the most widely used and recognized quality control tool by the industries (Montgomery 2009). E. Deming was greatly championed from the work of W. Shewhart and continued

his contribution to the world of quality control and quality improvement methods. His book "Out of the Crises", published in 1986, which was and still is a landmark in quality improvement - his teachings are key to this thesis and therefore will be described in detail, especially the Deming´s fourteen key principles for transforming management.

It was R. A. Fisher who formally developed the concept of statistical experimental design in 1935, with an initial work applied to agriculture, by studying the crop's variation. These studies are considered as the first era of the modern development of statistical experimental design, also know as Design of Experiments. Four to five decades later it was G. Taguchi who worked on the development of robust parameter design and orthogonal arrays to solve problems related to process or product robustness, more targeted to manufacturing industries. Design of experiments has then spread to other type of industries like automotive, semiconductor, electronics and aerospace (Montgomery 2008).

2.2.2. Deming´s philosophy of quality improvement

Although Deming started giving seminars on his vision of quality management and quality improvement since 1950, his famous 14 points for transforming management were only officially published in 1986. It has been said that his teachings were influenced from the statistical quality control theory first published by Shewhart (1931).

After 30 years of continuous effort revolutionizing business in Japan, Deming´s next target was America and Europe. Most of his seminars were strongly focused on the need for statistical methods and statistical thinking in order to solve the problems in quality, uniformity, and economy (Gogue 2005). The summarized Deming´s 14 points for management are presented below (Deming 1986):

1) Create constancy of purpose toward improvement of product and service, with the aim to become competitive and to stay in business, and to provide jobs.
2) Adopt the new philosophy. Western management must awaken to the challenge, must learn their responsibilities, and take on leadership for change.

3) Cease dependence on inspection to achieve quality. Eliminate the need for inspection on a mass basis by building quality into the product in the first place.

4) End the practice of awarding business on the basis of price tag. Instead, minimize total cost.

5) Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs.

6) Institute training on the job.

7) Institute leadership. The aim of supervision should be to help people and machines and gadgets to do a better job. Supervision is in need of overhaul.

8) Drive out fear, so that everyone may work effectively for the company.

9) Break down barriers between departments so that people from different departments work as a team.

10) Eliminate slogans, exhortations, and targets for the work force asking for zero defects and new levels of productivity.

11) Eliminate work standards (quotas) on the factory floor. Eliminate management by numbers. Substitute leadership.

12) Remove barriers that rob the worker of his right to pride of workmanship. The responsibility of supervisors must be changed from sheer numbers to quality.

13) Institute a vigorous program of education and self-improvement.

14) Put everybody in the company to work to accomplish the transformation. The transformation is everybody´s job.

Quality and productivity improvement, the principal theme of this thesis, was clearly the main focus of Deming´s 14 points. Over and over again he emphasized the importance of focusing on process variability, statistical thinking, and a need of fundamental change in the way individuals think about the problems (Snee 2008). Furthermore, apart from his focus on quality improvement, productivity improvement was also a major concern. In one of the discussion of buying new machinery and gadgets for quality and productivity improvement, he stated (Deming 1986):

"If I were a banker. I would not lend money for new equipment unless the company that asked for the loan could demonstrate by statistical evidence that they are using their

present equipment to reasonably full capacity, and are at work on the 14 points and on the deadly diseases and obstacles".

In his 14th point, Deming referred the Shewhart Cycle as a simple procedure to follow for quality and productivity improvement for any problem (Figure 8).

Act
- Managing Nonconformity
- Improvement
- ISO 9001 Certification
- Cultural and Organizational Aspects
- Total Quality Management
- Environmental Management Systems
- Management System Integration

Plan
- The Quality Concept and Objectives
- Statutory Considerations
- Product Liability and Product Safety
- Training for Quality
- The Control of Design

Check
- An Introduction to Statistics
- Control Charts
- Inspection
- Functional Testing
- Inspection and Measurement Equipment
- Metrology
- Quality Audits and Reviews
- Quality- and Safety-related Cost
- Benchmarking

Do
- Procurement
- Just-in-Time Supplies
- Process Capability
- Product Reliability
- Materials Handling
- Servicing
- Service Quality
- Documentations and Records
- Controlling Changes
- Standards, Standardization, Conformity and
- Compatibility

Figure 8: Shewhart Cycle or Deming Cycle or PDCA (Sokovic, Pavletic, and Pipan 2010)

Deming called this cycle as the Shewhart Cycle, in 1950. It became one of the most popular tools for quality improvement in Japanese industries, often referred as the Deming Cycle. However, in modern quality world, the Shewhart or Deming cycle is most widely known as the PDCA cycle (Plan, Do, Check, Act)(Folaron 2003).

Despite Deming´s intelligent philosophy of management, he did not provide a framework or a step-by-step methodology to implement this philosophy (Snee 2008). Nevertheless, many modern quality improvement methodologies have been influenced from the Deming´s philosophy of management and tried to build on its principles by providing a more structured approach to problem solving, such as, for example, Total Quality Management (TQM), Six Sigma and Lean Manufacturing (Kumar et al. 2008) (Brady and

Allen 2006) (Black and Revere 2006). These methodologies have extended Deming´s philosophy by providing a holistic approach in which quality control and improvement tools are organized and deployed to provide maximum effectiveness (Snee 2008).

TQM has been a famous management approach during 1980´s. Its development resulted from a combined effort of the quality management philosophies of Juran, Deming, and Feigenbaum. It began informally during 1950´s, when Armand Feigenbaum first introduced the concept of total quality control in the first edition of the Total Quality Control book, published in 1951. Albeit, TQM failed to impress top management due to its less focus on the monetary-value of the bottom line benefits, as well as the fact that it didn´t propose a well-disciplined and rigorous methodology (Folaron 2003).

Six Sigma and Lean Manufacturing on the other hand, in the 21st century, have been the most successful, matured and widely adopted quality improvement methodologies to date. Snee (2010) argued that quality improvement methodologies are not fads, but every methodology learns the short comings and drawbacks from the previous ones, adding and building new approaches, tools, and ways to remove barriers and limitations previously identified.

In the next sections, Six Sigma methodology is reviewed comprehensively along with a comparison to other quality improvement methodologies.

2.3.   Six Sigma

The six-sigma spread in the distribution of a quality characteristic is an interval widely used in statistical quality control to evaluate process capability. It defines the capability of a manufacturing process to limit defects below 3.4 parts per million (PPM). Motorola´s Engineer Bill Smith in 1985 first coined the name of Six Sigma to a project-based problem solving and process improvement methodology. Six Sigma was initially developed as an operational philosophy of management that systematically employs statistical and non-statistical tools and techniques in order to reduce variability, eliminate waste, and improve process capability. Over the years Six Sigma has evolved into a competitive corporate strategy widely used throughout the corporate world (Kumar et al.

2008). In short, a process operating at a Six Sigma level has the capability to limit defects below 3.4 ppm, a very demanding target. However, this quality level should be seen with caution, and should not be considered as the objective for all the processes (J Antony, Kumar, and Tiwari 2005a). Although researchers argue Six Sigma´s existence as an extension to Deming´s philosophy of management, Joseph Juran´s teachings and TQM (Kumar et al. 2008) (Brady and Allen 2006) (Black and Revere 2006), the main credit for deploying such a structured framework should be given to Motorola.

Tjahjono et al., (2010) identified four streams of thought in order to define Six Sigma; (i) it is a process improvement framework consisting of statistical tools adopted from the theory of quality management (Kumar et al. 2008), (ii) it is an operational philosophy of management that can be applied not only to applications related to manufacturing as well as to new product development, marketing, service, purchasing and invoicing (J Antony, Kumar, and Tiwari 2005a) (iii) it requires continuous and dedicated commitment from top management along with application of statistical techniques and thinking in order to build a different business culture (G. J. Hahn 2005) (Snee 2010), (iv) it is a data-based approach that uses a scientific and well-structured continuous improvement methodology to reduce process variability and waste.

Over the years, Six Sigma has been impressively developed through application into many diverse industries. Antony (2007) identified three generations of Six Sigma; (i) Motorola was the pioneer of Six Sigma and the first generation was dedicated to Motorola´s development and deployment and was centered around manufacturing environment (Gerald J. Hahn, Doganaksoy, and Hoerl 2000), which lasted from 1987 through 1994, (ii) CEO of General Electric, Jack Welch, adopted Six Sigma as a central business strategy. The focus during this generation was primarily on cost reduction, spreading later to other business operations, specifically to those who have a high impact on the final customer (Gerald J. Hahn, Doganaksoy, and Hoerl 2000). (iii) Application of Six Sigma is now spreading to other industries, from manufacturing to services as well as to new product design and development. Also, now the focus is not only variability reduction, but also a lot of effort is put on waste elimination, overall costs reduction and defect prevention as early as at the design stage.

2.3.1. Six Sigma main principles

Pande & Holpp (2000) explained three approaches that a company can implement within Six Sigma; (i) A complete business transformation where a company undergoes entire rehabilitation of its business processes when a company is losing customers and subsiding revenues, (ii) Strategic improvement of one or two business processes where a company believes to have opportunities to regain its product quality level, (iii) A problem-solving or process improvement approach where a company focuses on the existing issues.

For all the three approaches, six sigma follows two sub-methodologies (Gerald J. Hahn, Doganaksoy, and Hoerl 2000) (Brady and Allen 2006); the most widely known framework is DMAIC (Define, Measure, Analyze, Improve, and Control), which is aimed at improving the process or product quality. Second is DMADV (Define, Measure, Analyze, Design, and Verify) also known as Design for Six Sigma (DFSS), which is aimed at creating new product or process designs.

Six Sigma projects require specially trained personnel, called Green Belts (GBs), Black Belts (BBs), Master Black Belts (MBBs), and champions. GBs have training of about one to two weeks and assist on major project teams or lead smaller projects. GBs have knowledge of basic Six Sigma tools.

BBs have more specialized training than GBs, of about four weeks and is usually spread over a four-month period with an ongoing project work. BBs have knowledge about simple as well as complex Six Sigma tools like DOE, and lead teams that are focused on projects with both quality and economic impact of an organization.

MBBs train GBs and BBs, write and develop training material, and involve in project definition and team selection. MBBs also work closely with the business leaders of an organization called champions, who are project sponsors and are the members of top management team.

For the scope of this thesis Six Sigma´s DMAIC methodology will be discussed in detail, which is reviewed from the literatures of (Gerald J. Hahn, Doganaksoy, and Hoerl 2000) (J Antony, Kumar, and Tiwari 2005b) and (Montgomery and Woodall 2008).

1. Define: What is the problem?

The define phase is the crucial step of the DMAIC approach, where the problem to address is elaborated in terms of scope and customer requirements. Then, the team responsible for the project should clearly specify and discuss the boundaries of the problem, clarifies the project aim and estimated duration. This team should always comprise a champion, preferably from the top management of the company, who sponsors the project and assures that the project is aligned with the company's strategy. The other team members should include green belt experts, black belts, and master black belts with all the roles of the team clearly stated. In this phase it is also essential that the financial benefits are clearly scrutinized, as well as a prior identification of the key critical-to-quality (CTQ) characteristics driven by customer requirements. These objectives are achieved by using a wide variety of tools in a structured way such as Brainstorming, Process Mapping, Flow Charts, and SIPOC diagrams, to connect customers´ requirements and the inputs of the process.

2. Measure: How big is the problem?

In the measure phase, the key processes that influence the CTQ characteristics are identified. The main goals for this phase are to translate customer requirements into measurable characteristics i.e. into sigma level. This can be achieved by analyzing and verifying the measurement capabilities, establishing a baseline for the current defect rate and setting goals for improvement. Furthermore, in this phase, all possible and potential causes for the problem under analysis must be identified. Main tools applied during this phase are Ishikawa Diagrams, Pareto Charts, Process Capability Studies, Gauge Repeatability and Reproducibility Studies, Matrix Diagrams and Quality Functional Deployment (QFD).

3. Analyze: What is causing the problem?

In this phase, data obtained from the measure phase is used to determine preliminary cause-and-effect relationships, as well as an attempt is made to understand the different sources of variability present in the process. Plus, the gap between the target and the actual state is clearly defined in statistical terms and, with the aid of statistical analysis, possible sources of variation that might lead to the problem are identified. This approach normally includes identifying key variables of the processes for its occurrence and optimizing them to obtain an optimum response. Tools applied during this phase are mostly Hypothesis Testing, ANOVA, Regression Analysis and Design of Experiments.

4. Improve: What can be done to eliminate/reduce the root cause of the problem?

In this phase the significant process variables are confirmed by quantifying their effects on the CTQ characteristics, along with identifying the acceptable limits. This can be achieved either by (i) modifying process variables according to the previously identified results and comparing the results with the goals set during the define phase, (ii) performing trial runs for a planned period of time to ensure the improvements are significant and repeatable. Tools applied during this phase are mainly Cause and Effects Analysis, Regression Analysis and Design of Experiments; Response Surface Methodology.

5. Control: How will the process be monitored to ensure gains are sustained?

In the control phase, achieved results are standardized, monitored and controlled as part of the running process, in order to produce long-term financial benefits. The project is handed-over to the project owner along with a process control plan and other required documentation to ensure the intended goals are met. Meeting intended goals and assuring long-term results are the greatest challenges in any Six Sigma project that requires sharing of results and extensive training, not only to the process owner and shop floor operators, as well as to everyone who is somehow connected with the process. Tools applied during this phase are mainly run charts, control charts and process sheets. The Six Sigma´s five-step methodology is illustrated below (Figure 9) as a continuous cycle:

CONTROL
· Ensure that the results is sustained
· Share the lessons learnt

DEFINE
· Identify project that is measurable
· Identify project CTQs
· Develop team charter
· Define process map

Control   Defin

MEASURE
· Select CTQ characteristics
· Define performance standards
· Measurement system analysis

Improve   Measure

Analyze

IMPROVE
· Screen potential causes
· Discover variable relationships
· Establish operating tolerances

ANALYZE
· Establish process capability
· Define performance objectives
· Identify variation sources

Figure 9: Cycle of a Six Sigma methodology (J Antony, Kumar, and Tiwari 2005b)

In each phase of the DMAIC methodology there are a set of tools used. These tools are not the new tools proposed in any Six Sigma projects. In order to have a deeper insight of the application of specific tools, next section discusses some of the tools used within each phase of Six Sigma´s DMAIC methodology.

2.3.2. Tools used within Six Sigma

For a solid quality improvement, the use of a large range of available quality tools for the diagnosis and control of the different manufacturing processes is mandatory. A positive correlation between the quality levels of a given company and the application of the quality tools was studied by J. J. Tari and V. Sabater (2004), showing a positive correlation between the application of quality tools and quality management programs, pointing out to the importance of management actions related to leadership, and planning with the technical tools and techniques that support the quality improvement process. Among the most widely used tools are the seven basic quality control tools shown in Table 2 (Joseph M. Juran and Godfrey 1998) (Montgomery 2009). These seven basic

quality tools are a first set of tools that can support quality improvement decisions in almost any process. They have reached their maturity and are applied from the product conceptualization to management of processes, on a day-to-day basis (Paliska, Pavletic, and Sokovic 2007). Nevertheless, and although being very intuitive and easy to use, these tools are not extensively applied as a regular tool for continuous process analysis in most SMEs. According to Bamford and Greatbanks (2006) these tools allow a greater understanding of the processes by the managers and operators due to: (i) in-depth knowledge of the processes and products; (ii) formal training in problem solving activities; (iii) suitability of tools selected for different requests and (iv) simple models at all levels in the organizations to aid communication and learning.

Further to the seven basic tools, seven management tools have emerged to complement a systematic quality control. These tools are focused on complex products and processes, promoting new ways to innovate, communicate and plan as shown in Table 2. The seven management tools have been interconnected to the higher innovation in new products and processes, moving from a cost oriented attitude to an innovation-oriented attitude. This trend has been visible in high-tech products and has being disseminated to more traditional products (Duffy et al. 2012).

Table 2 Quality improvement tools and techniques (Montgomery and Woodall 2008) (Tari and Sabater 2004)

The seven basic quality control tools	The seven management tools	The seven statistical tools	Other tools and techniques
1. Cause and affect diagram 2. Check sheet 3. Control chart 4. Graphs 5. Histogram 6. Pareto diagram 7. Scatter diagram	1. Affinity diagram 2. Arrow diagram 3. Matrix diagram 4. Matrix data analysis method 5. Process decision program chart 6. Relations diagram 7. Systematic diagram	1. Design of Experiments 2. Process capability analysis 3. Hypothesis tests 4. Regression analysis 5. Failure mode and effects analysis 6. Gauge R&R 7. SPC and process control plans	1. Benchmarking 2. Brainstorming 3. Process maps and Flow charts 4. Lean tools 5. Sampling 6. Problem solving techniques 7. Quality costing 8. Quality functional deployment 9. Quality improvement teams

The added value of the Six Sigma methodology lies mostly in the successful integration of a large set of already known tools and techniques within a very detailed framework

(Table 2), rather than the discovery of any particular new technique. Thus, in a Six Sigma project the used tools can range from either design tools to management tools, or from very simple statistical tools (i.e. histogram), to more advanced statistical tools (i.e., design of experiments). Choosing the most appropriate tool and applying it successfully is the key in Six Sigma programs. Practitioners and researchers have defined the application of tools for each phase of the DMAIC methodology of Six Sigma, to illustrate an example few tools are listed below (Montgomery and Woodall 2008) (Snee 2008) (Aichouni 2012).

Table 3 Application of some tools in DMAIC

Tool	Define	Measure	Analyze	Improve	Control
Project charter	X				
Process maps & flow charts	X	X			
Pareto chart	X		X		
Cause & effects analysis		X			
Scatter diagram		X	X		
Process capability analysis		X			X
Hypothesis tests			X		
Regression analysis			X		
Gauge R&R		X			
Failure mode & effects analysis			X		
Design of experiments			X	X	
SPC & process control plans		X	X		X

The tools discussed were significantly applied previously in other improvement methodologies as well, however what is so innovative in Six Sigma is discussed in the next section while presenting comparison with other improvement methodologies.

2.3.3. Six Sigma over other improvement methodologies

Six Sigma takes users away from intuition-based decisions to fact-based decisions. Most importantly, top management involvement in Six Sigma projects is considered crucial for its success. The importance of top management involvement has always been considered critical for a project to succeed, as Deming clearly stated in one of his 14 points. In fact, Deming once denied to attend a meeting with a giant automotive company because the CEO of the company had no time to be present at the meeting (Deming 1986).

There are many key aspects of the Six Sigma approach to quality improvement that really differ from other improvement methodologies. Few of them, which showed great interest to many practitioners, are presented below:

1. Six Sigma focuses on the monetary value of the bottom-line results and clear identification of project´s return on investment (Snee 2010) (Jiju Antony 2007). There is a strong focus to develop metrics with financial targets, as well as to clearly establish the critical to quality characteristics (CTQs) (G. J. Hahn 2005);

2. Six Sigma should have the continuous commitment and involvement of top management and follows a top-down approach (Snee 2010). Often, quality improvement programs are initiated by middle or lower management and follow a bottom-up approach, rather than a top-down approach. This fact led to the failure of many programs due to less up-front investment, less rewards and compensation, as well as less enthusiasm spread from management to entire workforce (G. J. Hahn 2005);

3. Six Sigma has a continuous focus on the identification and rectification of root causes of the defects (Black and Revere 2006);

4. Six Sigma integrates both the human and process aspects of improvement (Snee 2010) (Jiju Antony 2007);

5. Six Sigma puts an enormous emphasis on reducing process variation, which is considered as a critical factor to any customer-touching process. Six Sigma projects have the objective to strongly reduce variation, a process that is only possible by implementing a "Variance Based Thinking" attitude (Gerald J. Hahn, Doganaksoy, and Hoerl 2000);

6. Six Sigma approach has been applied from manufacturing industries to service industries to information technology industries and still spreading to those industries that have not yet received its attention (G. J. Hahn 2005);

7. Six Sigma employs statistical and non-statistical tools and techniques for quality improvement using a systematic problem-solving framework DMAIC, which is very quantitative and data oriented (G. J. Hahn 2005) (Jiju Antony 2007);

8. Although Six Sigma is not a completely new approach, the reason for its success relies on the combination of different elements in a disciplined, rigorous, and well-

documented manner, such as: process mapping and understanding, data-driven decision making and a strong focus on the end business results focus (Folaron 2003) (G. J. Hahn 2005).

One survey conducted by the company DynCorp evaluates which methodologies or tools have yielded the greatest results, for companies that have used Six Sigma and other improvement methodologies (Dusharme, 2006). A summary of these results is presented in Table 4:

Table 4: Greatest results achieved by Quality Improvement Methodologies or Tools (Dusharme, 2006)

Quality Improvement Methodologies	
1. Six Sigma	53.6%
2. Lean Manufacturing	26.3%
3. ISO 9000-based standards	21.0%
4. Total Quality Management	10.3%
Quality Improvement tools	
1. Process Mapping	35.3%
2. Root cause analysis	33.5%
3. Cause-and-effect analysis	31.3%
4. Process capability	20.1%
5. Statistical Process Control	20.1%
6. Control Charts	19.2%
7. Process Management	18.8%
8. Project Management	17.9%
9. Design of Experiments	17.2%
10. Poka-Yoke	16.5%
11. Work breakdown structure	3.1%

According to this survey, when compared with lean manufacturing and total quality management, Six Sigma seems to be the most successful quality improvement

methodology. In the next section a brief discussion over the similarities and differences among TQM, Lean and Six Sigma is presented.

2.3.3.1.   TQM, Lean Manufacturing and Six Sigma

Although TQM, Lean Manufacturing and Six Sigma share same objectives, their approach, definition, methodology and used tools somehow differs. This section is dedicated to discuss and compare the similarities and differences among the three methodologies, integrating the point of view from multiple practitioners and researchers, concerning their definition, methodology, tools, effects, and criticism. Table 5, extracted from (Andersson, Eriksson, and Torstensson 2006) (Bertels 2003) (Jiju Antony 2011) (Snee 2010) summarizes these different views.

The table shows clear similarities between TQM and Six Sigma improvement methodologies. For example, a clear focus on customer values, bottom line financial gains, a strong application of statistical tools, and most importantly an underlying cyclic methodology. However, the success of Six Sigma lies in performing systematic improvements through individual projects one at a time, with a strong top management commitment. This means that the project selection is closely tied to the business objectives of the company and these objectives represent customer requirements. In the end, as Six Sigma projects talk the manager's language, i.e. financial gains that will be achieved with a project, top management strong involvement in a project from day one implies the difference between success and failure.

Table 5 TQM, Lean Manufacturing and Six Sigma

TQM	LEAN MANUFACTURING	SIX SIGMA
DEFINITIONS		
a. It is a corporate culture characterized by increased customer satisfaction through continuous improvement, in which all employees in the firm actively participates. b. It is an evolving system of practices, tools, and training methods for managing companies to provide customer satisfaction in a rapidly changing world. *c.* It is a continuously evolving management system consisting of values, methodologies and tools, the aim of which is to increase external and internal customer satisfaction with a reduced amount of resources.	*a.* It is about controlling the resources in accordance with the customers' needs and to reduce unnecessary waste. *b.* It is a systematic approach to identifying and eliminating waste through continuous improvement, flowing the product at the pull of the customer in pursuit of perfection. *c.* It designs systems to eliminate waste. By waste, we mean unnecessarily long cycle times, or waiting times between value-added work activities. Waste can also include rework, scrap, and excess inventory.	*a.* It is a business process that allows companies to drastically improve their bottom line results by designing and monitoring everyday business activities in ways that minimize waste and resources while increasing customer satisfaction by some of its proponents. *b.* It could also be described as an improvement program for reducing variation, which focuses on continuous and breakthrough improvements. *c.* It is a disciplined, project-oriented, statistically based approach for reducing variability, removing defects, and eliminating waste from products, processes, and transactions.
METHODOLOGY		
The improvement cycle is widely used as a methodology for TQM that comprises of four stages: plan, do, check, act (PDCA)	Lean manufacturing is derived from Toyota Production System, which was developed between 1948 and 1975. However, the term lean was first coined in 1988 in a master thesis at MIT sloan school of management. Lean is acknowledged by the following principles: *a.* Understanding customer value *b.* Just-in-time (Flow) *c.* Autonomation (smart automation)	There are two methodologies used within Six Sigma: *a.* DMAIC (Define, measure, analyze, improve, control) *b.* DFSS (Design for Six Sigma)
TOOLS		
Tools used within TQM are: · Seven quality control tools; and · Seven management tools; · Seven statistical tools; · Seven project tools.	Tools used within Lean Manufacturing are mainly: · Value stream analysis; · Total productive maintenance; · Kanban; · SMED (Single Minute Exchange of Die); · 5S; · Poka-yoke.	Tools used within Six Sigma are: · Seven design tools; · Seven statistical tools; · Seven project tools; · Seven lean tools; · Seven quality control tools; · Seven management tools.

When Six Sigma is compared with Lean, some fundamental differences arise. In fact, although both focus on reducing waste, Lean has a clear objective of improving process flow and increasing productivity, while Six Sigma has an objective of minimizing variation. As Lean focuses on cost reduction by eliminating all non-value adding activities, Six Sigma focuses on a cost reduction by systematically examining the costs of poor quality (Jiju Antony 2011). Figure 10 shows improvement objectives for an organization considering six sigma and lean methodologies.
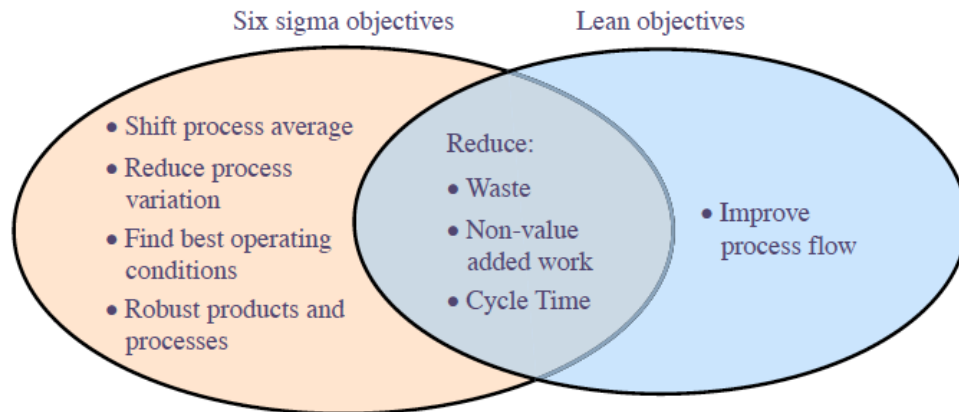
Figure 10: Improvement objectives of an organization (Snee 2010)

2.3.4. Lean Six Sigma and the future of improvement methodologies

Analyzing the nature of Six Sigma and Lean, researchers and practitioners have come up with the term Lean Six Sigma. This means that both can be simultaneously deployed in a given project, aiming to provide bottom-line financial gains through improvements, as well as satisfying customer needs by reducing significantly the number of defects, reducing waste and minimizing lead times at the minimal cost. This merger can trace back to the Six Sigma practices at General Electric, when they realized that the two concepts complemented each other in a positive way, i.e. Lean principles can be considered as an approach for inter-process improvement addressing process flow and waste, while Six Sigma can be considered as an approach for intra-process improvement addressing variation (Andersson, Eriksson, and Torstensson 2006) (Jiju Antony 2011) as illustrated in Figure 11.

36

Step A

Material and
information
flow between
process steps

Step B

Six
sigma

Lean

Value-adding
transformations
occur within
process steps

Step C

Customer
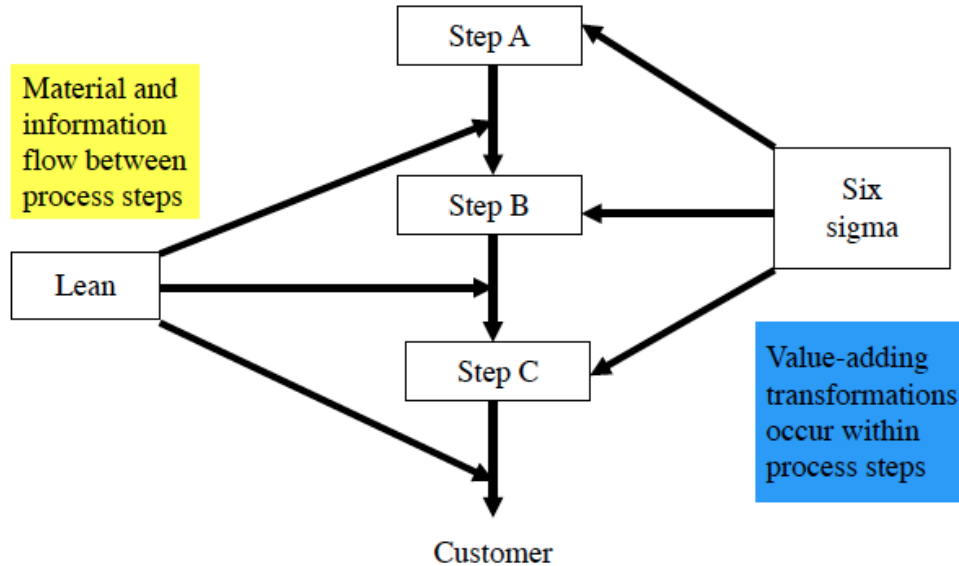
Figure 11: Improvement opportunities occur between and within process steps (Snee 2010)

Lean Six Sigma is designed in a way that it gives better results than other methodologies because it comprises simultaneously the human and process aspects of improvement. Snee (2010) argues that many improvement methodologies focus on few elements of human and process aspects together and none integrate them all. In order to produce breakthrough results, it is required to integrate human and process aspects convincingly. On the other hand, Lean Six Sigma provides a supreme combination of features because it has (i) a structured framework of DMAIC that is applied to improve business excellence, along with (ii) a clear-focus on bottom-line financial gains, and (iii) a philosophy of integrating human and process aspects.

Now the questions arise, which problems better suits which methodology, and also, which Lean Six Sigma tools should be used? Hoerl & Snee (2013) built a matrix that shows an example of identifying an appropriate improvement methodology (Figure 12).

Figure 12: Methodology options in process improvement (Hoerl & Snee 2013)

Snee (2010) presented an example to illustrate the application of Lean Six Sigma, where value stream mapping (VSM), as a Lean tool, is initially used to uncover less-complex problems followed by the use of other Kaizen or other Lean tools to solve them. However, when the problem under analysis uncovered by VSM is complex, with no known solution, Six Sigma might be the answer. Then, within Six Sigma projects where there is the possibility of small improvements, Kaizen projects can be added.

Furthermore, since Lean Six Sigma methodology is recently developed and the number of organizations that have yet adopted Lean Six Sigma as a business improvement philosophy is low, it still faces many challenges. First, what does Lean Six Sigma mean? What benefits does an organization achieve in implementing Lean Six Sigma? Which tools should be used? Which problems should an organization tackle? Although these questions have already been answered by many authors in the past, in order to increase its industrial application, more successful project demonstrations are required to convince top management.

As Snee (2010) clearly pointed out, different improvement approaches might come and go, but improving the bottom-line results never goes out of style - this is the continuous innovation task that leads to more competitive organizations. Snee then emphasizes, practitioners acknowledge about improvement not Lean Six Sigma and Lean Six Sigma is the method, only to realize improvement. This results in an introduction of a "Holistic

Improvement", which is defined as "An improvement system that can successfully create and sustain significant improvements of any type, in any culture for any business".

As Snee (2010) stated, improvement methodologies are not fads: in fact, by learning from the shortcomings of the previous approaches, new improvement methodologies and tools are able to tackle problems of higher complexity. Similarly, in this thesis an innovative attempt is made to introduce a Systems Engineering tool called Design Structure Matrix (DSM) in the define and measure phase of DMAIC methodology. DSM is proposed with the objective of reducing the complexity of modeling the manufacturing system and simultaneously analyzing and highlighting the critical manufacturing processes that require improvements. The DSM tool is discussed in detail in the next section.

2.4. Design Structure Matrix and its applications

The Design Structure Matrix (DSM) was developed as early as 1960s, as a tool to analyze tasks dependency and their sequence. However, this tool only became popular in the 90s applied in product and process development of complex systems (Carrascosa, Steven D. Eppinger, and Whitney 1998) (Browning 2001). DSM is a N×N matrix based tool that represents the interactions between N different elements, which compose the system. Representing the relations inside a system in a matrix form provide intuitive and compact representation of complex systems, being easily adjustable and scalable in order to take into account the different interactions of product or process development. With this matrix it is also possible to operate mathematically, revealing information about the interactions that can be used for further system scrutiny and optimization.

An example of a DSM is shown in Figure 13, where shaded squares along the diagonal represent elements. An off-diagonal sign symbolizes the dependency of one element on another. Reading across a row reveals what the element of that row provides to other elements; reading down the column reveals what the element of that column depends on other elements. In other words, scanning down a column reveals input sources, while scanning across a row reveals output sinks. As a result, from Figure 13 element I provides something to elements A, C, and E and it depends on something from elements B, C, D, and E (Browning 2001).

Figure 13: Example of a DSM (Browning 2001)

The matrix can also be written contrariwise, that is scanning down a column reveals output sinks and scanning across a row reveals input sources. The information is exactly the same however the matrix would be a transposed matrix. The way the matrix is written shows just a convention. If the relationships between all the matrix components are bidirectional, then the matrix would be symmetric relative to its diagonal. Commonly, DSM exploration involves three major steps: (i) identification and decomposition of the elements that compose a system; (ii) identification and interpretation of the interactions between the elements and (iii) analyses of potential reintegration of the elements with matrix operations.

Several advantages of the DSM tool were pointed out by Eppinger and Browning (2012): conciseness of the information; easy visualization of the interactions between system components; intuitive understanding of the data; perform analysis based on matrix mathematical tools; flexibility to be adapted for different situations and problems. As DSM represents the elements that comprehend the process in a very compatible and less complex manner, it has a great advantage over network graphs, by its nature more confusing. This quality can be easily seen with an example from (Batallas and Yassine 2006), where the authors applied DSM and network graphs to the same problem, with the purpose of comparing their complexity. Figure 14 represents an illustration of 54 teams and their respective communication needs (links) through a network graph. The graph shows a very complex interaction behavior among the links, being very difficult to track

their dependencies. The same elements and information gathered from the 54 teams are represented in an Organizational DSM in Figure 15. The DSM shows the same information in a very compact and readable way, being easier to track the dependencies and to represent the elements quantified with numerical values.
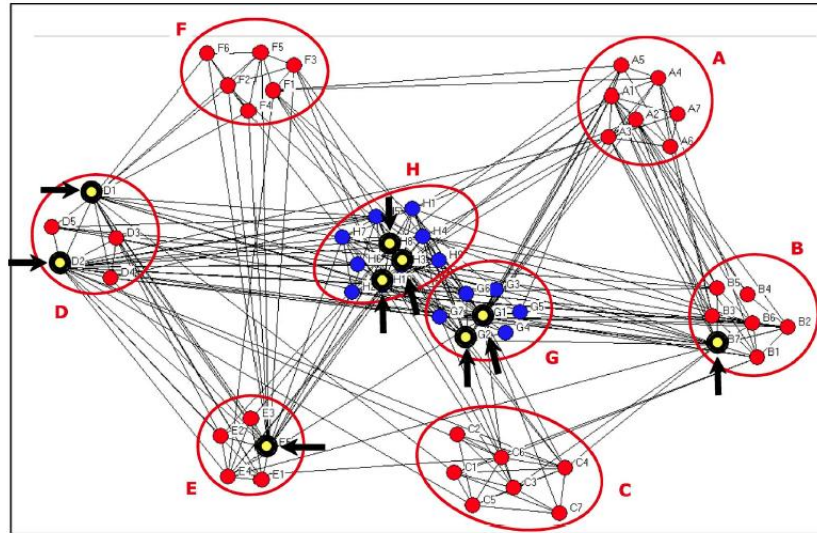
Figure 14: Team interaction graph (bi-directional) - Large commercial aircraft engine (Batallas and Yassine 2006)

Figure 15: Team interaction graph (bi-directional) - Large commercial aircraft engine (Batallas and Yassine 2006)

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Currently, there are two types of DSMs, a static DSM and a time-based DSM. The static DSMs represent system components existing simultaneously, such as product architecture or groups in an organization, which are the two static DSM applications and are formally called: 1) component-based (mainly for products); 2) people based (for organizations management). Static DSMs are usually analyzed through applying clustering algorithms. Whereas, time-based DSMs show sequence of the activities (in both rows and columns) relative to time, which means upstream activities precede downstream activities. Two DSM applications represent time-based DSMs: 1) activity based (mainly for activities and processes); 2) parameter-based (low level processes as design decisions). Time-based DSMs are usually analyzed through applying sequencing algorithms (Browning 2001).

Since the focus of the thesis is quality improvement of products or processes, an activity-based DSM is the type of DSM more targeted to the problem at hand, thus requiring a more thorough analysis. This kind of DSM is used for modeling process elements of a system that is based on several activities, as well as the information flow and/or the dependencies among the activities. This DSM also allows highlighting iteration (feedback) and coupled activities in a process. In fact, the principal objective in a basic activity-based DSM is to minimize feedback-relations, which can be achieved by restructuring the process. Browning (2001) further emphasized that process structure or architecture affects process efficiency and effectiveness. Process architecture can be better understood by using process models, especially those that offer process decomposition and integration.

Browning (2001) described three steps in modeling a process into an activity-based DSM:

1. Decompose the process into activities;
2. Document the information flow among the activities (their integration);
3. Analyze the sequencing of the activities into a feed-forward process flow.

First, the boundary of the process to be modeled, as well as how the process will be decomposed, must be determined. This decomposition allows the model to grow

exponentially in size, until the level of detail to which it is desired to understand and control the process is achieved.

Second, the DSM is built by collecting the activity data and these activities are ordered chronologically as shown in Figure 16. Therefore, upper diagonal elements show feed forward information and lower diagonal elements show feed back information – the potential for rework and iteration in the process.
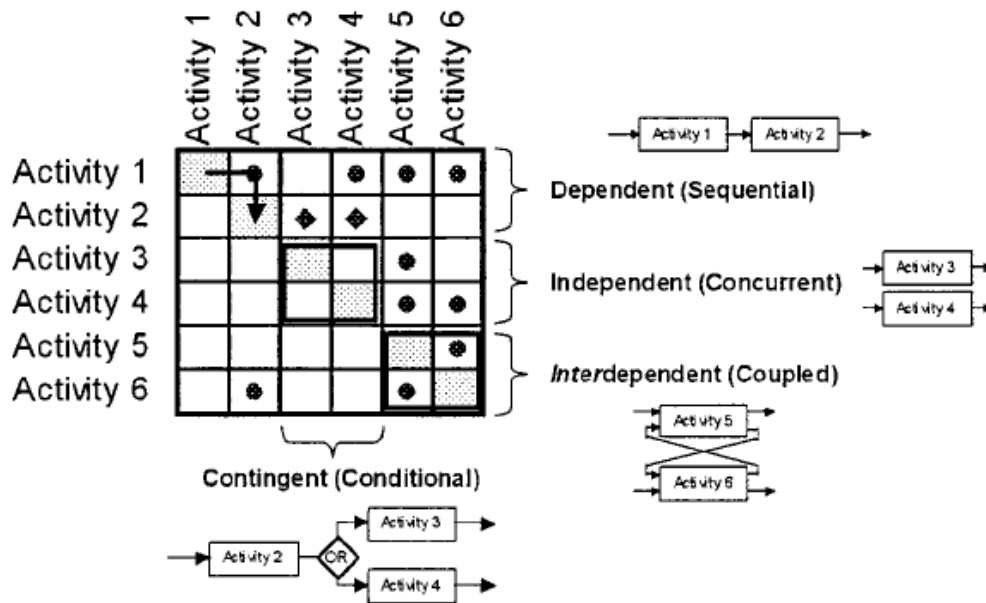
Figure 16: Four types of activity relationships in an activity-based DSM (Browning 2001)

There are two possible ways of modeling the information flows: in a clockwise direction or in an anticlockwise direction. The DSM showed in Figure 16 is modeled in a clockwise direction. If activities in rows and corresponding columns have no direct interfaces, they are independent, and entries in the matrix will be zero or empty (e.g., activities 3 and 4 of Figure 16). If, on the other hand, activities in rows and corresponding columns are filled, this indicates two-way interdependency or coupling between the activities (e.g., activities 5 and 6 of Figure 16).

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2.4.1. Data Gathering and Matrix Operations

Data collection for a good DSM construction is essential for the success of this technique. Most of the times, all the relations between all the elements of the DSM are not obvious, requiring the involvement of many stakeholders related to the system, in order to identify and understand all possible relations. Typical questions asked from the stakeholders are (Browning 2001):

a) What outputs or products must the activity produce?

b) Where do these outputs go to (another activity or outside the process)?

c) What inputs does the activity need?

d) Where do these inputs come from (another activity or outside the process)?

The answers to these questions will help filling the rows and columns of a DSM. It is always a useful activity to build two DSMs – a first DSM based on questions one and two, and a second DSM based on question three and four. Then, these two DSMs are combined to built a single DSM, representing a consensus between supplier and consumer perspectives.

After data gathering and building the final DSM, several matrix operations can be done to further process and analyze the matrix, such as:

- Clustering;
- Sequencing;
- Optimization of the information flow (partitioning);
- Decomposition or integration;
- Tearing;
- Identification of correlation levels.

The most common operations in DSM are clustering and sequencing of the matrix. However, the clustering operation is applied to a static-based DSM, while sequencing operation is applied to a time-based DSM. This thesis will discuss more in detail about the sequencing operation of the time-based DSM because of its focus on quality improvement of the processes.

Figure 17 shows an example of sequencing using a generic matrix. This operation is composed first by re-sequencing the rows and columns of the matrix, which is called partitioning or block triangularization (Figure 17 b). This partitioning operation helps to reorder the elements of the matrix to the upper triangular or lower triangular form as much as possible, with a minimum number of sub-diagonal marks coming as close to the diagonal as possible and are grouped in blocks. The clustered blocks (Figure 17) identified by this partitioning operation represent several directions of analysis for future process simplification. Within this clustered block, other possible operations can be applied to further simplify the matrix, like tearing, decomposition or integration.

a) Initial system   b) Partitioned system   c) Clustered system
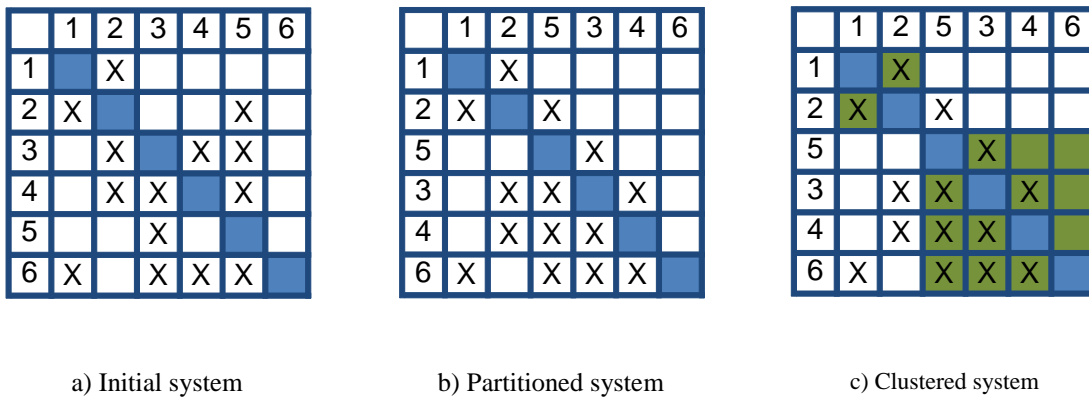
Figure 17 Generic DSM operation.

Browning (2001) listed down some of the pros of time-based DSM. The first advantage he mentioned is that a DSM provides immediate process visibility and understanding. This allows tracking any changes from activities to other activities within a process. Second, the DSM highlights feedback relations and potential iterations. This feedback relation might be the potential process failure – therefore it can be said that DSMs also support process failure mode and effects analysis (FMEA). These advantages of highlighting dependencies, feedback and iterations provide an improved process understanding that, in turn, might lead to process improvement and innovation.

Table 6 illustrates the four DSM applications in a summarized format. However, only activity-based DSM was discussed in detail because of its relevance to the current thesis.

Table 6 Summary of DSM type characteristics (Browning 2001)

	DSM type	Representation	Applications	Operation via
Static	Component-Based or Architecture DSM	Components in a product architecture and their relationships	System architecting, engineering design, etc	Clustering
	Team-based or organization DSM	Individuals, groups, or teams in an organization and their relationships	Organization design, interface management, application of appropriate integrative mechanisms	
Time-based	Activity-based or schedule DSM	Activities in a process and their inputs and outputs	Project scheduling, activity sequencing, cycle time reduction etc.	Sequencing
	Parameter-based DSM	Parameters to determine a design and their relationships	Low-level process sequencing and integration	

After building the DSM and applying the appropriate operations, DSM is further evaluated and characterized for its complexity. There are numerous metrics developed to evaluate DSM´s complexity that will be analyzed in detail in section 2.4.2.

2.4.2. Measuring system complexity in DSMs for quality improvement

The characterization of the interactions between different elements of a complex system is essential in order to assess and fully understand its behavior. A system can be simple or complex depending on the number of existing elements, its structure, behavior and strength of interactions, as well as interactive patterns (Deshmukh, Talavage, and Barash 1993). A complex manufacturing system consists of many elements, whose connections and behaviors are partially unknown. This high complexity present in many manufacturing systems may be critical for producers, due to its direct impact on the quality and cost of the final product. Measuring, reducing and managing manufacturing system complexity will most likely increase product quality and maintain or reduce cost.

Modularization is a method that has been developed to reduce and manage system´s complexity. This method decomposes the system into modules or groups of similar families. Each module consists of elements (components) showing interaction between each other. These modules are organized in a matrix form showing tasks dependency and sequence in order to optimize system complexity (Hommes 2008).

Similarly, in order to measure system complexity for Design Structure Matrix (DSM) applications, component modularity metrics are commonly used. Components modularity is defined as the level of components dependence in the system, with other components at same level (Hommes 2008) or at different level (MacCormack, Rusnak, and Baldwin 2006) of the system. Freeman (1978) was one of the first authors who introduced the concept of centrality and presented different techniques for measuring it. Sosa et al. (2007) successfully transformed Freeman´s concept into a product design process concept for measuring modularity at component level. Many modularity metrics have been developed in the past years. Nevertheless, Gershenson et al. (2010) found that among this research, there is a significant lack of consensus on modularity measurements and modular product design methods, since modularity and complexity are emergent properties. The disagreement is only in presenting a set of different methods in order to accomplish similar tasks. Kreimeyer (2009) extensively reviewed DSM metrics to measure structural complexity in network, software, processes, and engineering design.

In this thesis only three modularity metrics that were identified as meaningful for DSM complexity evaluation in the application of quality improvement will be discussed: the Whitney index, the propagation cost or change cost and the visibility-dependence scatter plot.

The Whitney Index (WI) is defined as the number of interactions per system element (Whitney et al. 1999). This index is a good indicator of how well the system is modularized, reflecting the overall density of the system. However, it should be noticed that this index does not show the density of individual modules within the system.

The WI index is defined as:

$$WI = \frac{number\ of\ interactions\ in\ a\ DSM}{number\ of\ elements\ in\ a\ DSM}$$

The WI might be used to compare different systems, by analyzing whether one system is sparser or denser than the other one. Whitney evaluated this index for multiple matured systems from their DSMs and concluded that many mature systems have WI values of around 6.3 interactions per system element, as shown in Figure 18.
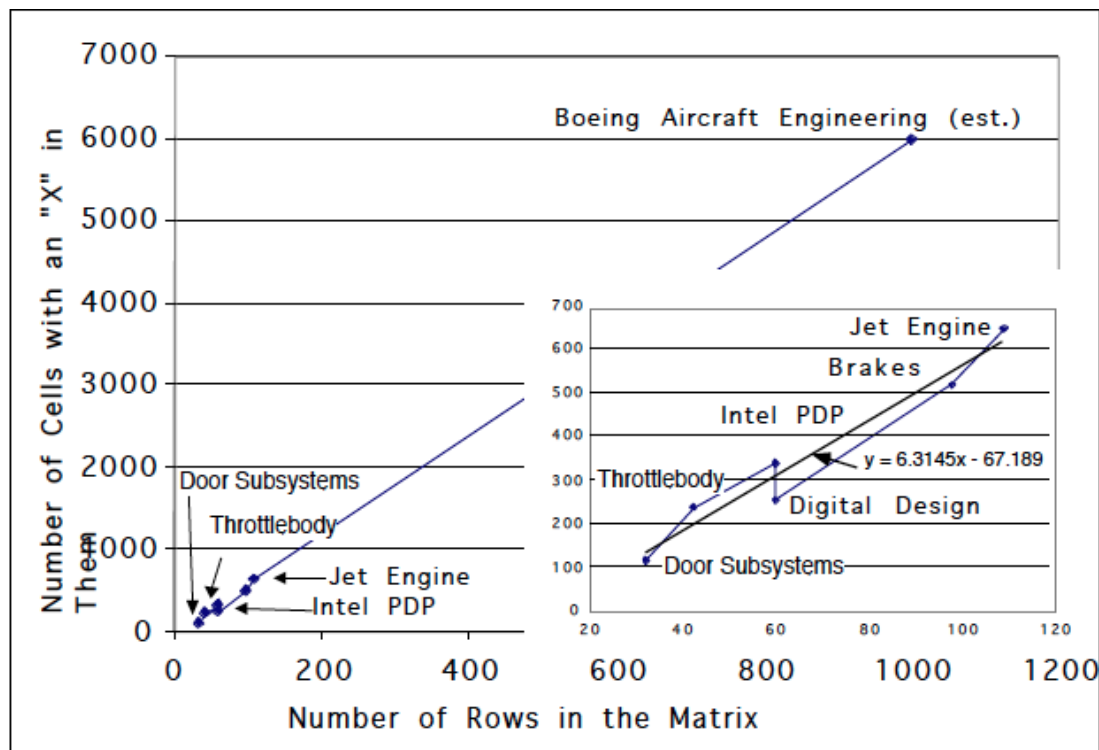
Figure 18: Statistics on the number of entries in a DSM per row. In the insert, trend line has a slope 6.36 and R^2 = 0.95 (where "X" means interaction between the system elements) (Whitney et al. 1999)

The second modularity metric is the propagation cost or Change Cost (CC), which is defined as the degree to which a change made to a single element in the system causes a change to the overall system. In other words, how many elements in a system are affected when a single element is changed (MacCormack, Rusnak, and Baldwin 2006). The CC concept calculates the indirect impact and indirect dependency of each element in a DSM and expresses this impact in percentage terms.

Warfield (1973) was one of the first authors who presented the concept of CC by defining the number of steps in obtaining the indirect dependency of an element in a system, the matrix obtained from this procedure is called reachability matrix. Sharman et al. (2002) and Sharman & Yassine (2004) applied the concept of reachability matrix in a DSM by calculating the hidden and visible links, called visibility matrix (VM), as shown in Figure 19 and Figure 20. Figure 19 shows a system of 5 elements; a change in element A has direct consequences on elements B and D, and indirect consequences on elements C and E. Similarly, a change in element D has only direct consequence on element E not on elements A, B and C.
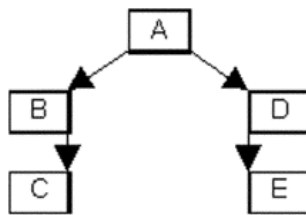
Figure 19: Binary hierarchical system (Sharman & Yassine 2004)

Figure 20 shows the visibility matrix of the system shown in Figure 19. The visibility is a simple and direct multiplication of a matrix by itself, until the matrix becomes empty and then all the matrix cells are added.
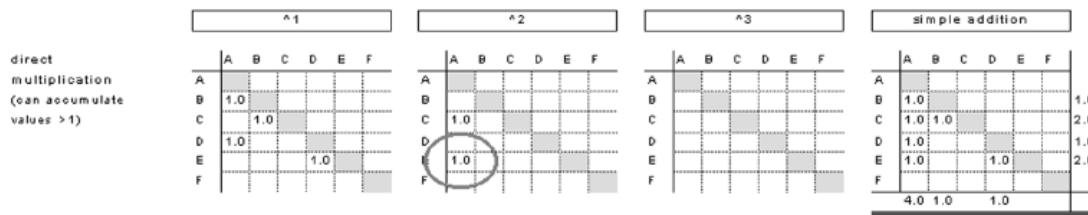
Figure 20: The visibility matrix of a DSM (Sharman & Yassine 2004)

Now the CC of the system is calculated by applying the following formula on VM of Figure 20.

$$CC \text{ of the system} = \frac{average\ of\ the\ sum\ of\ the\ rows\ in\ VM}{number\ of\ system\ elements}$$

CC of Figure 20 will be 0.166 (1+2+1+2/6*6) or it can be converted into a probability of 16.66%, which can be read as: a change in an element will impact 16.66% of the entire system.

The third modularity metric discussed in this thesis is the Visibility-Dependence scatter plot, which is a pictorial representation of visibility and dependence of all elements in a visibility matrix (Sharman and Yassine 2004) (Sharman, Yassine, and Carlile 2002).

$$\text{Visibility of an element} = \frac{sum\ of\ the\ rows\ of\ an\ element\ in\ VM}{number\ of\ system\ elements}$$

$$\text{Dependence of an element} = \frac{sum\ of\ the\ columns\ of\ an\ element\ in\ VM}{number\ of\ system\ elements}$$

Visibility is plotted in the vertical axis and the dependency is plotted in the horizontal axis. The scatter plot of visibility against dependence is a signature of the system. VD-plot is best used when interpreting the direct and indirect links of an element in a system using a graphical approach. Sharman et al. (2002) presented five characteristic plots that show the visibility-dependence signature of a system in Figure 21.
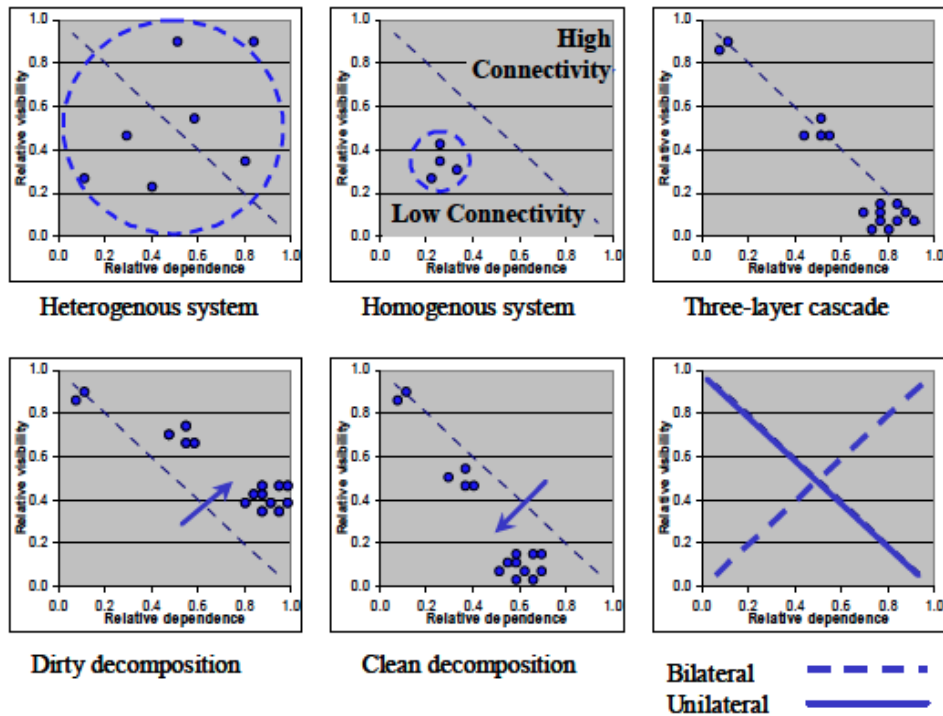
Figure 21: Characteristic types of visibility-dependence signatures of a system (Sharman et al. 2002)

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2.5.   Research Gap

The literature review presented in this thesis is focused in (1) quality control and improvement methodologies and (2) process modeling using matrix-based methods. The discussion on the evolution of quality management concepts has revealed notable developments in the improvement methodologies including TQM, Lean Manufacturing, Six Sigma and Lean Six Sigma. The discussion then leads to a far-reaching approach called holistic improvement, which is the future of improvement methodologies. As Snee (2010) clearly pointed out, improvement methodologies might come and go, but improving the bottom line never goes out of style.

An attempt is made in this thesis to contribute for such developments by introducing a matrix-based approach in order to reduce complexity during process modeling.

In fact, and according to the literature review, applications of System Engineering tools in quality improvement problems has not been attempted so far, being one of the research gaps that this work attempts to address. Although Systems Engineering tools were initially designed to be used for very complex systems, it is believed that integrating this approach in the new context of quality problems and exploring the benefits that might be achieved is a new avenue of research.

A discussion on DSM´s application shows that it can be applied for modeling the manufacturing processes innovatively, with less complexity, and with a possibility of highlighting critical manufacturing processes easily. In the context of improvement methodologies, DSM can be a productive tool in the Define and Measure phase of the DMAIC methodology.

A last note about the requirements of using engineering knowledge more deeply when tough quality problems are at stake – in fact, the intensive use of lean tools and the basic tools of quality improvement, often masks the inherent technical nature of these problems, weakening the proposed solutions.

Chapter 3 - Project description

The focus of this chapter is the detailed description of the Microleaks project. In the first section the problem definition is revisited and the scope of the project is more clearly defined. Then, section 3.2 introduces the multidisciplinary team that tackled this complex problem, comprising the project leader, three master students and university professors. This approach was designed in order to handle the different technical requirements of this demanding project.

In order to have a more comprehensive knowledge of the problem, it is important to have a basic understanding of the concept for Leaks, Microleaks, and Nanoleaks and the associated nomenclature used in the industry (section 3.3). Furthermore, some preliminary investigation on the leak detection systems is also discussed, comparing the current industry´s capabilities with the customers´ requirements.

In the next section, the working principle of all the equipment´s installed in the targeted assembly line are described, in order to assist in following the research done by the master students.

Section 3.8 discusses further the preliminary analysis of the aerosol cans through microscopic and macroscopic analysis, a fundamental investigation that highlights key areas of the aerosol can that might be important for the Microleaks.

At the end, the section discusses the research work performed by the master students, who are also lead engineers of the company. A summary of their work is presented, covering main objectives, work plan, key findings, recommendations, as well as a final discussion on how those key recommendations were continued by the work in this thesis.

3.1. Define clearly the problem to be analyzed and project scope

As discussed in chapter 1, Leaks and Microleaks are one of the major quality problems for Colep. The very first leak detected by the customer was in the year 2003 and since then, Colep has been constantly receiving complaints from customers. These complaints have risked backlogs and production delays as well as company´s reputation, loss of goodwill, and health and safety issues.

During the years 2007 and 2008, an internal 8D Quality project was launched in order to understand, analyze and solve the problem of Microleaks. One of the project's final proposals was a containment action of measuring leaks at the downstream process, based on an acceptance sampling procedure. As a result, and due to the fact that not 100% of the aerosol cans shipped to the customers were tested for Microleaks detection (the 100% test only detects regular leaks), Colep continued to receive complaints due to this quality problem.

In order to resolve the Microleaks, Colep and the MIT Portugal Program began their collaboration in 2012. During the initial meetings, objectives, Microleaks historical data and customers´ requirements were discussed. The project further progressed by defining the scope and the team assigned for the Microleaks project. At the time it was immediately understood that Microleaks occur in many aerosol can formats – therefore, and in order to start a systematic analysis of the problem, it was required to narrow down the scope of the problem

The aerosol manufacturing division of Colep in Portugal consists of six assembly lines and each assembly line produces various aerosol formats. An aerosol format is the combination of diameter (d) and length (l) of an aerosol can. Colep currently produces five aerosol diameters 45, 49, 52, 57, and 65 mm and six aerosol heights 96, 118, 195, 209, 240, and 300 mm. Since there are too many formats (d x l), the project was limited to a single format (e.g. 45x96) and the final results could then be extrapolated to other formats. In order to limit the scope and contain the problem, historical data concerning the production volume and the quality of the produced aerosols (measured in ppm of non-conforming cans, i.e. cans with leaks detected in production) was analyzed for the years 2011 and 2012.

Figure 22 shows data for six assembly lines (red squares) and nine aerosol formats (blue diamonds), both of them selected because of their relevancy for the Microleaks project. The following statements can be drawn from this graph:

- Line 15 has the highest production volume;

- The lines that produce the largest diameter formats (i.e. Ø65) have the most quality problems;

- The 52x195 format has the highest production volume and produces the smallest number of leaky cans;

- Seven out of the nine worst quality formats have a diameter of Ø65;

- Lines 12 and 27 have a poorer quality than other lines consistently, with line 27 being the most unstable;

- The 65x105 format has the worst quality level of all produced aerosol formats.
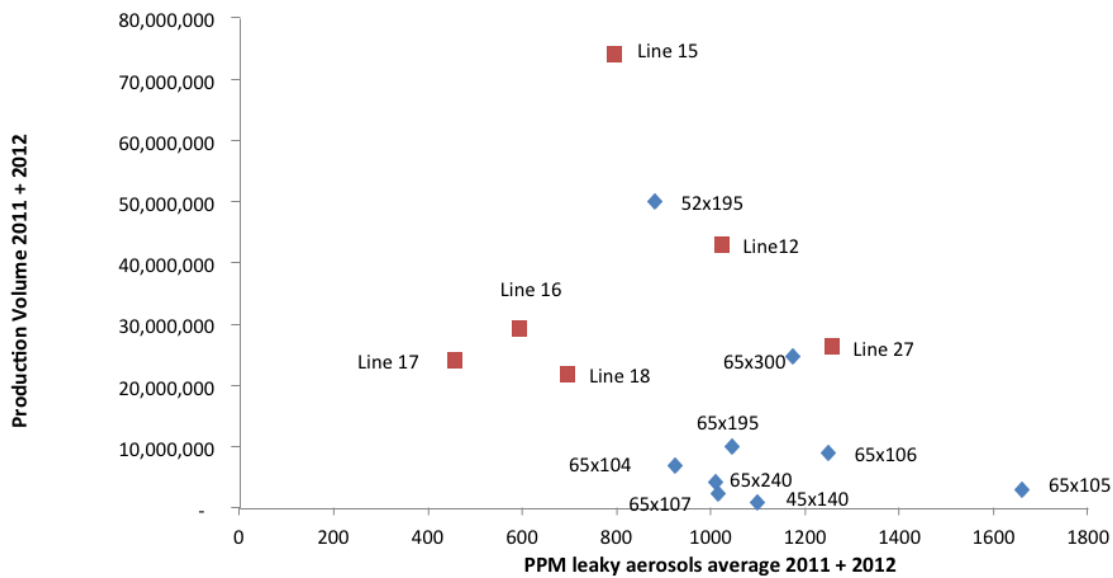
Figure 22: Production volume versus production quality (Parts Per Million – PPM) scope matrix

From this analysis a clear significant behavior can be seen for line 12 and line 27 in terms of the Microleaks. Furthermore, diameter 65 produces most of the Microleaks and Line 12 is a line that produces only diameter 65 cans. Also, in line 12, the format 65x300 produces most of the leaks: therefore this line and this format were selected for further investigation. Nevertheless, line 27 should not be overlooked because of its unstable behavior and the results achieved from line 12 will then be extrapolated to line 27, as well as to other lines and formats.

After narrowing down the scope of the project, the next step is the selection of the multidisciplinary team to achieve the objective of Microleaks project.

3.2.   Define Project Team

The team included a project leader, who is a PhD student enrolled in the LTI program, and three Technology Management Enterprise (TME) master students, who are among the lead engineers of the company. Each of the three TMEs had to solve, during one year, a particular technological work package related to the problem under analysis, work that was coordinated in all instances with the work of the LTI student. These three TMEs kept an active participation throughout the project. As the results of this work is considered very relevant to the Microleaks project, in the section 3.9, the TMEs work plan, challenges as well as important results, will be briefly presented.

The Microleaks project was also supported by a team of nine faculty members of the Faculty of Engineering of the University of Porto (FEUP) with different roles, considering the multitude of problems that the project involves (project manager, PhD thesis supervisors, master thesis supervisors, specialists, and etc.). Several Labs at FEUP and associated institutes have performed an array of tests to carry over the research program. Similarly, some tests have been performed either at one of Colep's plants or at Colep´s suppliers, and some tests were even performed by Colep's clients. Furthermore, the Industrial Director of Colep sponsored the project as well as coordinated the LTI student as a tutor, continuously participating and contributing with his invaluable insights for the problem solution. This attitude reflects a strong leadership and continuous management commitment from the company, a compulsory requirement in any quality improvement project. The role of each member of the Microleaks team is presented in Table 7.

Along with leading the project, the PhD LTI student also coordinated the work of the three TME students. The coordination work includes:

- Assist in the development of short term and long-term goals;
- Organize and establish meetings on a regular basis;
- Keep all the team members up-to-date about the latest developments by presenting the work on a monthly basis;
- Coordinate the experimental work performed by the TME students;

- Provide support in the development of the TME work;
- Perform and analyze experimental analysis at the suppliers' production site.

Table 7: Microleaks project team management

Project role	COLEP	EDAM
Project leader		PhD LTI student
Steering committee	Industrial director Managing director	Professors at FEUP
Project coordination	Industrial director	Professor at FEUP
LTI faculty orientation		2 Professors at FEUP 1 Professor at MIT
TME students and tutors	Production manager Engineering manager Technical manager	3 Professors at FEUP
TME team coordination		PhD LTI student
Project specialists		Specialists from INEGI

After defining the project goals, problem definition, project scope as well as the team, it is essential to discuss the concepts and the nomenclature used by Colep for Leaks, Microleaks, and Nanoleaks.

3.3. Leaks, Microleaks and Nanoleaks

A leak is a small cavity that is generated in the aerosol can due to a imperfect manufacturing processes. The industry under analysis has defined a nomenclature of a leak for any aerosol can, when it has a leak rate above 2 ml/min. Similarly, any leaky aerosol can having a leak rate between the ranges of 2 ml/min to 10^{-1} ml/min is called Microleaks.

The company uses the definition of Nanoleaks, considering leaky aerosol cans that have leak rates below the level of 10^{-1} ml/min, being only detectable at the customer facility due to its more precise detection systems. The Nanoleaks are so small that cannot be detected with the manual waterbath leak detection system at room temperature. These

Nanoleaks are only detectable using manual waterbath leak detection system through simultaneously increasing the temperature as well as the duration of the test, thus raising the sensitivity of the system.

In order to detect aerosol cans with leaks, leak detections systems are installed in the industry. A further explanation regarding the type and working principles of leak detection systems is presented in the next section. A preliminary analysis is also presented for the leak detection systems that helped the team to understand the current capabilities of the industry to detect leaks and compare it with the customers´ requirements.

3.4. Leak detection systems

There are two leak detection systems installed in Colep: the first one is a 100% automatic leak detection system and the second one is a manual waterbath leak detection system, working on the basis of a sampling procedure.

3.4.1. 100% Automatic leak detection system (Wilcomat)

The automatic leak detection system is the only detection system that detects leaks for 100% of the produced aerosol cans. There are two different equipment's installed in Colep for measuring 100% of the aerosol cans. The type of equipment installed in line 12 is a Wilcomat machine.

The Wilcomat machine is a precision tester designed for leak detection that has a maximum leak detection limit of 2 ml/min and has a maximum production speed of 280 cans/min. A Wilcomat machine for aerosol can leak detection is illustrated in Figure 23. First, the aerosol cans are fed to the tester by means of a conveyer belt (1) and a screw conveyer (2). The feeding star (3) in turn positions the can onto the turntable (6) beneath the test cylinder. While the turntable moves the cans along, the testing procedure takes place.

After the testing procedure, the aerosol can is released from the testing station and moved onto the conveyer belt by an outlet star (5). Tested aerosol cans that are considered as leaky are pushed off the conveyer belt at the rejection point. Aerosol cans that have

passed the test stay on the conveyer belt and are moved on to the next step of the production line.
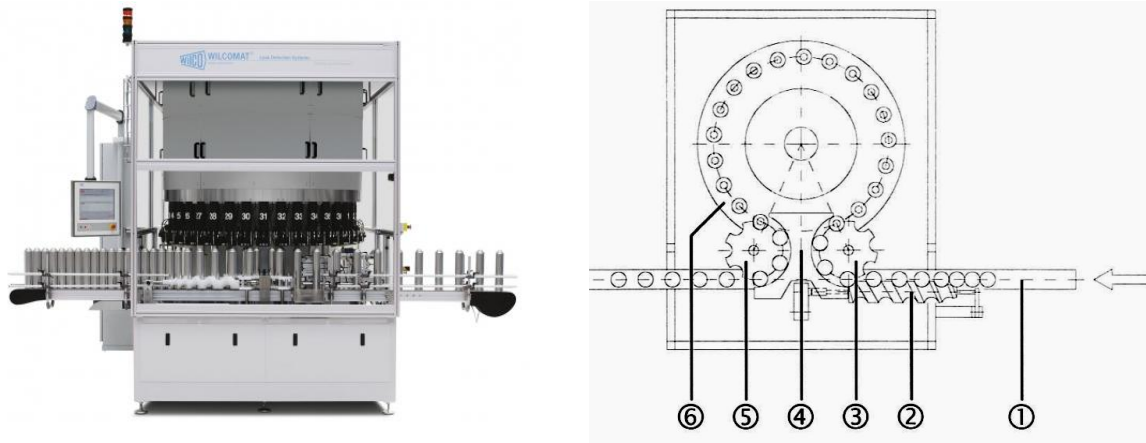
Figure 23: WILCOMAT machine for aerosol can leak detection (AG 2015)

The testing procedure of the Wilcomat machine works according to the pressure testing method. In this method, first an in-feed star wheel places the sample onto a carrousel (first figure on the left side of Figure 24). Then, the aerosol can is lifted by a pneumatic cylinder into the test chamber. Once inside the chamber, the aerosol can is hermetically separated from the chamber by an expander and suspended freely as shown in Figure 24. This allows the analysis of critical areas such as the welding bead as well as the seamed components (Teixeira 2013).
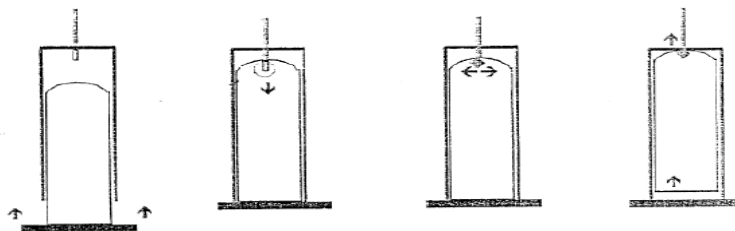
Figure 24: Scheme of Wilcomat sealing system (Teixeira 2013)

Inside the chamber, first the burst test takes place followed by a leak test. The burst test creates a near perfect situation for a consecutive leak inspection through increase in the pressure. The (high) burst pressure is used as (high) filling pressure for the aerosol cans and the safety chamber that surrounds them allows measuring any pressure increase. This test is advantageous because:

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- A high filling pressure forcedly opens any cracks or openings of the can and creates just the situation in which leaks are most likely to appear;

- A high filling pressure also allows detecting smaller leaks. If a filling pressure of 10 bar is used, a lower leak rate can be detected than if a filling pressure of only 1 bar was used.

In the leak test, first the aerosol cans are tightly locked and then filled with filtered compressed air. The testing chamber is filled normally with atmospheric pressure and if the air pressure inside the chamber is increased due to a leaky test sample, a high accuracy pressure transmitter detects this increase and the part is rejected (Teixeira 2013).

Following the 100% testing in the automatic leak detection system, aerosol cans are then tested for leaks using manual waterbath leak detection system based on an acceptance sampling procedure.

3.4.2. Manual waterbath leak detection system

The manual waterbath (Figure 25) functions on a sampling basis because of the difference in measuring speed of the manual waterbath (max 6 cans/min) relative to the actual production speed of aerosol cans (200-280 cans/min). This machine has a maximum leak detection limit of 10^{-1} ml/min at the standard testing procedure described below, value that could be improved by increasing the testing time and the temperature of the water.

The working principle of the standard procedure is very simple. The aerosol cans are:

(i)   first clamped into the machine;
(ii)   submerged into water at room temperature;
(iii)   filled with compressed air at 10 bar pressure;
(iv)   tested for any leakages through identifying the bubbles at the welding bead and seaming joints using graduated cylinders.

If there is any leaky can found, then the operator measures the leak rate using a graduated cylinder. Therefore, it can be said that this machine detects leaks and measures the leak rate of defective cans.

Figure 25: Illustration of manual waterbath method (8 heads – Colep has 6 heads machines)

During normal production, the time spent by an operator to measure leak rates is 5 min for setting up the test, where 6 aerosol cans are measured at the same time.

Testing aerosol cans for longer time periods can increase the capability of manual waterbath systems, but, due to time constraints, this is only possible when offline testing are performed as a consequence of claims from customers. For example, in one of the aerosol cans claimed by the customer, manual waterbath detected a leak rate of 10^{-4} ml/min in 45 hours. The process of performing offline tests for longer time period is different from what it has been described previously. The procedure is described below as well as some example pictures are illustrated in Figure 26 (Teixeira 2013):

(i)   first aerosol cans are clamped into the machine;

(ii)   a rod is fixed to support graduated cylinders (used to measure leak rate);

(iii)   graduated cylinders are placed at the possible location of leaks so that leaks can be measured;

(iv)   the machine is filled with water at room temperature;

(v)   aerosol cans are filled with compressed air at 10 bar pressure;

(vi)   time is recorded in order to observe significant leak rate.

Figure 26: Examples of manual waterbath leak testing (Teixeira 2013)

Aerosol can samples shown in Figure 26 were previously tested on a standard procedure of manual waterbath, where no bubbles were observed. While testing these samples using the procedure described above, bubbles were observed as well as leak rate was recorded in a significant time period (Teixeira 2013).

Table 8 illustrates a comparison in terms of leak measurement capabilities among available technologies in the market, in Colep and at Colep´s customers. This comparison is made regardless of production speed and investment costs.

Table 8: Leak detection systems; A Comparison among the available technologies in COLEP, in the market and respective applications (adapted from Teixeira 2013).

Technological capabilities to measure leaks	Tracer gas sensing / High Vacuum Helium				Bubble testing (water submerse) / Air decay					
Leak rate in ml/min	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	2	5
Microleaks project relevance					Customer claims			Manual waterbath machine	Automatic leak testing machine	

Applications	Aerospace missiles, Electronics	Airplane tanks, Automobile, Refrigeration	Food packaging, Watches, Industrial applications	Others

The next section revisits the definition and working principle of aerosol cans and highlights which locations in an aerosol can might be critical for leaks.

3.5. Aerosol can and its critical locations

The working principle of an aerosol can is revisited in Figure 27. An aerosol can is a pressurized container, which contains essentially one fluid/gas that boils well below room temperature (called the propellant – represents 50% to 90% of the container volume) and a mixture (solvent(s) plus active ingredients dissolved or suspended) that boils at a much higher temperature called the product (e.g. insecticides).
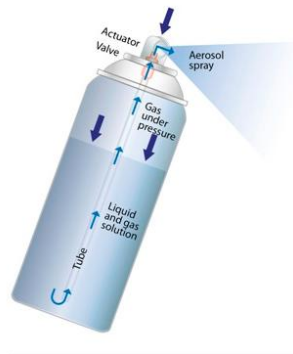
Figure 27: Working principle of an aerosol can (FEA 2015)

Pressing the actuator activates the valve, opens a passage from the inside of the can to the outside. Consequently, the propellant exerts pressure on the active product and solvent solution, forcing the liquid up through the dip tube and through the valve when opened. As a result, the product is expelled together with the propellant in the form of droplets, foam, paste or powder. The product that is expelled out is called aerosol spray or simply aerosol (FEA 2015).

The goal of the thesis is to improve the final product quality by reducing the number of leaks for the empty aerosol can therefore the study of valve, actuator, and cup are out of scope in this thesis. The empty aerosol can is revisited in Figure 28, where it shows three important components: the top, the bottom, and the body. The important areas of the empty three-piece aerosol can are the connections between these three parts, which are seamed together, and the lateral joining (welding bead) of the cylinder, highlighted with red lines in the figure.
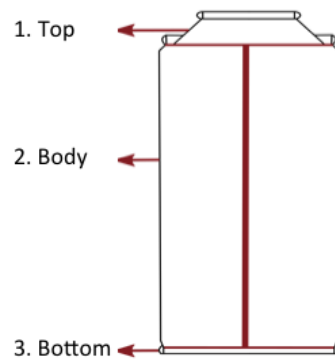
Figure 28: Basic components of an aerosol can

Understanding the details of the welding and seaming processes is an important step to analyze the leaks in the aerosol cans. The working principle of these processes and their equipment´s is discussed in the next section.

3.6.   Welding process

The welding process starts from feeding the rectangular tinplate into the welding machine. First the tinplate is converted into a cylindrical shaped tinplate and then it is welded. The type of welding process performed in Colep is the Resistance Seam Welding (RSW), which works on the principle of electrical resistance welding. In this type of welding, two surfaces are joint together by a succession of points through the application of electrical current and a mechanical force. The resulting weld is a series of overlapping resistance spot welds made progressively along a joint by rotating the electrodes. In this type of welding, there are two electrodes involved: first is called the outer welding roller and the second is called the inner welding roller. The important components of the welding machine in Colep are illustrated in Figure 29.
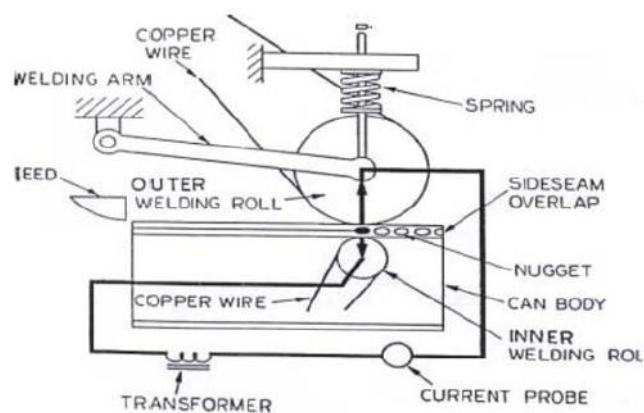
Figure 29: Components of welding machine in Colep (Valente 2013)

In the welding process, the concept of overlap is of utmost importance and will be discussed in the next section.

3.6.1. Overlap

During the welding process, the overlap of the mating surface plays an important role, because the semi-molten overlap surfaces are pressed together by the welding force, causing them to bond together into a uniform welded structure after cooling. The mating surface before the welding process is called an overlap, and the uniform welded structure that is formed after the welding process is called extrusion, which is further explained in section 3.8. A closer illustration is presented in Figure 30, showing the relation of welding rollers and overlap of the mating surface being welded.
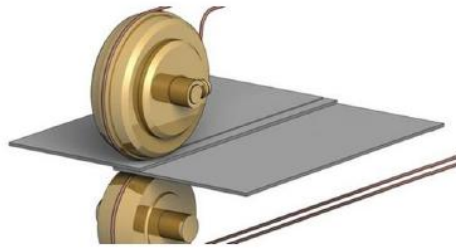
Figure 30: Illustration of a mating surface being welded (Valente 2013)

For a smooth production of aerosol cans, the overlap must lie within the defined limits throughout the production setting. The precision of overlap measurement is 0.05 mm and the recommended value of an overlap defined by the equipment supplier at the beginning of the weld is between 0.5 – 0.6 mm, whereas at the end should be 0.4 – 0.5 mm. However, as the machine produces more and more aerosol cans, overlap values tend to vary. Also, there is no continuous monitoring system that can give feedback over the variation. Therefore, the production team measures the overlap intermittently to guarantee that the overlap is within the specified range.

Measuring overlap is a challenging task because the measurements are manual and the involved values are very small, therefore subject to human error. The procedure of overlap measurement is the following: first the machine setting is changed in order to weld the aerosol can in such a way that it leaves 5 mm unweld seam area from the beginning and end of an aerosol body. Then, the beginning and end of an aerosol body is

manually cut until the overlap is visible at the 5 mm distance. The overlap is then measured using a measuring gauge; a skilled team member is required to use such measuring gauge to measure the overlap. On average, it takes 4-5 minutes to measure the overlap at the beginning and end of an aerosol can. A cross-sectional view is shown in Figure 31 where U is the overlap.
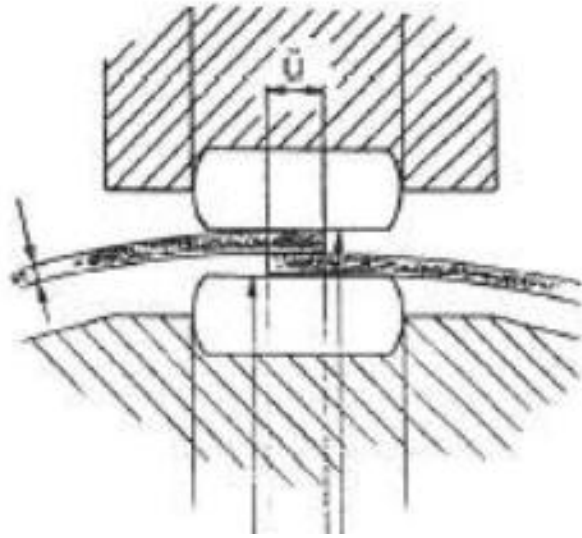
Figure 31: Overlap measurement (Valente 2013)

A slight variation in the overlap value can significantly affect posterior processes: if the overlap is considerably smaller than the tolerance limit, the welding can break and the aerosol can can leak. Similarly, if the overlap is considerably bigger than the tolerance limit, the required aerosol can diameter might not be attained and would not be possible to do the subsequent seaming operation.

The welding process parameters (welding current and voltage) are monitored by an automatic welding monitoring system and the working principle is next discussed.

3.6.2. Welding Monitoring System

The welding monitoring system is installed in the assembly line 12 immediately after the welding process. The main objective of this system is to detect faults in tinplate welding. These faults can occur during the welding process due to: presence of dust or oil that can locally increase the resistance therefore modifying the electrical behavior of the system;

holes in the tinplate that can allow direct contact between electrodes; and random variations of the tinplate thickness (Lanzoni and Salomoni 2010).

In order to detect these faults, the system measures two key parameters for welding quality evaluation: welding current and voltage difference across the welding rollers. The working principle of welding process used in the industry is revisited in Figure 32, whereas Figure 33 shows the electrical schematic of welding machine power circuit. V_R represents the voltage between the welding rollers. The system features two transformers; one transformer is used to measure the current flowing through the primary coil of the other (power) transformer (PT) and the second transformer is an ammeter (TA).

At each cycle of the welding process, the analog samples are stored and digital signals are processed. At the end of the welding period (i.e., when a new trigger event is detected - which is 0.7 ms), the collected analog samples are evaluated to obtain the nugget quality factor (QF) expressed by the average conductance (i.e., the reciprocal of the resistance) during a single welding period. The QF, determined by the current and voltage waveform during welding, is automatically compared with operator-defined limits, and if these are exceeded, a fault signal is produced and the faulty can is ejected.
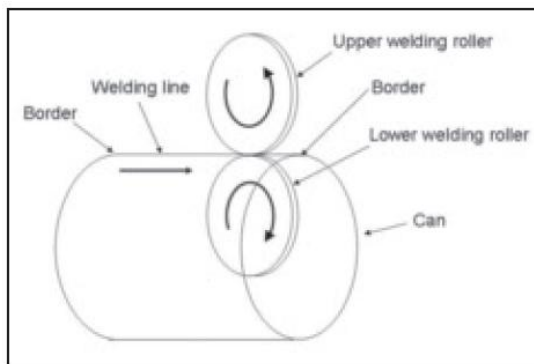
Figure 32: Working principle of welding process (Lanzoni & Salomoni 2010)
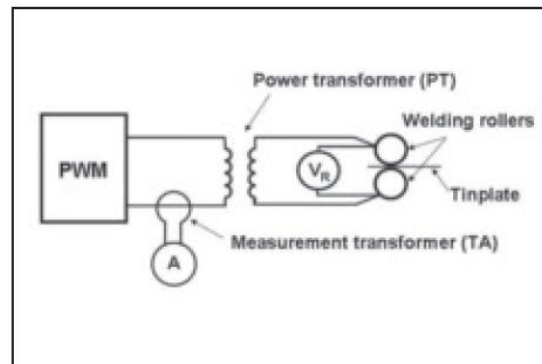
Figure 33: Electrical schematics of the welding machine power circuit (Lanzoni & Salomoni 2010)

Figure 34 illustrates the transport and ejection system for the welding monitoring system. Figure 35 analyzes results for a single can, while each point in the figure represents the quality factor (QF) of a nugget along the weld interface. As it can be seen in the figure, a set of nuggets exceeded the allowed thresholds (Lanzoni and Salomoni 2010).

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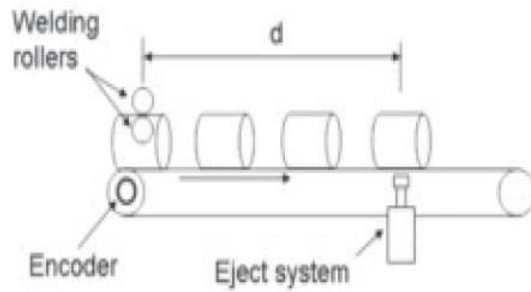
Figure 34: Schematic representation of the transport and ejection systems of the welding monitoring system (Lanzoni & Salomoni 2010)
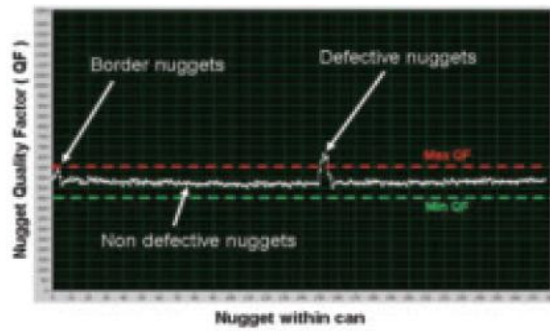
Figure 35: Results of the analysis of a single aerosol can (Lanzoni & Salomoni 2010)

Product quality standards can be easily defined by the operator choosing the number of tolerable faults that depends on the application. For example, cans for aerosol normally require zero defects while those for solid contents are more tolerant. To manage this parameter, the operator can easily define/modify the limits for defect detection.

Furthermore, the welding monitoring system does not measure the leaks or Microleaks directly; nevertheless it measures one of the important parameters, that is, conductance (reciprocal of resistance). During discussion sessions with the production team, it was discovered that they are not fully knowledgeable about the system, therefore not taking full advantage of it. The operator sets the limits on a basis of rule of thumb and varies according to the results. The main concern for the operators is the welding rollers and the welding machine only, which can be damaged due to high current value. In fact, the quality of the aerosol can, especially leaks, is not an immediate concern for them.

3.7. Seaming process

The type of seaming process applied for aerosol cans is the double seam because they need to be hermetically sealed. The double seam is a metal-to-metal joint formed by five layers of metal, three from the component (references 1, 3 and 5) and two from the body (references 2 and 4) as shown in Figure 36. These layers are then duly compressed in order to form a hermetical seal.
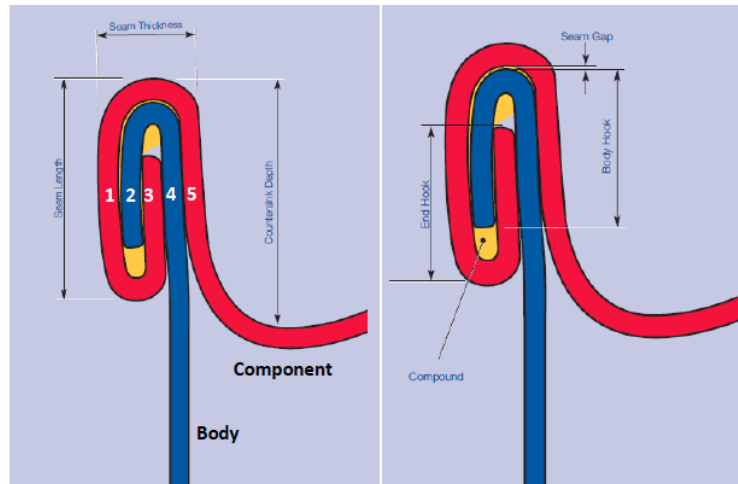
Figure 36: Seaming process nomenclature (Valente 2013)

The typical process of double seaming is divided into two operations. In the first operation, seaming roll will be responsible for forming the curl of the component under the flange of the body as shown in Figure 37.

In the second seaming operation, pressing different layers tightly completes the closing process. The sealing compound that was already applied in the top and bottom components will form an elastic gasket to compensate possible imperfections of the main components, ensuring the hermetic can closure.
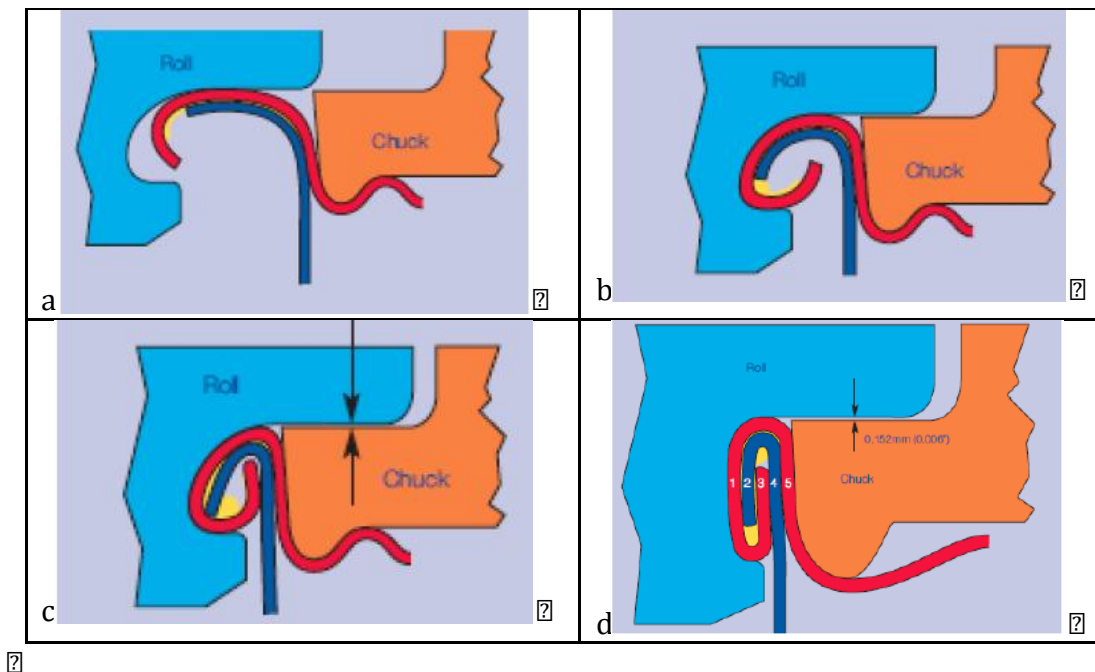
Figure 37: Sequence of seaming process (Valente 2013)

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Based on all these studies, the Microleaks team decided to investigate further and analyze the welding bead of the aerosol can at the INEGI laboratory, by performing microscopic and macroscopic analysis. These analyses helped the team to understand in depth the physics of the Microleaks.

3.8. Microscopic and macroscopic analysis

The microscopic and macroscopic analysis of the welding bead performed at this stage of the project had the purpose of further comprehending which points of the welding bead are important for the generation of Microleaks.

During macroscopic analysis, the equipment´s used was a stereoscopic glass (Olympus model SZH) and the parameters measured were:

- Heat affected area at the weld seam area;
- Heat affected area at 3 mm from the weld seam area.

An illustration in Figure 38 shows the heat-affected area. The picture is taken at the outside area of the aerosol can using a stereoscopic glass and is magnified by 10 times. The length of the heat affected area is measured manually using a measuring scale that has a precision of 0.1 mm.
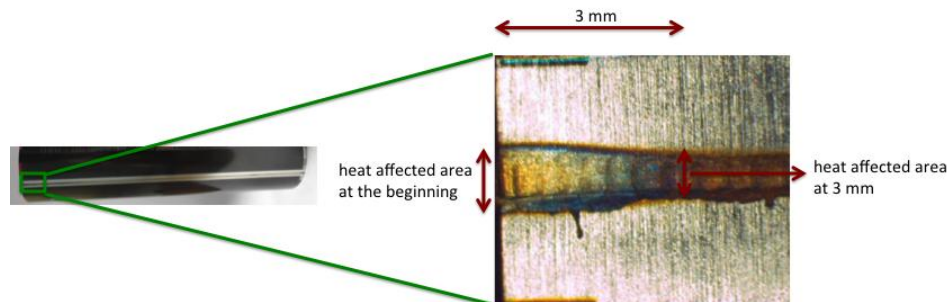
Figure 38: Illustration of heat-affected area at the beginning and at 3 mm of an aerosol can (magnification of 10x)

Microscopic analysis was performed with an optical microscope (model PMG3) measuring the following parameters:

- Thickness of welding seam at the weld seam area;

- Extrusion at the weld seam area (overlap + extruded area).

In order to measure microscopic parameters, first the specimen is grinded from 0.5 – 0.7 mm range, and then the analysis is performed. It was required to grind this length in order to create a clear surface for the analysis. Figure 39 illustrates microscopic parameters at the welding bead after grinding at 0.7 mm. Both the parameters are measured using computer software and each of them has a precision of 0.01 μm.
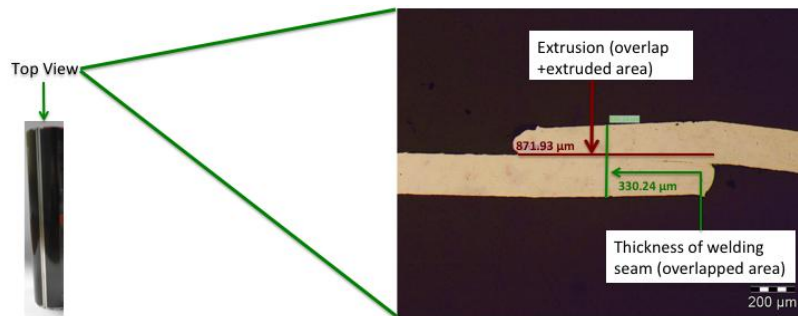
Figure 39: Illustration of thickness and extrusion at the welding seam area of an aerosol can (magnification of 75x)

Both the macroscopic and microscopic work was supported and analyzed at INEGI.

Five samples were prepared for analysis at different locations of the welding bead as shown in Figure 40. The preliminary results show that welding top and bottom of an aerosol body might be critical to analyze further. These analyses were also utilized during the master´s student work and during DoE analysis (chapter 5) to analyze the problem of Microleaks with depth.

a: Analyzing welding top (magnification = 75x)

b: Middle of welding (magnification = 75x)

c: Welding seam (magnification = 75x)

d: Macroscopic view of welding bead
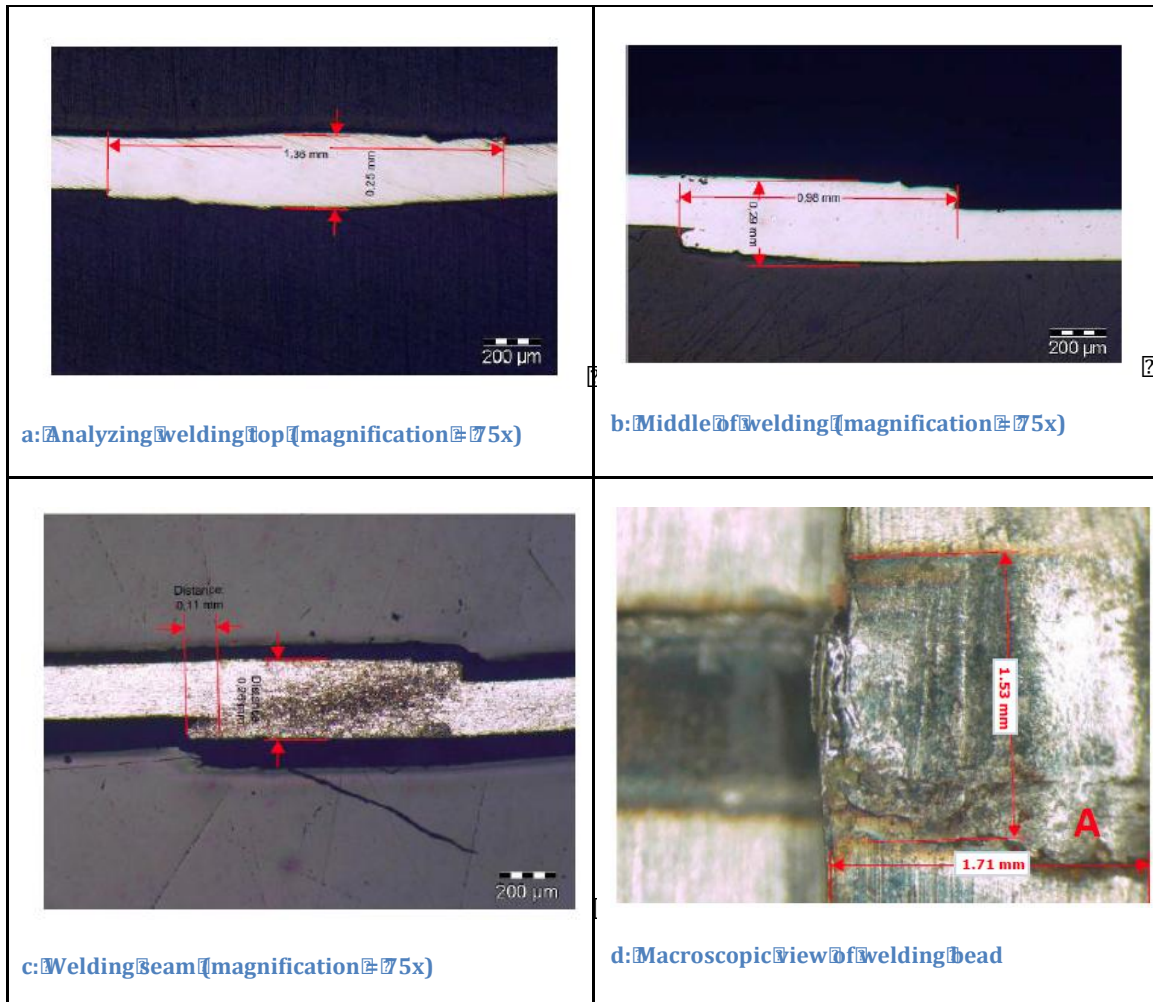
Figure 40: Some examples of the microscopic and macroscopic analysis (Valente 2013)

The discussion is now emphasized on the work of three TMEs whom had spent 1 year in developing an individual work package for the Microleaks project.

3.9.   TMEs work packages

Due to the relevance of their work to the Microleaks project, a synthesis of the work packages proposed to the three TMEs engineers will be presented. The themes addressed were:

  i.   Material analysis and characterization (Melo 2013)

 ii.   Welding and forming processes (Valente 2013)

iii.   Detection systems (Teixeira 2013)

These themes were proposed to the three TMEs because it was thought that the root cause of the problem might be related to these overarching areas. A brief discussion over the objective, challenges, main results, and recommendations of each of the TME work is presented below:

3.9.1. Material analysis and characterization

The objective of this work was to:

- Study the material (tinplate) characterization of the incoming material from different suppliers;
- Compare the quality characteristics of the incoming material with the quality characteristics specified by the international standards;
- Analyze the variation in the material properties and composition due to deforming processes;
- Find possible correlations between the material characterization and the Microleaks;

The challenge of this study was the collection of data, performing microscopic analysis at a secondary institute, studying the process of tinplate production, and find any correlation between the material properties and the Microleaks.

The work plan defined to achieve the objective of the study consisted in analyzing:

- Chemical composition of tinplate;
- Macrostructure and microstructure properties of processed and unprocessed tinplate;
- Mechanical properties of tinplate;
- Metallographic and micro-hardness analysis.

The last two bullet points of work plan were focused on comparing the final product quality in terms of Microleaks. In other words, the aerosol cans that were claimed by the customers were analyzed and investigated in order to identify correlations with the ongoing analysis.

As an example, the Figure 41 shows some of the analysis performed during the research work.

| a: Microstructure analysis of the unprocessed tinplate | b: Microstructure analysis of the welded tinplate |

#	Zone
0	Base tinplate (longitudinal/transversal)
1 and 7	Base tinplate
2,3,4,5 and 6	Intersection (Base tinplate + welding)
4	Welding

c: Illustration of micro hardness indentation and respective identification
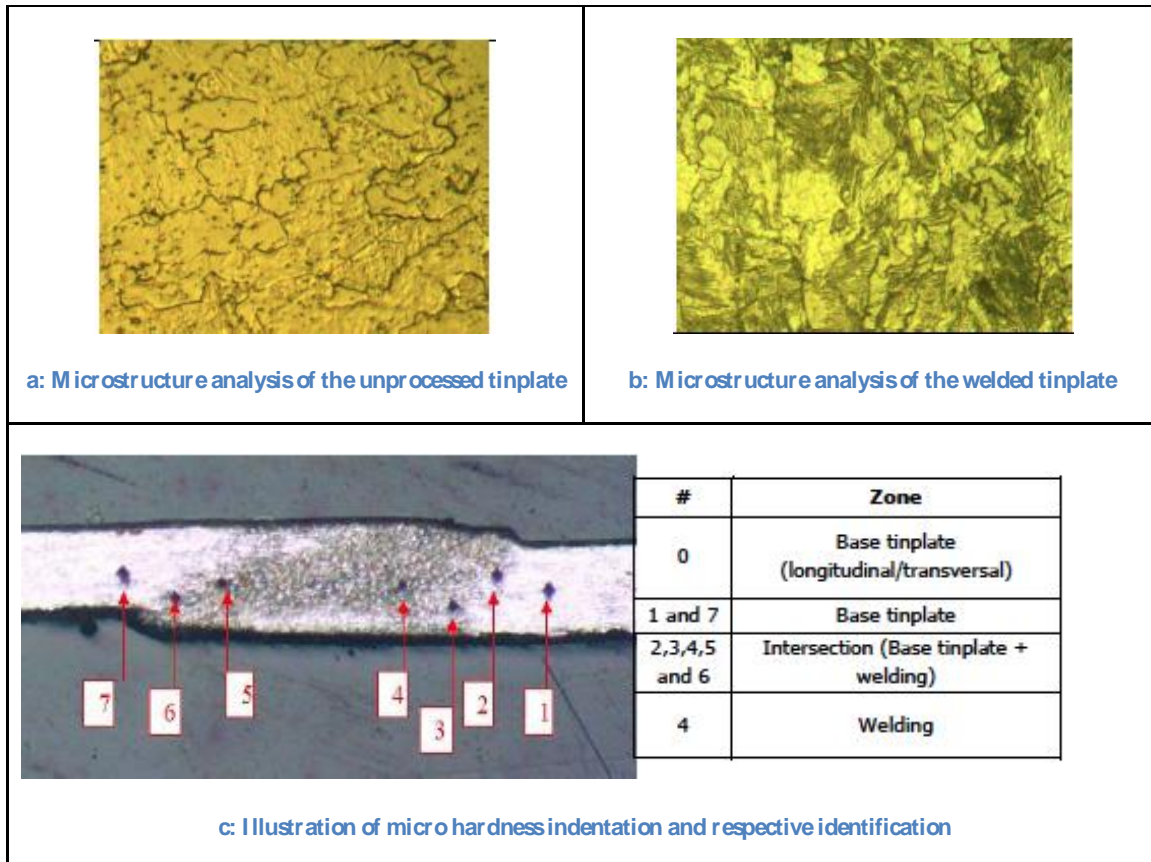
Figure 41: Analysis of the research work

An important conclusion of the research was that the industry sometimes receives material from suppliers that is not in accordance with the established specifications. Also, there are no significant monitoring systems currently present in the industry that can investigate the incoming material and provide immediate feedback to the suppliers. A list of important findings is presented below:

- Thickness and low yield strength of the tinplate did not follow the specifications. However, there were no correlations recorded between these properties and the Microleaks;

- Chemical composition was concluded to be out of specification for a reduced number of suppliers;

- Microstructure analysis for non-processed material showed regular structure, with the exception of a reduced number of suppliers that had coarse enlarged grains. Also, there were no correlations found between these analysis and the Microleaks;

Important recommendations of the research were:

- Monitor tinplate´s key quality characteristics through investing in monitoring systems;
- Add a heat treatment process after welding process to reduce its localized hardness and increase its ductility. This could be made, for instance, with a resistance spot welding;
- Investigate the application of a non-destructive test like Eddy Current process to measure and reject any discontinuity after the welding process.

3.9.2. Welding and forming processes

The objective of this work was to perform a deeper analysis of the deformation processes (welding and seaming) of aerosol cans in order to reveal correlations between the deformed tinplate and the Microleaks. Furthermore, another aim of the research was to analyze current technologies, investigate improvements and propose alternative technologies for future implementation.

The work plan developed to achieve the aforementioned objectives were the following:

- Macroscopic analysis of aerosol cans: in this analysis lateral expansion (called extrusion) of the welding seam was investigated, as shown in Figure 42 (a);
- Microscopic tests of welded cans: further in depth analysis was performed to investigate the metallographic structure of the welded cans. In this analysis, seam thickness, total length of the seam, cracks and overlaps were observed as shown in Figure 42 (b) and Figure 42 (c);
- Process deformation measurement: strain evaluation of the aerosol cans was performed and the method selected was grid marking, as shown in Figure 42 (d);
- Welding body tensile test: the tensile tests of welded aerosol cans were performed for multiple supplier's data and compared with the international standards.

a: An example of a macroscopic analysis	b: An example of a metallographic analysis
c: Another example of metallographic test showing crack in a conform can	d: The process of strain evaluation (grid marking)
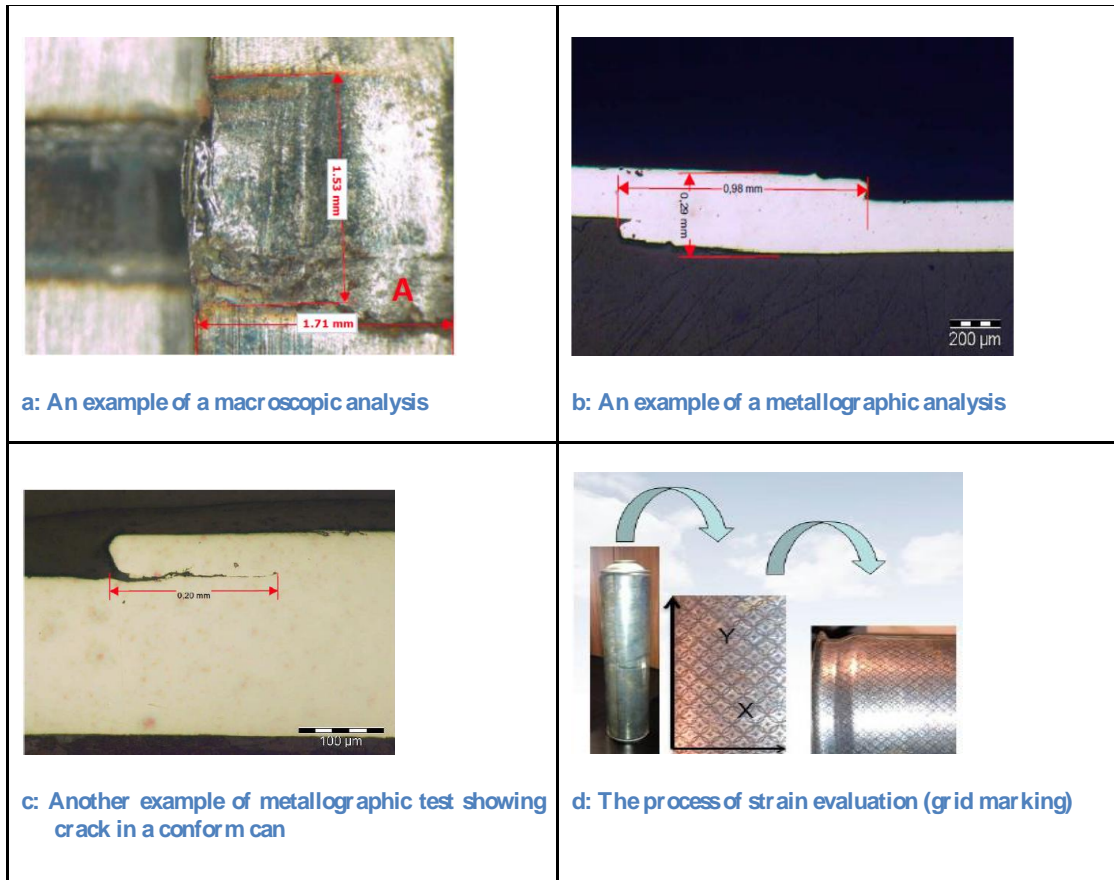
Figure 42: Analysis of the research work

The tests performed in this research work package were aimed at investigating the deformation processes. In particular, the welding process was investigated in detail and the results showed directions for future research. Nevertheless, these results do not point to any significant root cause, neither any particular correlation with the Microleaks. The main results were:

- The macroscopic and microscopic results illustrated interesting results about the welding seam of aerosol cans. A clear variation in terms of extrusion, thickness, and overlap was found between different regions of the welding seam;

- The tensile tests performed for both welded area and non-welded area were compared with the international standards. The results showed that a reduced number of suppliers are not fulfilling the specifications. Again, these results do not show any correlation with the Microleaks;

The research proposed the following recommendations:

- X-ray imaging system terahertz tomography (3D tests): microscopic and macroscopic two-dimensions tests were performed, showing that the parameters analyzed are varying on a can-to-can basis and it was difficult to find a useful correlation with the Microleaks. As a result, the idea of this proposal is to test aerosol cans in three-dimensions and investigate parameters for correlations;
- Process parameter validation: study the influence of welding parameters on the Microleaks by investigating through microscopic and macroscopic analysis;

- Laser Welding: an application of laser welding to weld the aerosol cans instead of resistance seam welding was proposed. Laser welding allows edges to be butted together, thus reducing the use of material. However, this kind of welding has very slow production speed as well as it requires high investments.

3.9.3. Detection Systems

The objectives of the research work were:

- To investigate the capabilities of current in-house detection systems;
- To quantify the customer claims in terms of leak rates;
- To investigate the type of existing detection systems available in the market that might be suitable for integration into the current system.

The main challenge of this research work was the detection and measurement of leaks that have very high sensitivity, like, for example, 10^{-3} ml/min and above.

The work plan for the detection systems project was:

- Investigate the capabilities of in-house leak detection systems;
- Explore leak detection systems available in the market and discuss the feasibility of integrating these detection systems in the current production system;
- Perform experiments with the leak detection system to quantify leak rates claimed by the customer and establish the acceptable limits.

The most relevant results of this research were the following:

- A leak rate distribution was drawn considering internal records and external claims. The results in Figure 43 shows that the claimed aerosol cans have very small leak rate values compared to the capability of online detection system available in the industry;
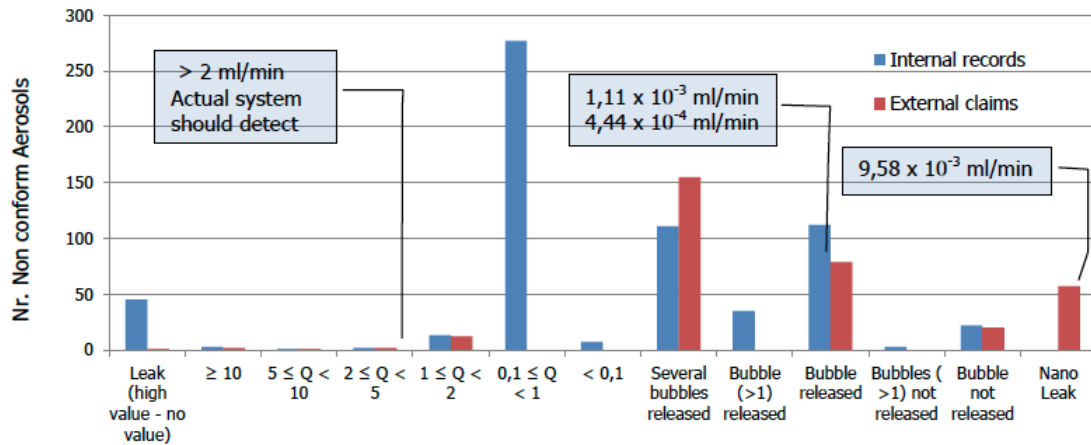
Figure 43: Distribution of leaky aerosol cans in ml/min, considering internal records and external claims

- Along performing experiments in-house using manual waterbath technology, an external company was also contacted to perform leak tests using a gas-tracing method. In this method, samples of aerosol cans were pressurized with helium gas and leaks were detected using a helium sensor mass spectrometer. The capability to detect a leak from such method is in the order of 10^{-6} ml/min;

- The research work on the alternative detection systems available in the market is summarized in Figure 44. These detection systems are compared taking into account the sensitivity to detect a leak and investment costs;

Relevant and important points extracted from the road map proposed in this thesis include the following tasks:

- Perform more tests to further characterize the leak rate;
- Verify alternative leak detection systems with higher resolution;
- Investigate the process parameters and understand their impact on the Microleaks;
- Perform cost analysis of the alternative leak detection systems and analyze their feasibility.
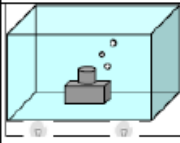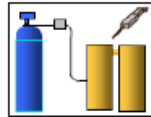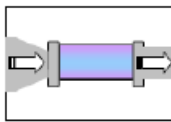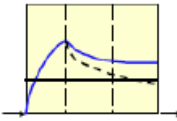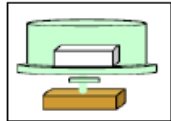
		ADVANTAGES	DISADVANTAGES	APPROXIMATE SENSITIVITY	RELATIVE COST
Bubble ("Dunk") Testing		Simple Inexpensive	Operator dependent/Non-quantitative	10^{-2} to 10^{-3} sccs	$100-$1,000
Trace Gas Sensing		Low Cost, Best as leak locator	Not usable for sealed packages	10^{-4} to 10^{-5} sccs (helium)	$3,000-$10,000
Mass Flow Sensing		Fast response Quantitative	Ambient air pressure sensitive	10^{-2} to 10^{-3} sccs	$4,000-$10,000
Pressure Decay Testing		Quantitative 2-4 sec. Tests	Sensitivity is dependent on part size and test time	10^{-4} to 10^{-6} sccs	$5,000-$12,000
Mass Spectro-metry		Extremely sensitive	Slow, high cost to run and maintain	10^{-9} to 10^{-11} sccs	$25,000-$100,000

Figure 44: Summary of the alternative leak detection systems (sensitivity in ml/min)

Extension of the TME research work:

The research work conducted on material characterization, welding and forming processes, and detection systems demonstrated interesting results. The LTI student further studied the key findings of this research, and the TME students continued their contribution with their valuable insights to the Microleaks project. The key findings that were studied further are:

- An important recommendation that stemmed from this initial research was the study of welding process parameter validation. Design of Experiments was used for this analysis, and the results achieved are promising (chapter 5);

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- Gas tracer leak detection system using hydrogen or helium gas was further explored with the support of external suppliers. The experiments performed to evaluate this technology is further discussed in chapter 6;

- Development of cost of quality model was recommended in all of the three TME research work, being considered a key aspect of the problem. The technologies selected for the cost models were the gas tracer leak detection and other technologies that have been developed later in the project.

Nevertheless, all the significant work performed so far still doesn´t completely answer the relevant question of identifying unequivocally the root cause of the Microleaks. Therefore, this was a key concern for the LTI student from the first moment: the identification of the major root cause. In order to address this problem, in chapter 4 a comprehensive process mapping along with systems engineering methodology will be presented.

3.10. Summary

In this chapter, the Microleaks project was further discussed, and the scope of the project was narrowed down to a single format. Based on the historical data analyzed, assembly line 12 and format 65x300 were considered to be the most appropriate starting point. It was also discussed that after achieving convincing results for this format, extrapolation of the results to other formats and assembly lines will be accompanied.

Considering the scope as well as complexity of the Microleaks, a multidisciplinary team was selected, which includes a project leader, project manager, academic professionals, research specialists, and lead engineers of the company.

The chapter further discusses working principle of all the equipment´s installed in line 12. A preliminary analysis on the leak detection systems is also presented that helped in:

- Determining the capability of in-house leak detections systems;
- Identifying relevant leak detection systems available in the market;
- Establishing leak rate limits according to what customers can measure.

A further preliminary analysis performed using microscopic and macroscopic procedures highlighted welding top and welding bottom of an aerosol can as the key areas of the Microleaks occurrence.

A summary of the work performed by master students, who are lead engineers of the company and were part of the team is also discussed. The key areas of their work include: microscopic and macroscopic analysis of the unprocessed and processed tinplate; metallographic analysis of welded seam of aerosol cans; leak detection systems synthesis; exploring alternative technologies for solving the problem of Microleaks.

Chapter 4 - Process mapping and Development of Non-Conformity Matrix

This chapter first discusses in detail process mapping of the three-piece tinplate aerosol can. Both the high-level and detail level manufacturing processes are explained. In each detail level mapping, those parameters that are important for Microleaks are identified. Then, quality control stations as well as quality characteristics that are measured at each quality station are specified.

The discussion on quality characteristics leads to the introduction of the development of the novel tool "Non-Conformity Matrix". Non-conformities play an important role in the generation of Microleaks, and section 4.3 discusses the challenges faced while collecting all the non-conformities generated along the manufacturing process, as well as systematic analysis performed on these non-conformities to extract valuable results. The important results obtained from this analysis are then further analyzed using quality improvement tools.

The discussion on the novel tool triggered the development of Systems Engineering methodology solving complex manufacturing problems, which require studying multidisciplinary subjects. In order to challenge such complex problems, Systems Engineering principles are applied that integrates technical and management sciences. A 10-step methodology for the specific case of Microleaks is presented.

Section 4.5 of this chapter discusses the analysis of leak locations using quality improvement tools and draws important conclusions for future actions. The next section discusses a general Systems Engineering methodology that can be applied to other similar manufacturing systems.

4.1. Develop detailed process map for the three-piece tin plate aerosol can

A brief product and process overview has been presented in chapter 1. This section discusses the entire production process in detail, highlighting parameters that are crucial for the Microleaks. Also, relevant quality control stations are highlighted at each process step, a procedure that is fundamental for a correct identification of all the non-conformities and further characterization of the problem.

Process Mapping: Aerosol Cans Manufacturing Process

The main objective of process mapping is to quickly understand the key features and bottlenecks of the global manufacturing process. The first step in achieving this objective is to understand what are the high-level and detail-level manufacturing processes. The high level production areas of a three-piece tin plate aerosol can are illustrated in Figure 45, being: incoming material, primary cutting/slitting, coating/varnishing, lithography, secondary cutting, stamping process & assembly process.
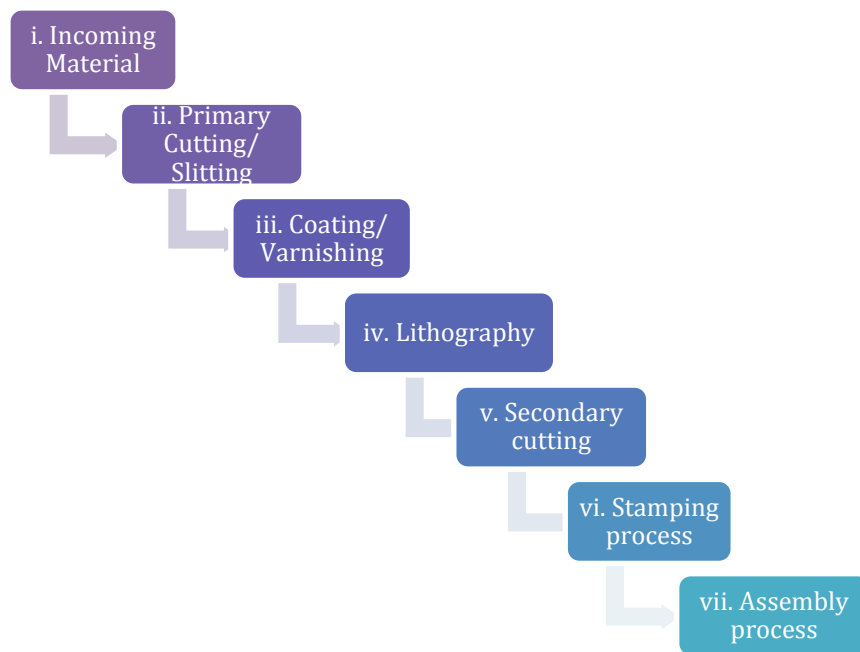
Figure 45: High-level 3-piece tin plate aerosol can manufacturing process

Each of these high level-manufacturing processes will be shortly explained in the next sections.

4.1.1. Incoming Material

The incoming material stage addresses the preliminary steps of the entire production process. It takes place either at the supplier premises or at the material receiving stages of Colep. There are more than six different tinplate suppliers for Colep, out of which two suppliers are the major ones. Altogether, Colep uses for their products approximately 90 references, and each reference is different because of the variations in the aerosol cans, i.e. width, thickness and gross weight.

The process of coil manufacturing begins at the supplier´s production processes. However, only the four steps considered important for retaining the perfect shape, size and quality of the final aerosol product are analyzed in more detail (Figure 46).
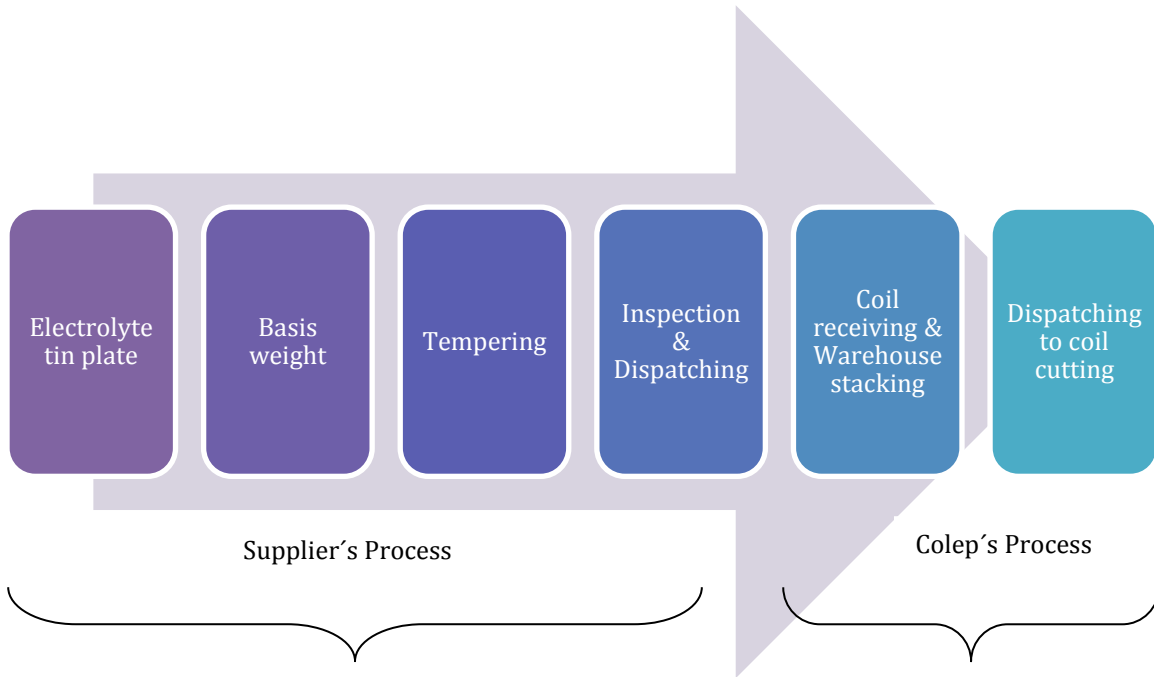
Figure 46: Process Breakdown for the Incoming Material

The first stage of the process shown is Electrolyte Tin Plating (ETP), which is a deposition of a very thin layer of tin by electrolysis process, and it refers to the amount of tin distributed on both sides of the plate. One of the main reasons of this application is to prevent the cans from rust. Tin-free steel is also used depending on the end application. Tin-free steel is electro-coated with a layer of metallic chromium covered by a layer of

chromium oxide. Depending on customers' requirements, tin coating can be different on each side of the sheet. The next stage refers to the basis weight, which is the process of conforming the coil according to the need of the customer, defining the plate thickness in kg/base box (the area of sheet). Then, the next stage of the process is tempering, which is a way of strengthening the plate to a certain level of hardness, which is an important characteristic to inspect the quality of the coil.

Hardness and the size of the coil plays an important role in the quality of the final product, because if any of these parameters do not meet specifications, they may generate additional non-conformities in downstream processes and contribute to the Microleaks in the final product.

4.1.2. Primary Cutting/Slitting

The purpose of the primary cutting process is to cut the coil in flat rectangular sheets. A detailed process breakdown is shown in Figure 47. The coil is first received from the warehouse and is then loaded into a cutting machine named Littel.
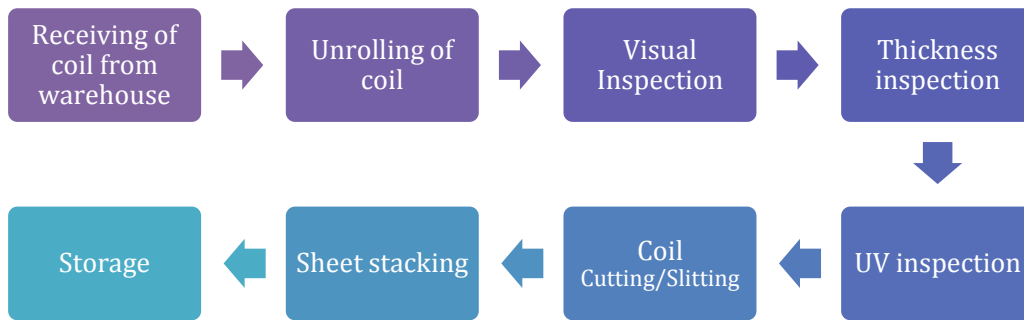
Figure 47: Process Breakdown for the Primary Coil Cutting/slitting process

The Littel machine performs the following operations:

- The metal sheet is unwound from the coil as shown in Figure 48;
- The coil runs in front of two mirrors (top and bottom) to allow operator for a visual inspection process, e.g. detecting large pin holes;

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- Coil runs through a thickness-measuring device (P and W Magnetic Continuous Gauge) with a thickness tolerance of +/- 0.01mm. This device only measures the sides of the coil;

- The coil then runs under an Ultra Violet (UV) pinhole detection with a minimum detection of 0.0254 mm in diameter. When a pinhole is detected, the machine discards 3 sheets, i.e. 2 OK (on either side) and 1 NOK with pinhole;

- The coil runs through the rollers to straighten the sheet (manual adjustment may be needed to ensure that the coil is straight);

- A guillotine then cuts the coil into sheets as shown in Figure 49 - from each coil there can be 1200-1400 metal sheets produced;

- The metal sheets run on a conveyor and are sorted into 2 different stacks;

- The metal sheets are then stored in the inventory area for around 2-3 months depending on the production demand.

Figure 48: Coil cutting process

Figure 49: Rectangular tinplate after the cutting process

In the case of Microleaks, it is important to focus on the pinhole detection, as well as the squareness of the rectangular tinplate. If at this stage there is any pinhole that goes undetected, or any tinplate not perfectly squared, non-conformities might be generated in the downstream processes, potentially leading to Microleaks in the final product.

4.1.3. Coating/Varnishing:

The primary purpose of the coating/varnishing operation is to build a barrier between the can and its contents. The aerosol can should exhibit resistance to chemicals and adhesion to metal surface. The first step of this process occurs when the sheets are unloaded from

the warehouse, followed by an operation of coating them internally with golden plate - this process is called internal coating. The internal coating can be done at the start or end of the process, depending on the final application of the product. A process breakdown is shown in Figure 50.

Figure 50: Breakdown Process for Coating/Varnishing (* Lithography is not a part of the varnishing process)

The internal coating, primary and secondary varnish have similar process steps and are showed in more detail in Figure 51. Colep has three dedicated lines for these processes. After the internal coatings, the next process is primary varnish followed by lithography. Lithography is not part of the varnish process; therefore it is discussed separately in the next sub-section. The secondary varnish is the last process in this high-level process breakdown, being an operation that is optionally applied to some products. Normally it is applied with the purpose of decoration, to protect the can from corrosion, to protect the printed designs from marring or abrasion, and to reduce friction in the bottom of the can in order to facilitate handling.
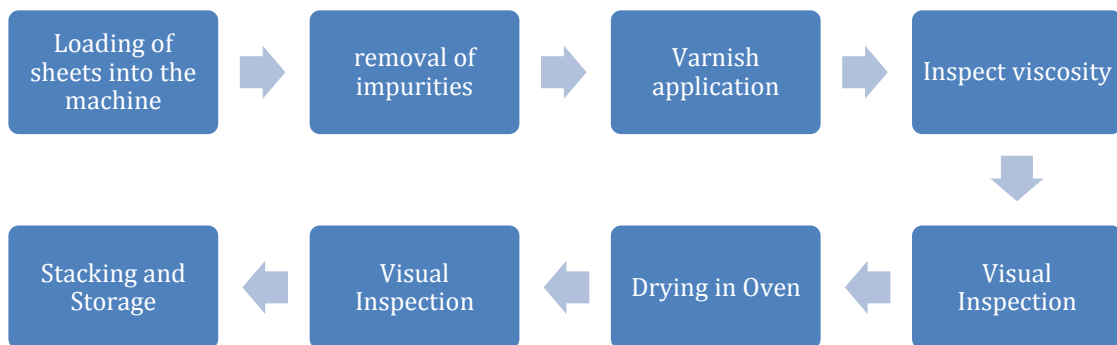
Figure 51: Process breakdown for internal coating, primary and secondary varnishing

The complete process steps for the internal coating, primary and secondary varnish are the following:

- The sheets are placed on the loading dock and driven through the rollers on the conveyor belt;

- The sheets pass through a burner in order to remove any impurities (coating is very thin and can easily have problems with dirt and dust);

- The varnish is then applied with the use of a roll;

- After the varnish, the inspection process takes place. For example, the viscosity meter is used to inspect the varnish viscosity and team members inspect visually the width of the weld area and humidity weight;

- The varnish is then dried in the oven;

- The second visual inspection is performed just after drying the sheets in the oven to inspect the weight of the sheet with varnish;

- The sheet is then stacked and stored in the warehouse for the next production step.

The importance of this process for the case of Microleaks is to make sure that there is no varnish present at the welding area of the tinplate. If there is some varnish left at the weld area during this process, then the welding process will not be smooth and perfect and may lead to Microleaks in the aerosol cans.

4.1.4. Lithography

The process of lithography is only performed to sheets that are later transformed into the shape of an aerosol body. The sheets required for aerosol tops and bottoms are not lithographed.

Lithography is a decoration that may be printed on the aerosol body or on paper labels that are then glued onto the aerosol cans. This process is done between the primary and secondary varnish process. Colep is producing only one kind of lithography, which is direct printing on the aerosol cans. Colep has total five dedicated lines for Lithography, two of them are conventional and three of them use modern technology, i.e. Ultraviolet (UV) Radiation cured coatings. The Ink used for printing must be cured because it is influenced by environmental factors, like humidity and temperature.

Although the UV coatings are expensive, they have advantages over the conventional ones, such as, (1) showing rapid curing, (2) being environmental friendly, (3) using low

process temperatures and low energy costs due to the elimination of drying ovens and (4) occupying less space than conventional lithography machines.

Similar to the vanishing process, the importance of the lithography process for the case of Microleaks is to avoid overlap of lithography imprints on the welding area, which can cause barriers in the formation of proper nuggets during the welding process.

4.1.5. Secondary Cutting

In the secondary cutting process, the lithographed sheets are cut in the shape of an aerosol body. Non-lithographed sheets are directly received from the coating/varnishing process and are cut in the shape of tops and bottoms of an aerosol body.

The tops and bottoms are produced using the scrolling machine, which enables a better utilization of the material by minimizing the waste, as shown in Figure 52. Colep has six scrolling machines in the production line, with two machines dedicated for general line products (i.e. food and industrial products) and four machines dedicated for aerosols cans.
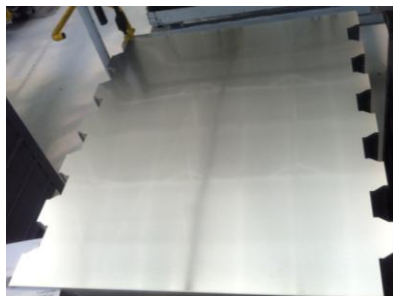
Figure 52: Scrolled sheet for tops and bottoms

Although the body, tops and bottoms are produced from different type of sheets, the sequence of operations is almost the same for both sub-products, as described below (as well as shown in Figure 53):

- Each sheet is individually pulled automatically into the machine;
- A visual inspector verifies the sheet is turned correctly, by analyzing the orientation of the product bar-code;
- The sheet passes through the blades and is cut vertically;

- The sheet passes through rulers that separate the sheet in individual strips;

- The strips belonging to the same sheet are cut in parallel into individual package layouts;

- The operator takes these individual package layouts and stacks them on a pallet;

- The end product is ready to be used in the stamping and assembly plant.

feeding sheets into the machine → visual inspection → vertical cutting → separation of the strips → horizontal cutting → stacking and storage
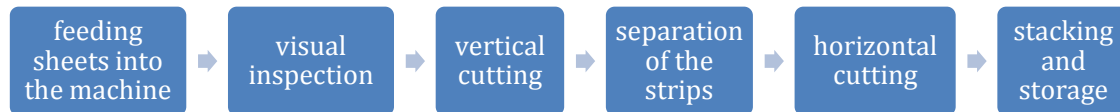
Figure 53: Process breakdown of Body and Tops and bottoms

To assure that the production of the body fulfills the required specifications, the following parameters are controlled and inspected: squareness, waviness and burs. These parameters are critical to control, because if the body is not perfectly cut according to the requirements, non-conformities might be generated either at stamping or especially at the welding processes, and those non-conformities might later generate leaks or Microleaks in the final product.

4.1.6. Stamping:

Only tops and bottoms of an aerosol can require the stamping process, following separate and distinct operations – the main features of this process will be further detailed below.

Top manufacturing

A detail level process breakdown for top manufacturing is illustrated in Figure 54. The scrolled sheets that are received from the warehouse are fed into the stamping machine. Then, the cutting operation of the scrolled sheets into smaller discs takes place. After this operation, the discs are punctured and deformed in a cup shape following blanking and drawing operations.
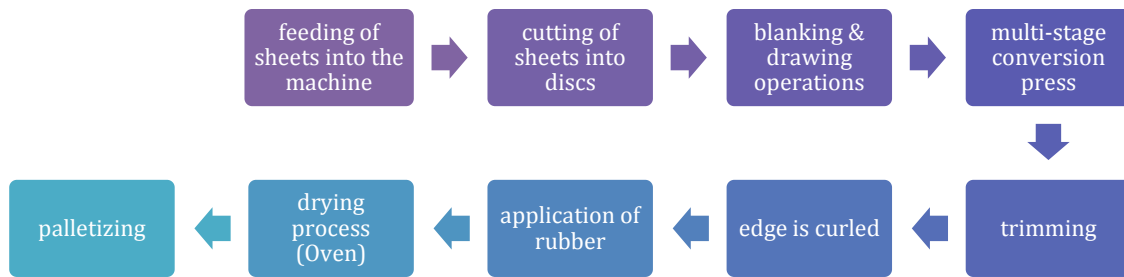
Figure 54: Process of Top manufacturing

The formed cup is then transferred through a multi-stage conversion press. It is important to note that the number of operations in a multi-stage press varies with respect to the product. In order to remove the edges that are formed in this operation, the cup is then trimmed and the edge is curled.

The next operation is the application of a rubber compound (as shown in Figure 56), which serves as a gasket in the double seam, ensuring a powerful seal, more resistant to any type of leakage. In the absence of rubber compound, chances are extremely high for double seam to generate leaks and Microleaks in the final product. The top is then passed through the oven to dry down the rubber compound, which is then stacked and ready for the assembly operation (as shown in Figure 55).

Figure 55: Top after stamping and application of rubber (Outer area)
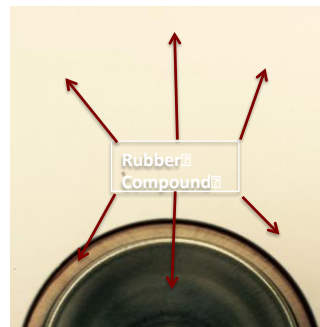
Figure 56: Top after stamping and application of rubber (inner area)

Bottom Manufacturing

Manufacturing the bottom part is comparatively easier than the top. The number of operations is thus lower than the number of operations to produce a top, but most of the

operations are similar. The main difference is at the blanking operation, where the blank is punched and the bottom is formed; i.e. only a single operation of stamping is required. Figure 57 shows the low-level process breakdown for bottom manufacturing.
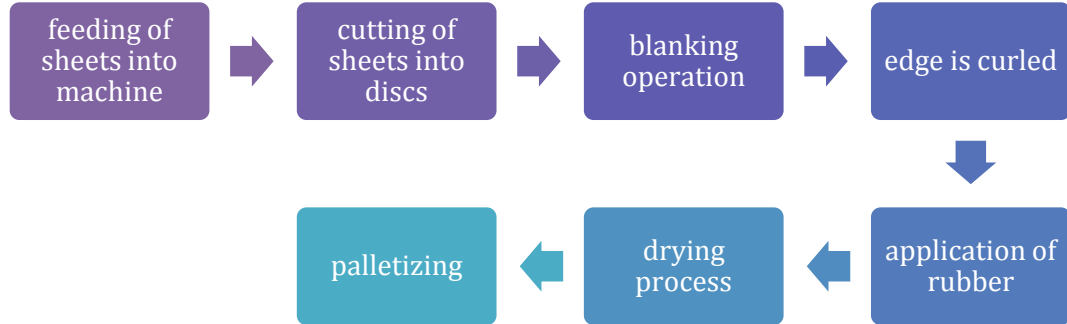
Figure 57: Process breakdown of Bottom manufacturing

Figure 58 and Figure 59 illustrates the final product of this process. Similar to top manufacturing, the rubber application is an important parameter in terms of leaks control.

Figure 58: Bottom after stamping and application of rubber (Outer area)

Figure 59: Bottom after stamping and application of rubber (Inner area)

4.1.7. Assembly

In this process the rectangular tinplate is first transformed into a cylinder, called aerosol body, with a standard overlap as shown in Figure 60. The method of resistance welding is applied to weld the overlapped surface, where two rollers press the aerosol body between each other. Then, varnish is applied to the entire weld areas of the can, behaving as a protective layer to the welded area. The aerosol body is then passed through a series of ovens to cure the varnish material.
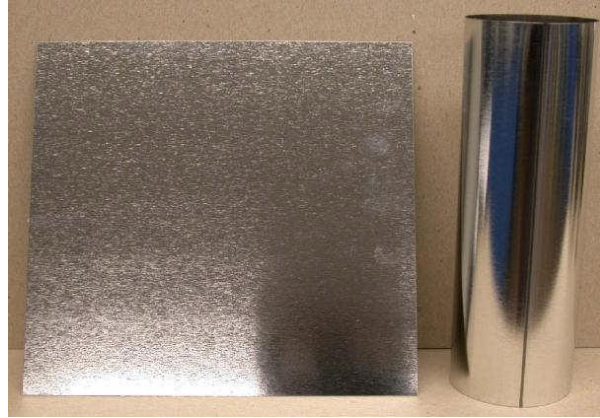
Figure 60: Transformation of rectangular tinplate to aerosol body

The aerosol body is then necked (necking process), a process that reduces the diameter at the top and bottom to give a cosmetic/appeal shape. As this process is not mandatory, it is applied in a reduced number of products. The next operation is flanging, where the cylinder is flanged and later becomes the body hook for the finished double seam (see Figure 61 and Figure 62).
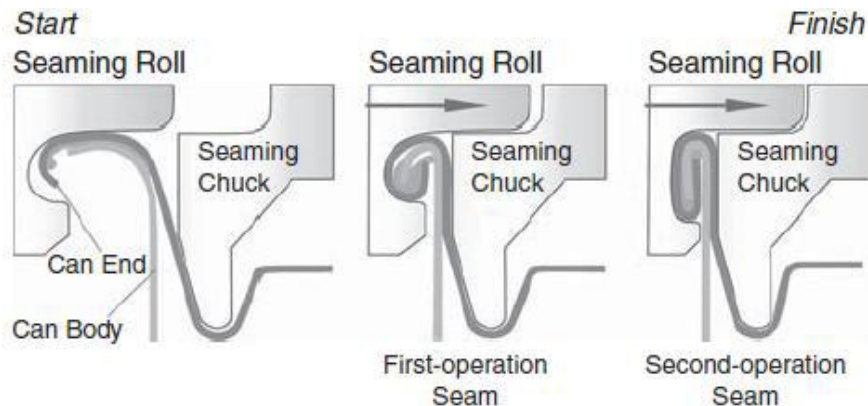
Figure 61: Seaming Process

Tops and bottoms are then assembled with the welding body using a double seam process. This is achieved first by seaming one end, top or bottom, then the other end. The seam is a three head operation, the first head aligns and deforms the body, the second head roles both bodies together, and the last head presses the rolled bodies together producing a hermetically tight seam. The aerosol body after the seaming process is called an aerosol can.
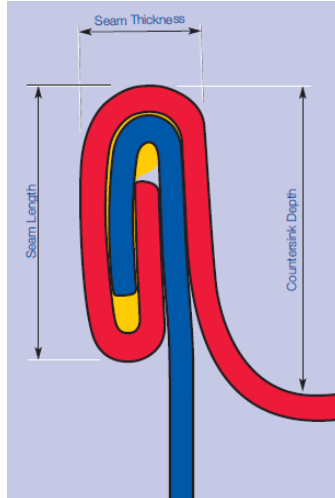
Figure 62: Double seam

The final stage of the assembly process is the testing of aerosols in order to detect possible leakages. As it was already discussed in chapter 3, there are two different kind of leak tests done at Colep, i.e. Automatic and Manual testing. Automatic testing is done at the automatic leak detection machine (named Wilcomat), which tests 100% of the produced aerosols. Whereas, the manual waterbath leak testing is performed on a sample and after the 100% automatic leak testing. A manual test is based on a sampling plan because of the difference between the production speed (200-280 cans/min) and sampling speed (6 cans/min). A detail analysis on the acceptance sampling schemes is presented in the chapter 6. Figure 63 shows the breakdown process for assembly and testing processes.
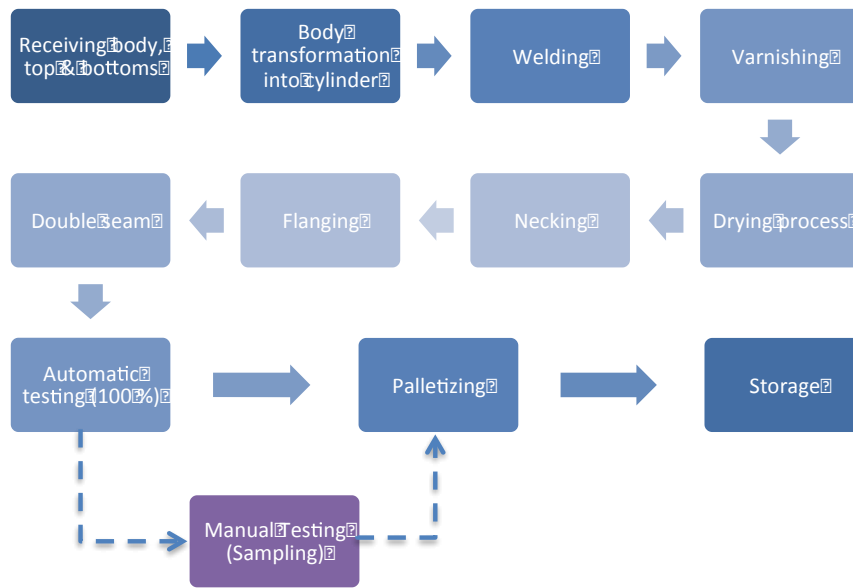
Figure 63: Process Breakdown for Assembly

In case of the Microleaks, both the welding process as well as the seaming process are considered to be key. In fact, it is common knowledge that if these processes are not perfectly fine-tuned, a high number of non-conformities might be generated, i.e. a high number of leaky aerosol cans.

The entire process of the three-piece tinplate aerosol can is comprehensively mapped as a single-flow, as illustrated in Figure 64 to: (a) clearly follow the process flow; (b) understand the inputs and outputs of a process; and (c) help in the identification of the quality control stations, as well as the quality characteristics measured at each station.
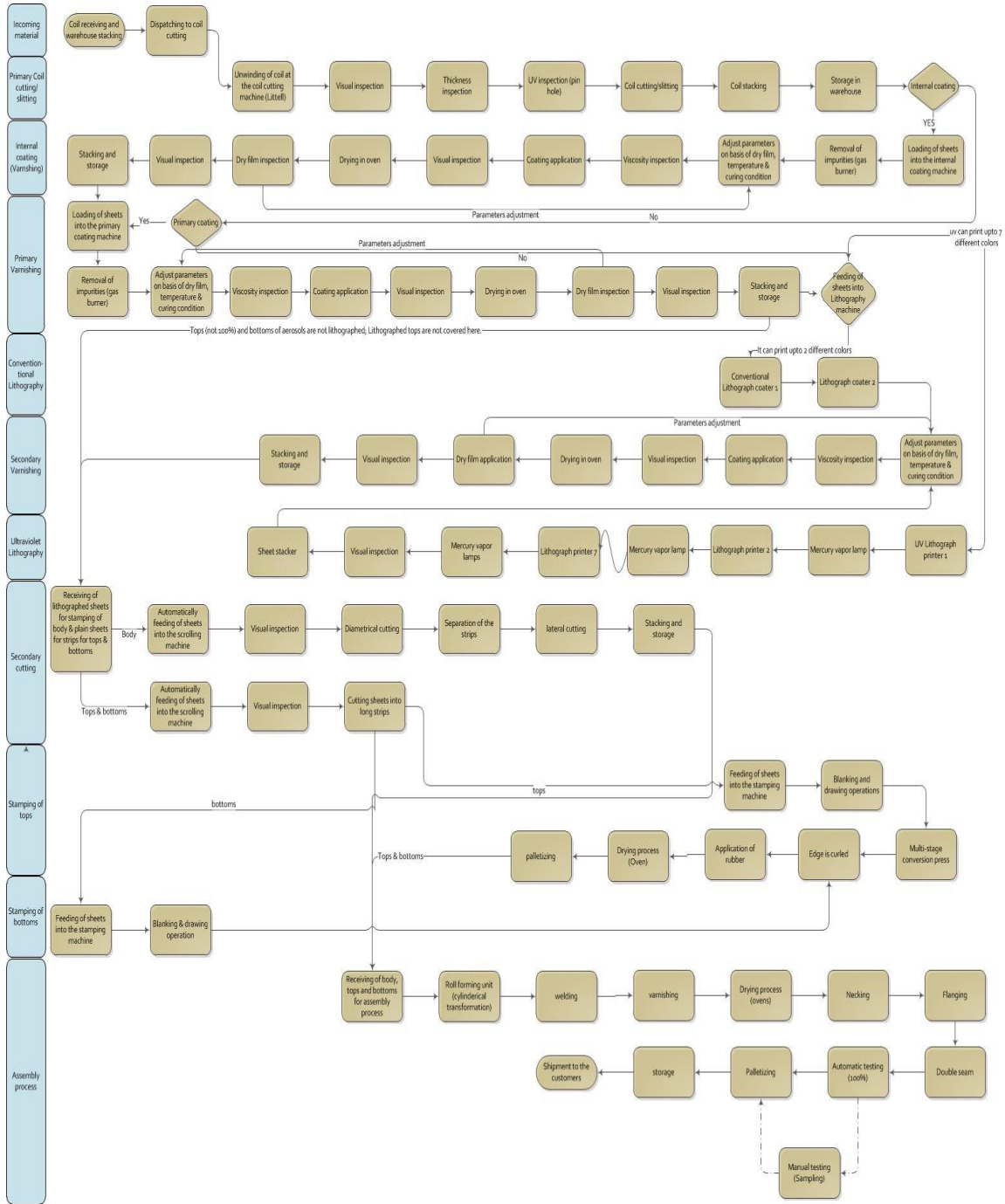
Figure 64: Single flow process flow of a three-piece tinplate aerosol can

A comprehensive work regarding the identification of quality control stations, which quality characteristics are measured at each station, as well as the type of inspection method used is presented in the next section.

4.2.   Identify quality control points relevant to the problem identified

This section discusses the most relevant quality characteristics at each step of the manufacturing process, explaining which quality stations are more critical for the occurrence of Microleaks. This is achieved through a detailed analysis of the processes, a careful interpretation of the available documents, as well as interviewing several people on the shop floor. First, a high-level process map (based on the detailed map of Figure 64) was designed, highlighting only the processes that have a quality control stations (Figure 65).

Each quality control station inspects a particular quality characteristic, in order to guarantee that the final products are according to specifications. Identifying these quality characteristics was possible with the available documents as well as knowledge of key people working in the company, in different functions and with different levels of responsibilities, since no single person is aware of all the technicalities and details of the complete production process. Thus, the initial list of quality characteristics was built with the help of the available documents as well as most knowledgeable people in each production process, by systematically asking them:

- Which process does a particular quality control station follow?
- What quality characteristics are measured in each quality station of the production process?
- How does each of the quality characteristics measured/inspected?

These questions helped the identification of all the quality control stations present in the production line, as well as the understanding of what are the quality characteristics measured at each quality station and what type of inspection method is used. The summary of these findings is depicted in Table 9.
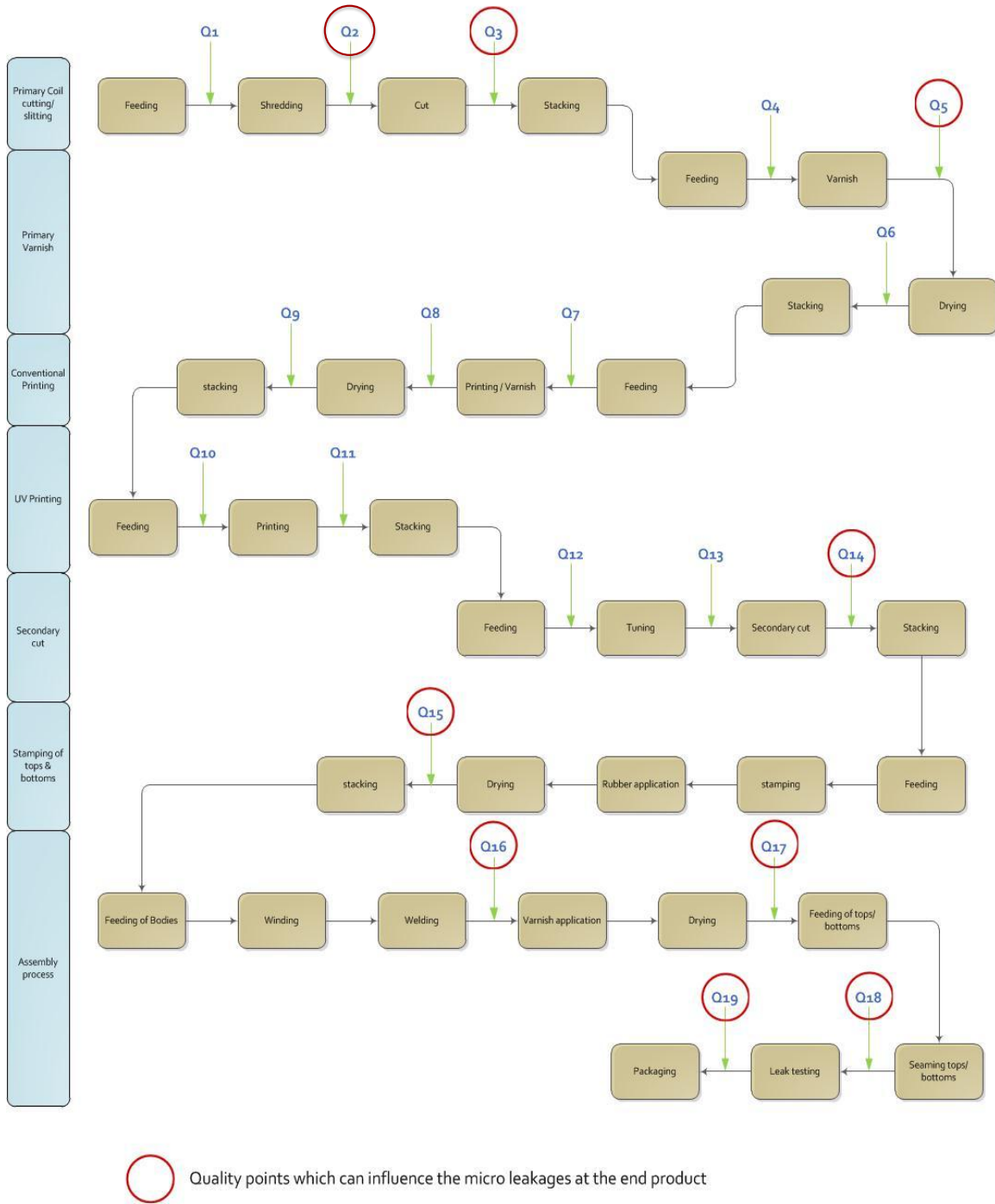
Figure 65: Quality control stations for a three-piece tinplate aerosol can

Table 9: Quality characteristics measured at each quality control station

Quality control stations	Type of quality characteristics measured	Type of inspection method used
Q1	Visible defects (e.g. leaf appearance)	Visual inspection
Q2	Porosity	Automatic porosity detector
Q3	Coil dimension Coil hardness Coil thickness Wrinkles Sheet squareness Sheet curvature	Measuring scale Hardness tester Thickness gauge Visual inspection Manually using a scale Visual inspection
Q4	Viscosity of varnish	Viscosity meter
Q5	Squareness Color pattern Weight of wet film	Manually using a scale Visual appearance Weight machine
Q6	Weight of dry film Porosity Adherence Varnish Curing Varnish Varnish Hardness	Weight machine Porosity detector Visual inspection Visual inspection Hardness tester
Q7	Viscosity of varnish	Viscosity meter
Q8	Printing process: Squareness Check Standard color Varnishing process: Squareness Weight of wet film	 Manually using a tool Visual appearance Manually using a tool Weight machine
Q9	Weight of dry film Porosity Adherence varnish Curing varnish Hardness varnish	Weight machine Porosity detector Visual inspection Visual inspection Hardness tester
Q10	Identification of color	Visual inspection
Q11	Squareness Check Standard color Adherence UV color	Manually using a tool Visual appearance Visual appearance
Q12	Burr Poor stacking	Visual inspection Visual inspection
Q13	Dimension of an aerosol body Burr	Measuring tool Visual inspection
Q14	Squareness Burr	Manually using a tool Visual appearance
Q15	Dimensional control Weight of rubber "Porosity (Just for Interior Varnish)	Measuring tool Weight machine Porosity detector
Q16	Proof of chunking Verify the start and end of welding	Visual Control Visual Control
Q17	Analyzing the varnish of weld area: Porosity Adherence (internal) Water absorption (net) Weight (powder) Curing (powder)	 Visual Control Weight machine
Q18	Control of seams	Visual Control
Q19	Leak testing	Automatic leak detection Water bath manual testing

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The quality characteristics listed in Table 9 are measured as a Standard Operating Procedure (SOP) in the industry. NCs are typically generated when these quality characteristics are out of specifications. For example, in Q14 station, the burr and the squareness of a rectangular tinplate sheet are tested after the secondary cutting process and in case these characteristics are out of specifications, NCs are generated. These NCs have a compounding effect downstream to the manufacturing process, and may (or may not) trigger Microleaks. Therefore, these NCs require a systematic analysis in order to allow a better understanding of the dependencies between them as well as its relationship with the occurrence of Microleaks. This systematic analysis of the NC is performed in the next section, with the help of a novel tool named Non-Conformity Matrix.

4.3. Development of a Non-Conformity Matrix (NCM) tool

Non-conformities (NCs) and non-conforming products originated along production lines are not always easily identified and analyzed. This is due to the multiple sources of variability present in any manufacturing environment, as well as to the complex correlations that exist between NCs. Similarly, despite knowing the fact that occurrence of Microleaks is the consequence of NCs generated along the production processes, the production team was not always clear in identifying the relation between the non-conformities i.e. which NCs generate which NCs and which NCs contribute more in the generation of Microleaks.

In order to have a systemic view of all the NCs and their dependencies, a new tool has been developed in this thesis based on DSM principles (chapter 2, section 2.4) in order to evidence and understand how NCs relate between each other and generates defects on products. This new tool, labelled Non-Conformity Matrix (NCM), allows to understand which NCs are the most important, which groups of NCs are related among each other, which NCs influence the final quality and which ones do not. This new tool is suitable for complex production processes, highlighting the processes and operations that are less reliable in the manufacturing processes, prioritizing the ones that should be the focus of the quality improvement teams.

This section is organized as following: First, the process of development of a good NCM, as well as the importance of how the data is collected to fill up the NCM is presented. This process has led to the development of three NCMs based on the knowledge of several stakeholders. A comparison analysis is performed among the three NCMs in order to choose the most appropriate for further investigation. Then, mathematical operations are applied on the selected NCM to highlight key areas for further analysis. At the end, a complexity analysis is performed using components modularity metrics.

The process of developing a NCM tool has faced several challenges. The first critical challenge was the identification of all the NCs generated along the production line. So, in order to be completely exhaustive and in addition to the information gathered about the quality characteristics evaluated in each quality station and the NCs along the production line (section 4.2), interviews with experts were conducted. This time the focus was more on the NCs terminology, rather than about the quality characteristics. The initial list of NCs was built with the help of the most knowledgeable people in each production process, by systematically asking them the following questions (Tavares et al. 2013):

- What NCs are measured in each activity of the production process?
- What NCs directly or indirectly affect the quality of the aerosol can?

The answers to these questions were used to list down the initial 65 NCs (also include NCs identified in the previous section), number that was later reduced to 46 NCs, after performing a second interview with the line managers. This second interview was required because DSM models represent extensive system knowledge and it is difficult to initially build them, as they depict data that are not always at hand, easily collected, or quickly assimilated. In fact, due to the difficulty in gathering accurate responses from the vast group of people involved in the process, building the initial DSM models was really challenging.

Reality shows that people tend to respond according to their prior beliefs and misconceptions about the way the process and/or machines work, conditioning the end result. According to Browning (2001) people associated with the specific activity under analysis tend to be more knowledgeable of their required inputs and outputs than of the

desired objective of the interview. As a preliminary conclusion, it can be said that the process of reducing the number of NCs in the matrix has a large impact on the time and effort required for a more comprehensive analysis of the NCM, so this process needs to be thorough.

Three iterations were performed to build a good NCM, resulting in three different NCMs: a Baseline NCM, an Experts input NCM, and a Corrected NCM. The type of DSM convention used to model all the NCMs is anticlockwise (chapter 2, section 2.4), meaning that when scanning down a column reveals output sinks and scanning across a row reveals input sources. Furthermore, NCMs are parsed by the high level manufacturing process, i.e., primary cutting, varnishing & lithography, secondary cutting, and stamping & assembly. Each of the NCMs is comprehensively explained below.

4.3.1. First Non-Conformity Matrix (baseline NCM)

The second challenge in a NCM tool development is revealing relations and interactions between the identified NCs. The 46 NCs were transferred into a matrix form with the help of the Cambridge Advanced Modeler (Wynn et al. 2010), generating a 46x46 matrix, having 2116 cells with 46 non-working cells (the diagonal elements), as shown in Figure 66. In fact, 2116 cells is an impressive number, particularly when considering that all cells require detail and thorough analysis.

The first NCM, called baseline NCM, was built based on the knowledge of the authors and available documents of the company. There are several challenges in building a NCM like this, such as the high number of written documents available that require processing, the search for specific knowledge in order to fully understand not immediate correlations, and finally, the inherent complications that arise when a quite recent methodology is used in a total different context (Farooq et al. 2014).

The NCs were filled with marks through exploring its interactions with other NCs. For example, NC1 (coil thickness) in primary cutting has interaction only with NC3 (coil dimension) and NC 7 (Wrinkles).

Figure 66: Baseline NCM

The first few rows and columns, corresponding to the first stages of the production process were occupied more quickly with interaction decisions, because most of them have no inputs. After completing the overall process of interpreting the interactions, only a small number of NCs were left without a thorough explanation or without any clue to estimate the interaction. Therefore, as it will be seen in the next section, the help and input of experts at each high-level activity of the production process played a fundamental role in uncovering and revealing interactions between the NCs.

4.3.2. Second Non-Conformity Matrix (experts input NCM)

Due to high complexity of the system it was immediately understood that it would be impossible to reveal all the relations and interactions between all NCs in the first iteration. Therefore, in order to gain a more comprehensive understanding of the process and incorporate missing information, it was decided to conduct extensive interviews with company experts (Farooq et al. 2014).

The second NCM was built with the additional information conveyed by these interviews with the key experts and the most knowledgeable employees, for each high-level production process. Each expert answered individually the following questions (Browning 2001) (Farooq et al. 2014):

- What output does the non-conformity produce?
- Where do these outputs come from (another non-conformity or outside the process)?
- What input does the non-conformity need?
- Where do these inputs go to?

The answers to these questions were used to fill in the rows and columns of the second NCM, named as "experts input NCM" (Figure 67). For example, the non-conformity "wrinkles" (seventh in the NCM list) produces no other output (non-conformity) within the primary cutting process and needs input from coil thickness (first in the NCM list) and coil hardness (second in the NCM list). This type of analysis was performed to all the other non-conformities, and it quickly became clear that the interactions marked in the first NCM were incomplete. In order to reduce the complexity of the process, NCMs were built separately for each high-level production process, as a result of separate interviews with the process experts. It is curious to highlight the fact that sometimes they require the help of other process experts with broad working experience in order to gain further understanding of the process, as no single person has a complete knowledge of every element interactions. As the separate filling of these high level NCMs were completed, then these individual NCMs were combined into one large NCM, with all the NCs of high level production processes sequenced chronologically from top to bottom and left to right (Farooq et al. 2014).

Interviewing with the experts also facilitated in reducing further the dimension of the NCM from 46 to 44 NCs. For example, the NCs "burst" and "body height", which are not related to the Microleaks under analysis, were removed from the list. After completing this process, the resulting NCM was a 44x44 matrix having 1936 cells with 44 non-working cells. Figure 67 shows the second NCM having 44 NCs arranged in chronological order of the high-level production process (Tavares et al. 2013).

Figure 67: Experts input NCM

The NCM has two outputs in each high-level production process for the same inputs i.e. internal output and external output. The interviewers were asked if the output of an element is produced from the element of the same high-level production process, called internal output, or if the output of an element is produced from the element of the different high level production process, called external output. Typically, most experts faced difficulties in eliciting external outputs, due to the lack of Systems Engineering thinking, difficult to achieve when you are highly specialized in a particular operation/process. For example, Figure 68 shows a matrix highlighting internal and external outputs for varnishing and printing process (inputs of NCs from 8 – 22).
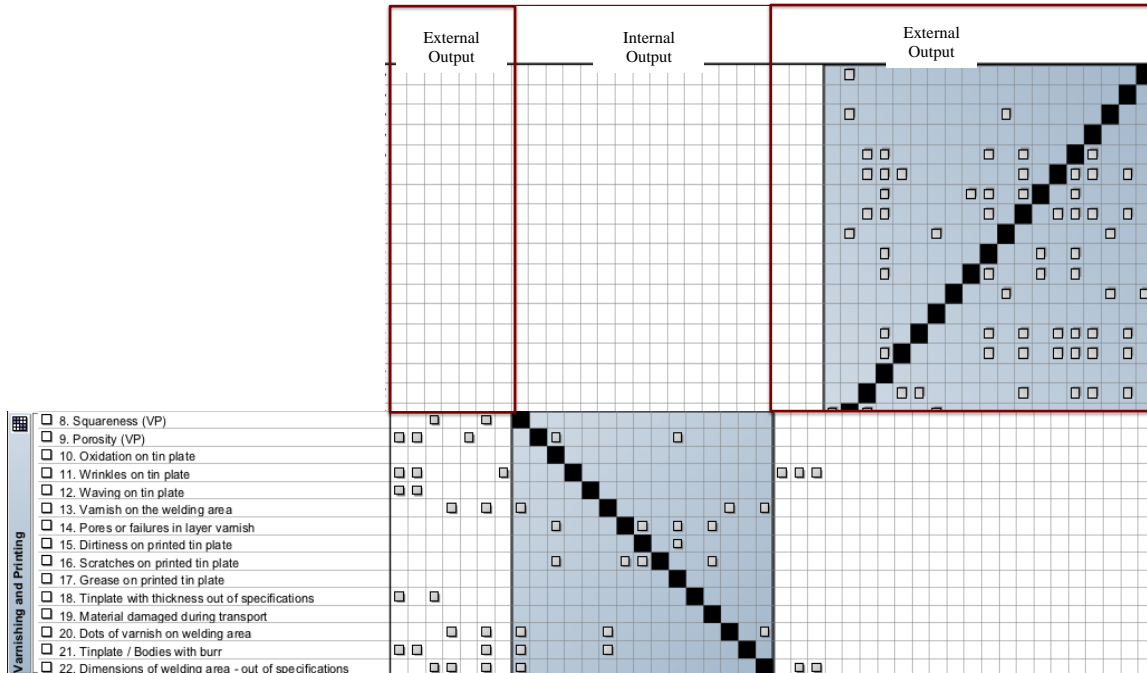
Figure 68: An example of internal and external outputs showing varnishing and printing process for experts input NCM (inputs of NCs from 8 – 22)

NC number 8 "Squareness" (first NC in varnishing and printing process) produces output to two of the elements of primary cutting process i.e. external output, while there is no output produced within the varnishing and printing process i.e. internal output.

4.3.3. Third Non-Conformity Matrix (corrected NCM)

The experts input NCM was made interviewing individuals of each high-level production process. The experts were handed over only the NCs, which are related to their usual function including the external effects of that function and not the complete matrix. For example, experts from the varnishing and printing function were handed over the complete rectangular matrix as shown in Figure 68. The reason for this procedure is two-fold: first, by only evaluating the relevant portion of the matrix that is related to their knowledge, they are not overwhelmed by the size of the overall matrix. Thus, the perception of the required amount of time to accomplish the task is feasible; secondly, it was acknowledged that typically they had little or no clue as of how to estimate the interactions for the rest of the matrix, so the effort of showing the complete NCM didn´t pay off. Plus, other than the advantage of reducing the rows of the second NCM, these

experts were more attentive of their required inputs, rather than the overall effect of Microleaks in the final product (Farooq et al. 2014).

In order to consolidate the final NCM, a brainstorming process was conducted among the project team members. The advantage of performing this additional process is to have an overall overview and understanding of all the NCs, and its impact on the final quality. Accomplishing this phase leads to the development of the third NCM called the corrected NCM as illustrated in Figure 69.

Figure 69: Corrected NCM

The difference between the second and third NCM is very small, with only 31 different cells out of 1892 (1.6%). Authors considered the corrected NCM as the most appropriate for further analysis because of its completeness. A comparison is presented among the three NCMs in the next section to demonstrate why the corrected NCM is the most appropriate among the three.

4.3.4. Comparison among the three NCMs

The three NCMs were compared for the number of rows and number of interactions as well as the ratio between them. Table 10 shows the comparison among the three NCMs built. It is clear from the interaction column that the baseline NCM, which was built based on available documents and a single person knowledge, although presents a higher number of non-conformities (number of rows), shows a smaller number of interactions when compared with the Experts Input NCM and the Corrected NCM. In fact, the additional advantage of interviewing experts and team members is to reveal the missing interactions that may be critical. This table highlights the fact that the system level information exists mostly in peoples´ heads (Farooq et al. 2014).

Table 10: Comparison among the three NCMs

Iterations	Number of rows	Number of interactions	Ratio interactions to rows	How
1st - Baseline NCM	46	150	3.2	Available documents
2nd - Experts Input NCM	44	202	4.6	Interviewing experts
3rd - Corrected NCM	44	233	5.3	Interviewing project team members

In the next sections, only the corrected NCM is further analyzed by applying analytical models, such as sequencing algorithms. Furthermore, the complexity of the corrected NCM was evaluated by measuring modularity metrics using components modularity metrics.

4.3.5. Application of mathematical operations to the corrected NCM

The "corrected NCM" was built using the Cambridge Advanced Modeler (Wynn et al. 2010). This modeler allows performing several mathematical operations on the DSM in a very expeditious way. Many different operations were applied to the "corrected NCM", but some of them didn't help in reducing the matrix apparent complexity. Thus, only the operations that were most successful in reducing the matrix apparent complexity are reported (Tavares et al. 2013).

The "corrected NCM" (see Figure 69) is already parsed by the high level manufacturing process. Nevertheless, inside each manufacturing process the order of appearance of the NCs is random. In all the successful operations done to the matrix, the high-level production processes were kept as primary clusters, and then operations of sequencing (time-based DSM – see chapter 2, section 2.4) inside these primary clusters were performed. Sequencing operations across the complete matrix (i.e., without any of the high level production process clusters) were carried out, but the resulting matrixes seemed even more complex than the original "corrected NCM". The sequencing operation inside each of the four high level manufacturing process clusters resulted in an apparently less complex matrix (see Figure 70), with most marks below the diagonal (lower triangular matrix). Also the marks above the diagonal appeared now much closer to the diagonal than before (Tavares et al. 2013).
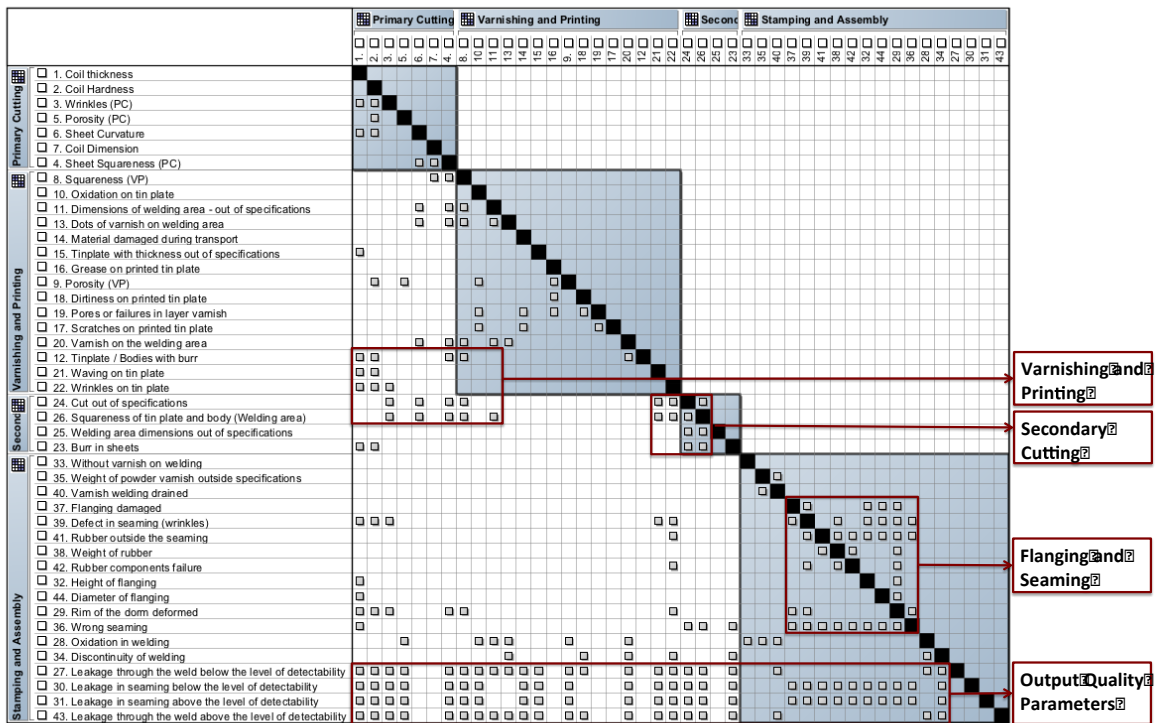
Figure 70: NCM built after sequencing algorithm

The importance of having a lower triangular matrix (a matrix with all marks below the diagonal) is that feedback type of relationships are eliminated: when a mark is above the diagonal it means that a NC that is written later in the NCM is generating a NC written earlier in the NC matrix. However, simple logic makes one expect that NCs generated at

the beginning of the process can generate other NCs later in the process, but NCs generated late in the production process shouldn't generate other NCs that were generated earlier in the process. The fact that the NCM, despite all the operations carried on it, still has some marks above the diagonal, shows that there are some complex relationships between those few NCs, whether because they can be generated in several points along the production process, whether because they can be generated at a certain point relatively early in the production process but only much later detected by the quality control system, or possibly because of other reasons. Although the complex relationships between the NCs, which have marks above the diagonal needs to be investigated, Figure 70 already allows to concentrate on few small blocks of NCs. This fact was not evident from Figure 69 (Tavares et al. 2013).

The NCM presented in Figure 70 also allowed to identify four important clusters of NCs. Varnishing and Printing NCs are influenced mainly by primary cutting NCs. Secondary cutting NCs are influenced mainly by varnishing and Printing NCs and also Secondary cutting NCs. Flanging and seaming NCs are mainly influenced by themselves (although with complex feedback relations), which is called modularity. Finally it can also be seen that leaks, which logically appear at the matrix end, are influenced by NCs generated all along the production process. Still it can be seen that some of the NCs don't affect the leaks, which is, by itself, already an improvement on the previous state of knowledge (initially there were 44 NCs potentially influencing the leaks, now there are only 31). The NCM in Figure 70 also shows many localized empty spaces in the lower triangular matrix. This, again, is a further simplification of the problem (Tavares et al. 2013).

The clusters of components highlighted in Figure 70 are the future work starting point. Also, it is important at the beginning to analyze a single block of clusters and narrow down the focus for thorough investigation. Undoubtedly, output quality parameters stand out among all the clusters. There can be different approaches applied to analyze output quality parameters. However, in the process of building the NCM and interviewing team members in the shop floor, as well as understanding the correlations between the NCs, it became evident that the most appropriate method to analyze output quality parameters´ NCs is to prioritize them in terms of leakage locations. The prioritized leakage locations

are then analyzed using quality improvement tools, in order to reveal possible root causes. The tool selected to analyze and prioritize these leakage locations is Pareto chart, which is a very simple quality improvement tool and is described in section 4.5.

Before presenting the analysis of leakage locations, the corrected NCM is further studied to characterize system´s complexity in the next section. This complexity characterization is important in order to identify the level of interactions among the NCs, serving as a basis for comparison with other complex systems.

4.3.6. Analyzing NCM complexity using components modularity metrics

The purpose of this section is to apply component modularity metrics on a corrected NCM (Figure 69), in order to characterize the system´s complexity using three selected modularity metrics, (1) the Whitney Index (WI), (2) the Change Cost (CC) and (3) the Visibility Dependence-Plot (VD). The procedure to calculate the three metrics is already been described in detail in chapter 2, section 2.4.2.

The simplest metric among the three is the WI, which is calculated by dividing the number of interactions in a NCM by the number of elements in a NCM. The WI for the current system is 5.3, whereas Whitney et al. (1999) observed WI of around 6.3 for many matured systems. This suggests that the three-piece tinplate aerosol can production system might be a system with an average complexity. As Whitney´s research was mainly centered on an analysis of system´s architecture complexity, the WI of 6.3 is a good indicator of the architecture complexity level (Hommes, Q., 2008) of mature systems. However, as the WI is applied in this research in a different context (NCs along a production process), the multiple WIs observed by Whitney might not be a good comparison criterion for the current system WI. In order to have a more precise value of the WI in this context, it is required to have a significant number of applications in other similar production systems.

Whitney et al., (1999) further studied that the number of interactions is nearly always about 5 or 6 times the number of rows and they have plotted the rows against interactions of various industrial case studies, especially for a product development process, as shown in Figure 71 (Farooq et al. 2013).
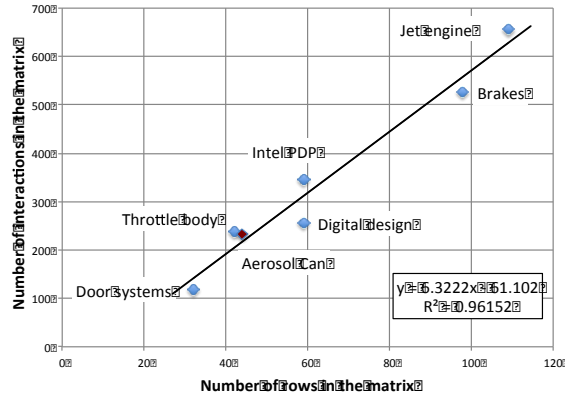
Figure 71: Number of interactions in a NCM per row (re-plotted from (Whitney et al. 1999)**)**

They presented a physical explanation of these results, highlighting the fact that industrial products cannot have too many or too less interactions, otherwise products might be too hard to make or too unreliable. The one discussed in this research is highlighted with a red color in Figure 71, with a ratio of 5.3. This number suggests that the three-piece tinplate aerosol can production system might be a system with an average complexity because Whitney et al. (1999) observed WI of around 6.3 are common for many matured systems.

In order to determine other metrics, it is required to calculate the Visibility Matrix (VM) of corrected NCM. Figure 72 shows again the corrected NCM in a different format computed in MATLAB, to calculate the visibility matrix (Farooq et al. 2013).
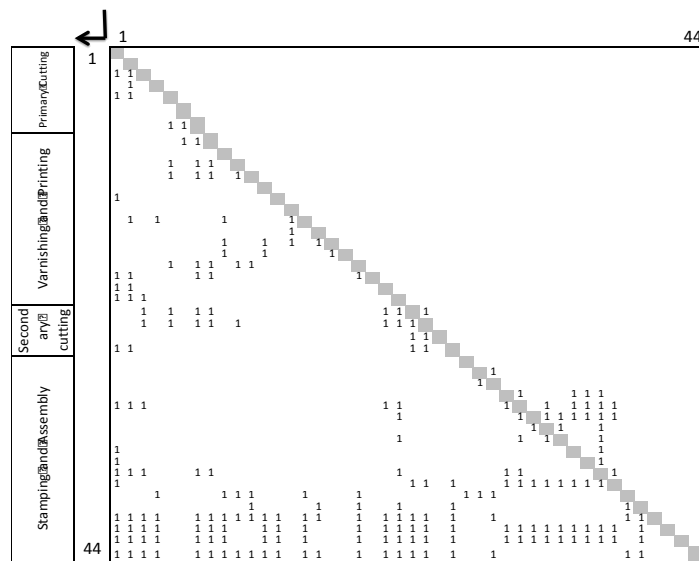
Figure 72: Corrected NCM

Figure 73 shows the visibility matrix (VM), calculated using the procedure discussed in chapter 2, section 2.4.2.
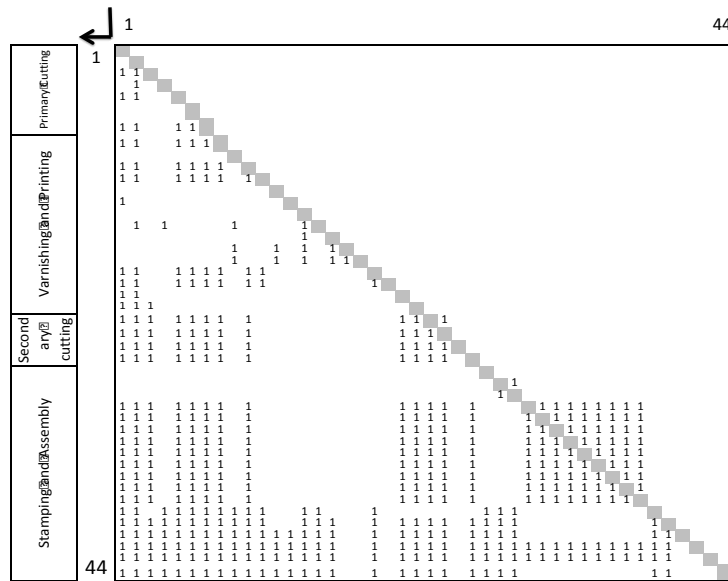
Figure 73: Visibility matrix

Figure 74 (b) shows an example of a visibility matrix (VM) for one of the stages of the manufacturing processes, the primary cutting process, where the tinplate coil is first unrolled, inspected and then cut into required tinplate sheets. The two indirect links are highlighted with red because NC 7 (coil dimension) has a direct link to NC 5 (porosity), and NC 5 (porosity) has a direct link to NC1 (coil thickness) and NC2 (coil hardness), therefore NC 7 (coil dimension) has indirect links to NC1 (coil thickness) and NC 2 (coil hardness).
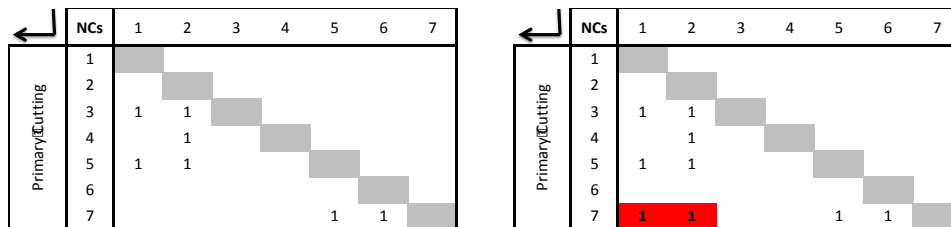
Figure 74: (a) Original NCM for a three-piece tinplate aerosol can (b) Example VM showing direct and indirect links highlighted for primary cutting process.

This VM helped in calculating the change cost (CC) of the system and its procedure is explained in detail in chapter 2, section 2.4.2. The CC value for the current system is 24%, which means that a change to a single non-conformity has the potential to impact

24% of the remaining system non-conformities, on average (Farooq et al. 2013). The highest and lowest CC of all the systems analyzed by Hommes (2008) and Whitney et al., (1999), are above 80% (very coupled) and below 10% (almost uncoupled), respectively. The aerosol production system is therefore somewhere in the lower mid-range. CC values can also be used to compare current systems modularity before and after an improvement. However, when considering NCs, this value might be high enough to make very difficult as well as very challenging to investigate the combined effect of the NCs.

The third metric is the visibility-dependence (VD) plot, shown in Figure 75, calculated from the VM of Figure 73 following the procedure described in chapter 2 section 2.4.2. The primary cutting NCs have highest visibility (influencing many other NCs), because, as expected, NCs generated at the beginning of the process can generate other NCs later in the process, but NC´s generated later in the production process shouldn´t generate other NCs that were generated earlier in the process.
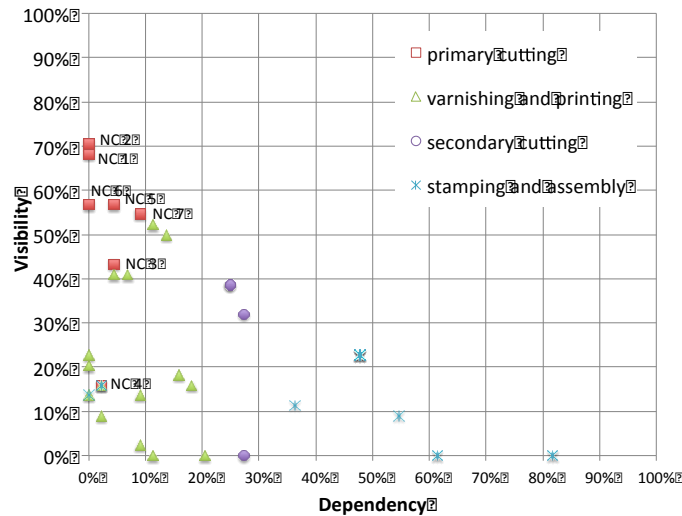
Figure 75: Three-piece tinplate aerosol can visibility-dependence scatter plot (primary cutting NC´s are highlighted as an example).

Furthermore, NCs generated in stamping and assembly processes have highest dependencies (influenced by many NCs) because they are either generated at the end of the production process or they are output quality parameters (leaks). For example, NC 7 (sheet squareness) has a dependency of 9% and a visibility of 55%. It means that a variation in NC 7 will affect 55% of the NCs and a variation in 9% of the NCs will affect

NC 7 (Farooq et al. 2013). Although the VD plot is a good tool to indicate what the important NCs are, it does not provide any indication of how the NCs are linked or are affected by others.

It is important to highlight the fact that the component modularity metrics discussed so far were solely used to evaluate system´s complexity in a new context, i.e. non-conformities at a manufacturing plant.

The discussion so far presented was on the investigation of the NCM tool that triggered the development of Systems Engineering methodology for quality improvement of manufacturing systems. The Systems Engineering methodology is based on the literature review performed in chapter 2 – particularly influenced from the DSM principles and quality improvement methodologies. The detail 10-step methodology is presented in the next section.

4.4. Introduction and development of Systems Engineering methodology

The Systems Engineering methodology for quality improvement of manufacturing systems is developed based on the theories of Systems Engineering and quality engineering and management. The principles discussed in chapter 2 on the topics of DSM and DMAIC have been taken as reference for its development. However, a more holistic and systematic 10-step methodology is presented that is highly difficult for complex problems when multidisciplinary fields are involved (Tavares et al. 2013)(Farooq et al. 2014).

1. Define clearly the project scope, the problem to be analyzed and identify the team;
2. Develop a global process mapping and identify the quality control points relevant to the problem under analysis;
3. Identification of all NCs along the production line of a product;
4. Collection and analysis of all relations between NCs with clear explanations about each dependency (including interviews to operators, quality control managers and engineers);
5. Transfer all the data to a NCM, parsed by manufacturing process, and evaluation of the final NCM;

6. Apply mathematical operations (e.g. clustering and sequencing algorithms) to the NCM and evaluate and characterize the final NCM;

7. Apply quality improvement tools based on the previous selection of what are the critical quality characteristics (response variable) under analysis;

8. Perform cost of quality analysis;

9. Improve the manufacturing process, according to the results;

10. Evaluate again the relations of NCs, deleting the NCs that were eliminated and update the NCM.

The first six steps of the Systems Engineering methodology have already been discussed in detail in chapter 3 as well as in this chapter. The next section discusses step 7 of the methodology and in order to analyse the location of leaks, a very simple quality improvement tool is applied.

4.5.   Analysis of leak locations

To analyze the location of leaks, a simple and straightforward quality improvement tool, Pareto chart, is applied. A Pareto chart or a Pareto diagram is a simple graph that ranks categories from most significant to least significant, displaying their relative importance in both raw and cumulative form. The Pareto chart is useful in identifying and displaying the so-called 80/20 rules: for example, 80% of sales revenue comes from 20% of the sales force or 80% of the problems in a manufacturing process come from 20% of the possible causes of problems. Pareto chart is practically used when (Tague 2005):

- Analyzing data about the frequency of problems or causes in a process;
- Identifying what are the most significant causes to further analyze, from a large group of potential causes;
- Analyzing broad causes by looking at their specific components.

Similarly, while analyzing the output quality parameters in the NCM, it was considered a priority to rank the location of leakages. During the NCM analysis and brainstorming with the team members in the shop floor, four important leakage locations were identified: leakage in welding area at the (1) beginning and (2) end of an aerosol can; leakage in seaming area at the (3) beginning and (4) end of an aerosol can. Furthermore,

during discussion among the team members of the Microleaks project, it was decided to reverse the orientation of the welding process for aerosol cans. Previously the aerosol can was welded from bottom to top, now it is welded from top to bottom as shown in Figure 76. As a result, two different Pareto charts were constructed based on aerosol can´s welding process orientation.
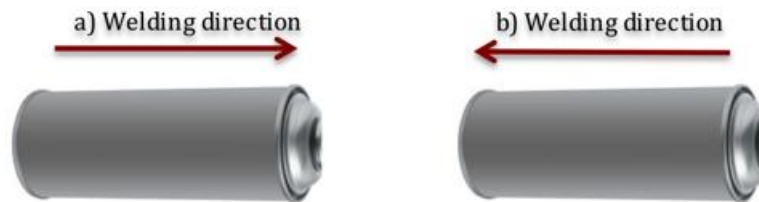
Figure 76: Welding direction of an aerosol can from (a) bottom to top; and (b) top to bottom.

Welding aerosol can from bottom to top is considered to be a conventional procedure in the current industry because most of the aerosol formats are welded in this orientation. However, the welding orientation was shifted from bottom to top to top to bottom, only for format 65x300. This shift was the result of increased claims in this format and therefore following discussion sessions among the Microleaks team, the production team members decided to invert the welding direction. While constructing Pareto charts, this important information was taken into consideration and a decision was made to illustrate two different Pareto charts: (1) welding an aerosol can from bottom to top as shown in Figure 77; and (2) welding an aerosol can from top to bottom, as shown in Figure 78.

Data for both orientations was collected during a significant period of (8-12 months) including information about the number of leaky cans detected for each cause (location of leak). The Pareto chart plots the causes on the x-axis in ranked order, whereas plotting on the left side of the y-axis the number (count) or frequency of leaky cans, and on the right hand side of the y-axis, the cumulative percentage. Furthermore, the graph also shows cumulative percentages in the lower x-axis, which signifies the 80/20 rules. These charts were plotted using Minitab software.

Moreover, other than the four causes (locations) of leakages highlighted previously, two more causes were revealed, i.e. "No Information" and "Other", as shown in Figure 77 and Figure 78. These two unknown causes at this first analysis were posteriorly investigated.

Figure 77 illustrates the first Pareto chart and the results clearly show that the most significant cause among the six causes listed is the "Welding-Bottom", which contributes to 66% of the total leakages. The second most significant cause is "Seaming-Top", which contributes to 13% of the total; together, these two causes contribute to almost 80%.
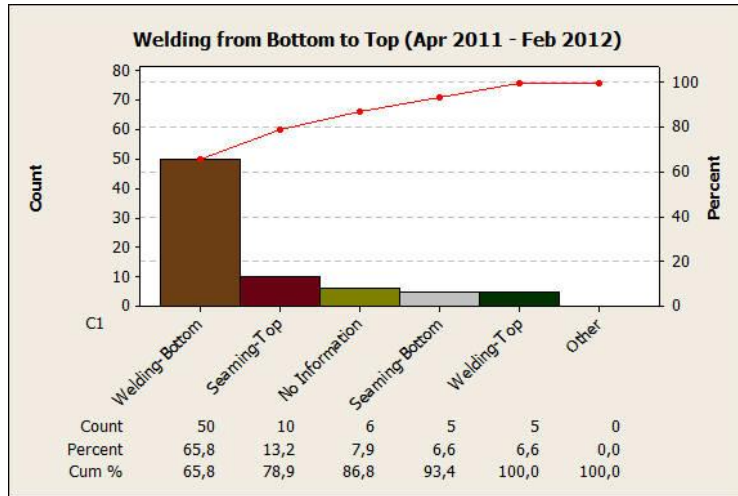
Figure 77: Pareto chart Analysis of an aerosol can - welding from bottom to top

If only one Pareto was made based on the available data and the important information of welding orientation was not taken into consideration, then, from Figure 77 it would be concluded that "Welding-Bottom" is the main root cause of the problem followed by "Seaming-Top". However, when the second Pareto was drawn taking into consideration the welding direction, an important additional conclusion was made.

Figure 78 illustrates the second Pareto chart when aerosol cans are welded from top to bottom. In order to make easier the comparison between the two Pareto charts, the causes in both charts are highlighted with the same color. The information in the second Pareto is quite different, with the "Welding-Top" being the most significant cause with 61.5% of occurrences, whereas in the first Pareto "Welding-Top" only contributed to 6.6% of occurrences. Also, "Welding-Bottom" and "Seaming-Top" contributes only to 14.3% and 5.5% respectively, whereas the second higher contribution is from "No Information". This adds an important conclusion to the previous inference, i.e., the main source of Microleaks is not the welding bottom but it is the welding beginning. Again, these first two causes in Figure 78 contributed to almost 80% of the problems. Following the NCM

and Pareto chart analysis, welding beginning has become the most important topic in the Microleaks project, as well as the prime focus for the entire team.
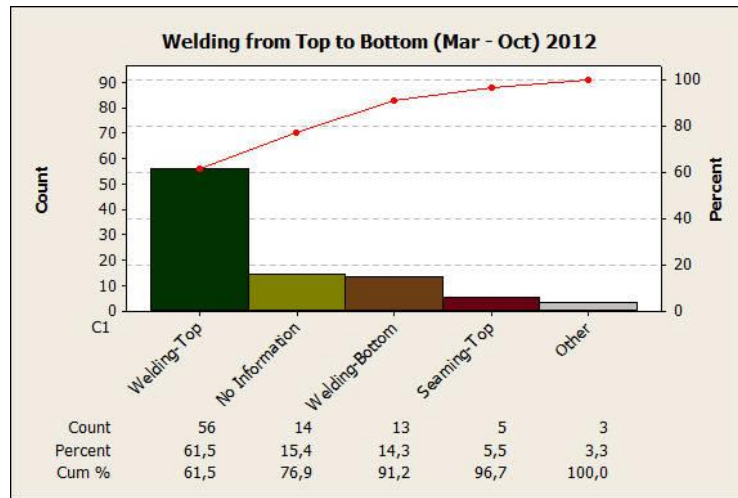
Figure 78: Pareto Chart Analysis of an aerosol can - welding from top to bottom

Despite knowing the fact that welding beginning contributes to more than 65% of the problem, other causes should not be overlooked – in fact, the Juran principle of "Vital Few – Useful Many" always holds. This means that after significant investigation on the root cause of welding beginning, the other causes must also be analyzed. Between the remaining causes, the other cause that was important to explore further was the "No Information" one, ranking second in the generation of leaks. Therefore, this cause was analyzed in detail in order to understand what is included in this category and what it represents.

Figure 79 illustrates causes classified in the "No Information" category, gathered from the analysis of the check sheets that accompany the manual waterbath leak detection system. By looking into detail to these sheets, it appears that the person who detected and measured leaks was unable to categorize the leaks. In other words, leaks were detectable as well as measurable, but it was difficult to identify the correct location of the leak. Also, Figure 79 highlights that most of the leaks (11/14) are at the location of either welding or seaming and very few are unknown (3/14). As a result, based on this discussion one can comment that the conclusion made previously is acceptable to focus on welding beginning and then further emphasize on other causes.

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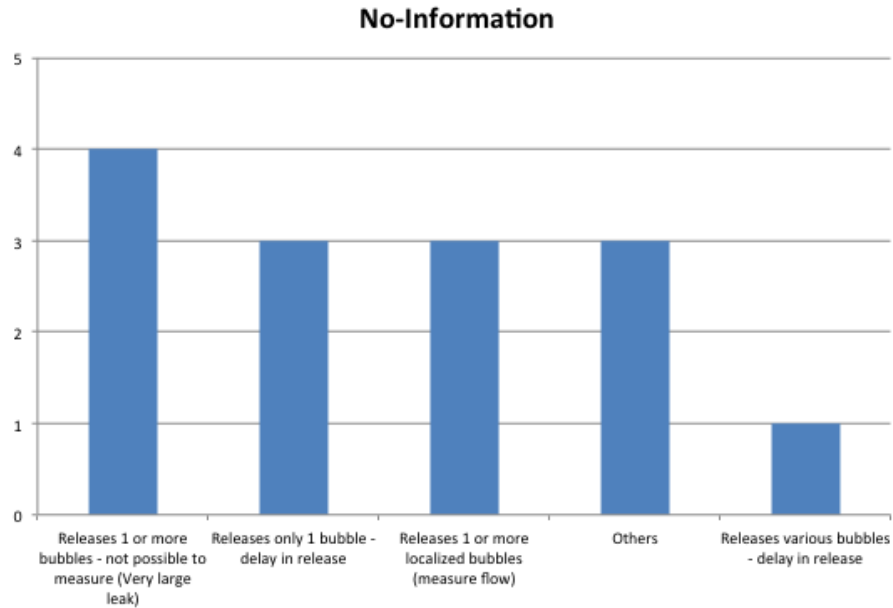
Figure 79: Further analysis of the "no information" cause from second Pareto Chart

Welding beginning has now been considered to be the center of attention for the Microleaks project. Sets of discussions were performed between the Microleaks project team members finding out the most appropriate tool or method to be applied to resolve this problem.

One of the possible solutions discussed to solve the problem consisted in cutting the beginning of each aerosol, a possible solution to eliminate the welding beginning problem, immediately after it is produced. As a result, an offline-trimming test was performed by one of the TME researcher (also a production manager at Colep) with a specialized company in the field of trimming technology. The test results were very convincing, showing no leaky aerosol cans produced when the welding beginning was cut (Valente 2013). A detailed analysis is presented in chapter 6, section 6.4 with these trimming tests, further possible technology development, as well as the costs involved with this solution.

Another important topic of discussion was the welding parameter adjustment – in fact, it is a strong possibility that there is a presence of noise factor(s) or welding parameters required to be optimized or both. Whenever the topic of parameter optimization or adjustment appears, the most appropriate tool considered is Design of Experiments

(DoE). The team agreed on studying the welding process and parameters, implementing DoE on the shop floor. One strong reason for mutual agreement on DoE implementation was that if the results are satisfactory, it is relatively easy and cost effective to implement DoE compared to the development of any innovative technology, like, for example the trimming solution. Nevertheless trimming technology is considered a solution supporting in reduction of the Microleaks rather than an alternative to DoE, as it was discussed in chapter 1.

4.6.   Summary

The chapter has discussed the as-is condition of the manufacturing process and successfully developed the high level and detail level process map. At each process step, it was defined which parameters are really important from a Microleaks perspective. As a result, quality control stations and quality characteristics measured at each station become easy to identify.

Section 4.4 successfully developed a Non-Conformity Matrix (NCM), through collecting and analyzing all the non-conformities generated along the manufacturing process. The mathematical operations applied to the NCM helped in identifying key manufacturing areas for future action.

Following discussion on the development of NCM tool, a 10-step Systems Engineering methodology for quality improvement of manufacturing systems was devised. This methodology was dedicated to the case of Microleaks however a general methodology for manufacturing systems is developed:

1. Define clearly the project scope, problem to be analyzed and identify the team;
2. Develop a complete process mapping and identify the quality control points relevant to the problem identified;
3. Identification of all elements along the production line of a product and collection of all relations between them;
4. Transfer all data to a DSM, parsed by manufacturing process;
5. Apply mathematical operations to DSM and evaluate and characterize the final DSM;

6. Use the most adequate quality improvement tools to further refine the critical quality characteristics and areas previously identified;

7. Perform cost of quality analysis to enable an informed choice;

8. Improve the manufacturing process according to the results;

9. Evaluate again the relations of elements, deleting the elements that were eliminated and update the DSM;

10. Standardize the results and refine the model over time.

Section 4.5 analyzes one of the key manufacturing area through investigating the location of leaks. A simple quality improvement tool, the Pareto chart, was applied that concluded that welding beginning is the main root cause of the problem, contributing to more than 65% of the problem. Furthermore, following this finding, the Microleaks team has discussed several possibilities to resolve welding beginning of the aerosol cans. As a result, Design of Experiments was selected as the most appropriate tool for further investigation to optimize welding parameters. The discussion on DoE is explained in detail in the next chapter 5.

Chapter 5 - Design of Experiments as an optimization tool

The objective of chapter 5 is to analyze the effect of welding parameters on the welding beginning of aerosol cans. In chapter 4, it has been concluded that welding beginning is a key location in an aerosol can and contributes to more than 65% of the total Microleaks.

The welding parameters that were identified as critical are analyzed applying Design of Experiments, one of the most widely used tools for process optimization. The successful implementation of DoE comprises eight steps, first step is to define the problem statement, which is already identified in chapter 4 as welding beginning of an aerosol can. Nevertheless, key aspects of the problem statement are discussed in detail.

In the second step, response variables are identified and developed: Those response variables that can directly measure the leaks are identified; those response variables that may show correlations with the leaks are developed.

In the third step, important controllable and noise factors that are affecting the response variables are identified. A method to carry out the pre-experimental runs, determining the range of each controllable factor is developed in this step.

In the fourth step, based on the objective, available resources, and number of factors, a type of experimental design is chosen.

In the fifth DoE step, discussion is presented on the method of performing the experiments as well as the challenges faced by the production team during the implementation.

In the sixth step, analysis is performed on the data recorded during the fifth step and important results are highlighted.

In the seventh step, confirmatory runs that are developed and implemented on the shop floor to validate the results are performed.

In the final step, a summary and conclusion that are proposed to be implemented on the shop floor for process optimization is presented.

5.1.   Introduction to Design of Experiments

Design of Experiments (DoE) is one of the most powerful tools for process improvement and optimization in the scientific and engineering disciplines. It is widely used to develop robust processes, so that they are less affected by external sources of variability. Objectives of DoE are to study the performance of processes and systems and to better understand the behavior of the process factors, as well as their impact on the quality characteristics of the product and process under analysis. In other words, experiments are performed to (Montgomery et al. 2000):

- Determine which controllable factors have most influence on the response(s);
- Determine where to set the significant controllable factors in order to assure that the response(s) are close to their target value;
- Determine where to set the significant controllable factors in order to assure that the effects of the noise (uncontrollable) factors on the response(s) are minimal.

Application of DoE in process improvements can result in improved process yields, reduced process variability and reduced overall costs (Montgomery 2008). Over the past many years, industries have successfully applied DoE to improve process performance and reduce variability (Montgomery et al. 2000) & (Javorsky, Franchetti, and Zhang 2014). However, other applications of DoE are also realized in the areas of product development (Fowlkes and Creveling 1996) and performance optimization of automation technologies (Subulan and Cakmakci 2011). For the current application case, the objective is to reveal the effect of welding factors on the welding beginning of aerosol cans, resulting in improved process yield and reduced process variability. Figure 80 illustrates key elements involved in the definition of design of experiments.
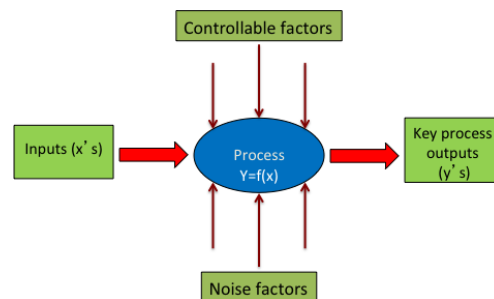
Figure 80: A basic illustration of key elements in Design of Experiments (Montgomery et al. 2000)

Factors are the input variables of a process that affect directly the response variables, which are the key process outputs. There are two types of factors: (1) controllable factors are those factors that the experimenter may wish to vary in the experiment; (2) noise factors are those factors that may have large effects that must be accounted for, yet the experimenter may not be interested in them in the context of present experiment.

The successful implementation of DoE comprises eight steps, as summarized in Table 11. The first four steps are termed as pre-experimental planning phase. The fifth step is the execution phase and the last three steps are termed as the phase of statistical analysis of the data collected and final recommendations (Montgomery 2008).

Table 11: Steps in Design of Experiments[1]

Steps	Phase
1. Problem statement and/or definition	**Pre-experimental planning phase**
2. Select the response variable(s)	
3. Factors selection and their levels	
4. Choose the experimental design	
5. Perform the experiment	**Execution phase**
6. Statistical analysis of the acquired data	**Statistical analysis and recommendation phase**
7. Results validation using confirmatory runs	
8. Conclusions and recommendations	

A detailed analysis over the three phases of DoE is presented in the next section considering the application case of the Microleaks project.

5.2.   Pre-Experimental Planning Phase

Pre-experimental planning is a key phase for the successful implementation of the experiments, because final conclusions largely depend on the way in which the experiments are planned. At the end of the pre-experimental planning phase, it is expected that the objectives of the experiment, the selection of response variables, factors and their levels required, as well as the choice of experimental design are clearly defined.

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[1] Steps 2 and 3 are often performed simultaneously or in reverse order.

5.2.1. Problem statement and/or definition

Definition of the problem is a critical step in any DoE analysis. Incorrect identification of the problem will lead to final recommendations that are not meaningful. Typically, in order to define and characterize the problem, cause-and-effect-diagram and Failure Mode and Effect Analysis techniques are applied as simple and straightforward methods. However, in this research, the NCM and Pareto chart analysis, complemented with analysis of cans at the microscope (with several magnifications), were successfully applied in identifying unambiguously the welding beginning as the problem that has to be further analyzed with the help of DoE. Therefore, the objective of the DoE analysis is to understand the effect of the welding factors on the welding beginning of aerosol cans that will ultimately lead to the generation of cans with Microleaks.

5.2.2. Select the response variable(s)

Identification and selection of response variables is an important and critical step in DoE. The experimenter should be certain that the selected response variables provide useful information about the process under study. It is also critical to identify how these response variables can be measured as well as any issues related to defining the responses of the selected variables (Montgomery 2008).

In the case of the Microleaks, number of leaky cans was selected as the response variable. The difficult task or the challenge was the lack of available equipment´s because there are only two in-house equipment´s that can measure leaks/Microleaks: one is automatic leak detection system that can measure only big leaks, second is manual waterbath leak detection system that can measure smaller leaks. Therefore, it was required to identify response variables, which do not measure Microleaks directly, however are important for the problem and may trigger Microleaks later in the process.

First the team worked on the identification of available in-house systems that can directly measure leaks/Microleaks:

a) Automatic leak detection system (Wilcomat)
b) Manual waterbath leak detection system

Then the team decided to investigate other response variables, which are not number of leaks but are critically important for the problem. These responses, if successfully measured, may help in identifying a relation with Microleaks in the future. These response variables are conductance measurement that is measured using welding monitoring system, overlap measurements, and response variables measured using microscopic and macroscopic analysis.

c) Welding monitoring system (Conductance measurements)

d) Measuring instrument (Overlap measurements)

e) Microscopic and macroscopic analysis

Figure 81 shows the location of these measurement systems in the aerosol cans production system.
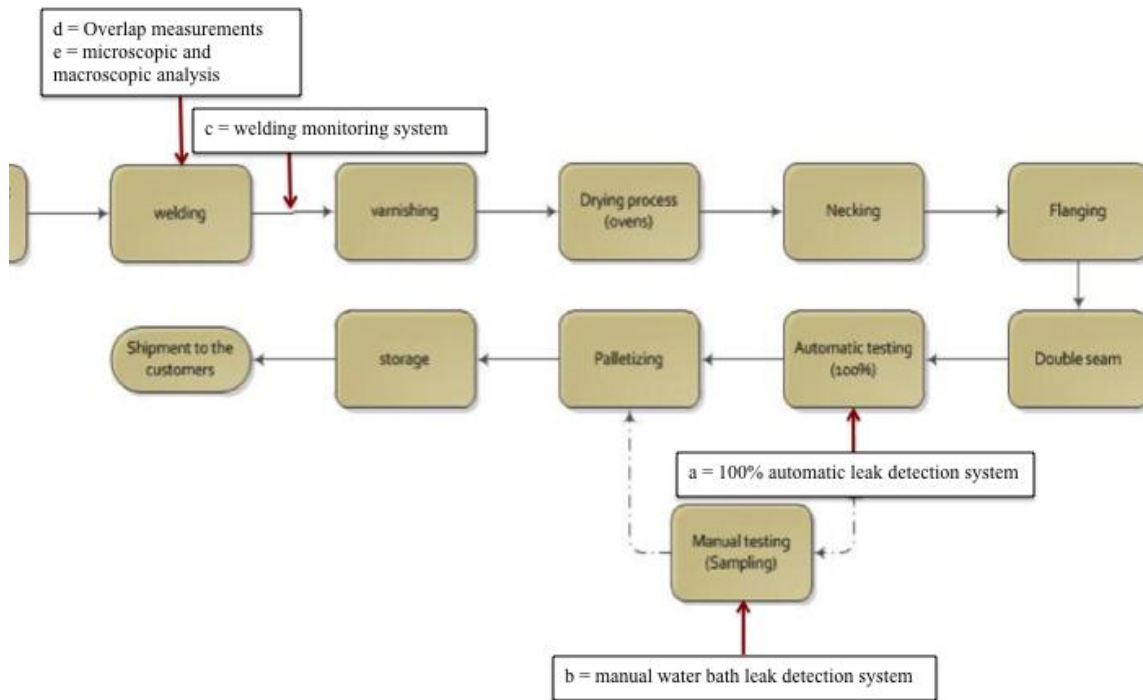
Figure 81: Location of measurement systems in the aerosol cans production system

The response variables that are measured through the system a, b and c are termed as online response variables because they will be measured during production of the aerosol cans. Whereas response variables that are measured through the system d and e are

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termed as offline response variables because they will be measured at a later stage as an offline testing.

The working principle of all these measurement systems as well as how the response variables are measured in each system was discussed in chapter 3. In this section, brief discussion for each measurement systems related to the DoE analysis is presented.

a. Automatic leak detection system (Wilcomat)

Wilcomat is a Go/No-Go type of measurement system because it only rejects aerosol cans and does not measure leak rate. Therefore, Wilcomat acts as a binary response variable for the current DoE. Furthermore, the rejected cans will be manually inspected using waterbath leak detection system to guarantee that the rejected aerosol cans certainly have leaks, since there have been innumerous situations in the past where good cans were rejected, i.e. false positives.

b. Manual waterbath leak detection system

During a normal production, the time spent by an operator to measure a leak rate is 5 min/setup and in one setup 6 cans can be measured, however because this method was used to measure response variable therefore 10min/setup was allowed. This was the time separately from loading and unloading time that the 6 cans were kept inside the water for testing. Further advantage of the increased time was already explained in chapter 3 section 3.4.2.

c. Welding Monitoring System

The interest of the present DoE is to study the aerosol can welding beginning. Unfortunately the welding monitoring system discards the first and last nugget of each can weld, therefore doesn't allow to directly concluding about the weld quality on the zone of interest (weld beginning). This is due to the fact that the voltage waveform across the welding rollers is not synchronous with the beginning of the tinplate to be welded and in order to avoid mistakes these values must not be considered.

Furthermore, the welding monitoring system does not measure the leaks or Microleaks directly; nevertheless it measures one of the important parameters, that is, conductance (reciprocal of resistance). It might be possible that following some experiments, there are correlations established between conductance and leaks even when the beginning nugget is neglected.

d. Overlap measurements

The importance of overlap as well as its brief measurement procedure was discussed in chapter 3. Because of its great significance to the problem, it was first considered as a control factor to investigate its impact on the output. However, due to the fact that it was very difficult to measure on-line as well as to vary its values therefore it was decided to keep it constant along all experiments and control it through a sample of 5 aerosol cans, measuring at the beginning and end at each run. The limitations and the reasons why overlap was not considered as a control factor are discussed in detail in the next section of 5.2.3.1.

5.2.3. Factors selection and their levels

Once the problem as well as the response variables are clearly defined, it is now important to select the right factors and levels that will be the subject of optimization through DoE, thus reducing the Microleaks.

In the case of aerosol cans, the selection of the right factors involved a process of brainstorming with key experts of the production that helped in listing down the controllable factors that affect the problem. At a second stage, and after all the controllable factors have been identified, brainstorming further reduced the number of controllable factors, simplifying the subsequent DoE analysis (Farooq et al. 2015). Table 12 shows the final list of identified controllable factors, which corresponds to the first part of step 2 of DoE in Table 11.

Table 12: Control factors[2]

Factors	Units
Overlap	mm
Welding current	kA
Welding force	Kgf
Welding speed	m/min
Space between welding bodies	mm

The aforementioned control factors are further explained below regarding their setup methods and precision measurements. Among these control factors, overlap has already been discussed in detail in chapter 3.

Welding current

Welding current is easy to set and vary through the human machine interface and has a precision of 1kA. In order to monitor actual welding current during welding, an automatic welding monitoring system is installed that measures the ratio of current and voltage in the form of conductance. Further detail about the welding monitoring system was presented in chapter 3 section 3.6.2.

Welding Speed

Similar to welding current, welding speed is also set easily through human machine interface and has a precision of 1 can/min. While increasing or decreasing the speed, it is also required to adjusting the speed of the entire production line that includes conveyer speed, monitoring system speed, seaming process and palletizing speeds.

Welding force

The welding force, comparatively with the other controllable factors, takes more time to set because it is only fixed manually. A technician varies the force with the help of a key placed in the holder and rotates for adjustment, as shown in Figure 82. As a result, the length of the spring, which is attached with the outer welding roller, varies. For example,

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[2] Approx. 0.1 kgf = 1N

if the length of the spring is 55 mm, then the force is 40 kgf. Increasing the spring length decreases the force and vise-versa.
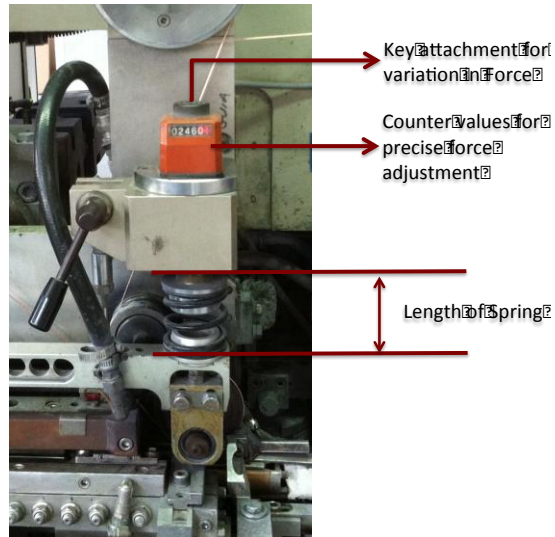
Figure 82: Welding force setting

Distance between welding bodies

Known from experience, the distance between welding bodies has a huge impact either at Microleaks as well as on productivity of the process (i.e. the smaller the distance is, the greater is the productivity and vise-versa). However, the distance should not be so small as to have adjacent aerosols being welded together, in the form of a tube. When that happens, the production line will jam downstream of the welding station. Also, the distance should not be so large that the outer welding roller becomes idle. Figure 83 shows the ideal and standard position of outer welding roller when both the aerosol cans are in contact with it during welding process.
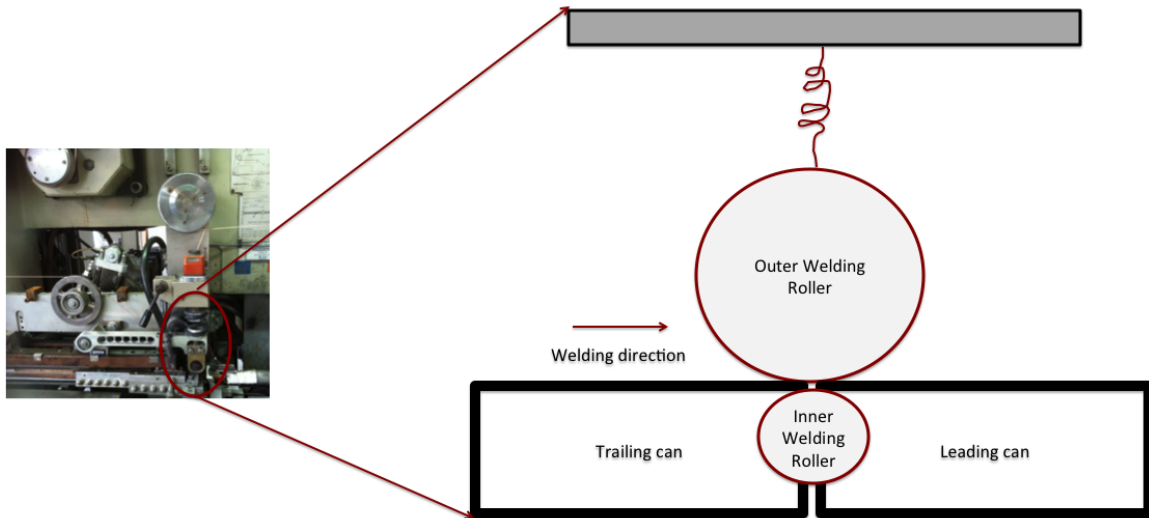
Figure 83: Ideal and standard position of outer welding roller during welding process

Figure 84 illustrates a situation where the distance is too large and the leading aerosol can has left the outer welding roller after welding process, yet the trailing aerosol can is not yet in contact with the outer welding roller. As a result, the outer welding roller jumps each time aerosol can starts welding, causing severe defects at the beginning of the welding process. Due to welding roller jumping, the first aerosol can of every welding sequence is automatically rejected by the welding monitoring system.
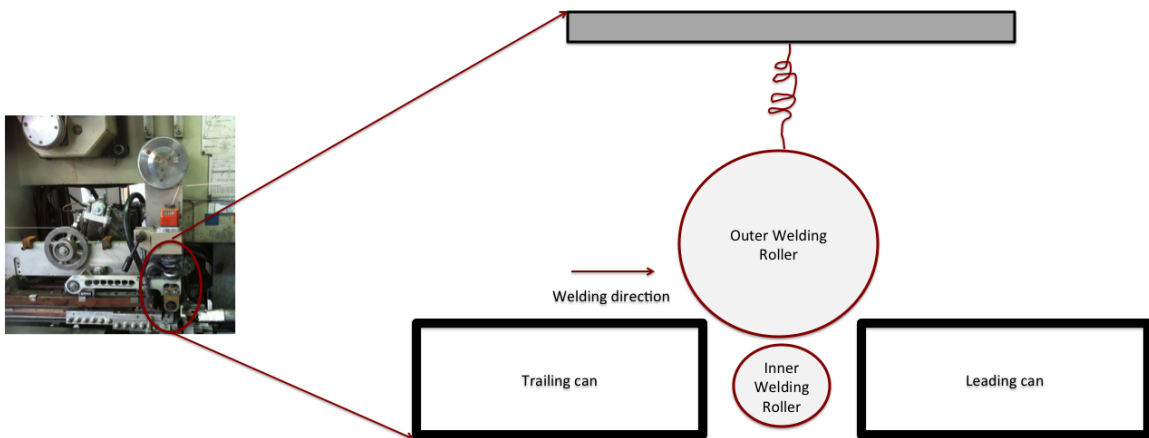
Figure 84: Distance between welding bodies is too large

The distance between welding bodies has a precision of 0.1 mm and is normally set by the production team at a value of 2 mm, which is based on experience and previous results. Furthermore, there is no systematic relation between this distance and Microleaks

as well as it is not known at what value of distance the upper welding roller becomes idle. This problem will be explored during the DoE analysis.

The distance is measured by tracing the marks on the copper wire that has already been used to weld the aerosol body using a vernier caliper. It is a manual process, which takes time to set up. Usually, most of the formats are set up at a constant value and its not required to set this factor each day or each machine setting.

Table 13 summarizes the list of discussed welding factors and their measurement precision.

Table 13: Summary of important welding factors and their measurement precision

Important factors	Measurement precision
Overlap	0.05 mm
Welding current	1 kA
Welding speed	1 can/min
Welding force	0.1 kgf
Distance between welding bodies	0.1 mm

Similarly, in order to understand and further define the noise factors for the welding process, several brainstorming processes were conducted. The noise factors that resulted from this discussion are shown in Table 14. It is important to highlight the fact that although these factors were not intentionally varied like controllable factors, they were however recorded each time one experiment was performed, in order to monitor their effect on the response variables.

Along with these noise factors, another important noise factor that should be considered is the coil, whose material properties vary between different coils, as well as within a coil. Therefore, in order to reduce the influence of this noise factor, a complete coil was reserved for this DoE campaign.

Table 14: Noise factors[3]

Noise factors	Units/comments
Z-bar	mm
Calibrating tool	Inspection by a responsible person
Cooling fluid (Temperature)	°C
Copper wire quality (supplier, batch)	Name of supplier and batch #
Copper wire profile (diameter)	mm
Sheet squareness (secondary)	mm
Material supplier	Name of supplier
Welding rollers diameter (outer)	mm
Welding rollers diameter (inner)	mm
Welding rollers profile	Inspection by a responsible person

The second part of step 2 of DoE is to select the controllable factors´ levels. If the factor levels are not correctly chosen, the subsequent statistical analysis and final recommendations might be misleading. As an example, Table 15 illustrates a clear definition of levels of a factor. A level is a setting where factor is normally set. There are two steps in defining a level, first number of settings (levels) are selected and then values of those settings at which factor will be run are defined.

Table 15: Definition of level of a factor

Factor	Level 1	Level 2	Level 3
Welding current	250	254	265

Selection of factor levels has to go through an iterative process. The first iterations of factor levels may imply an experimental design with too many experimental runs and might not be practically feasible. Therefore, based on available resources and experimental objectives, it may be required to reduce the number of experimental runs. The tools used for a comprehensive selection of factor levels are experimental objectives, theoretical knowledge, expert opinion, process knowledge, available resources, and previous experimental results (Montgomery 2008) & (Czitrom 2003).

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[3] An explanation is presented in the Appendix II regarding definition of each of the noise factors.

Generally, factor levels and their values are selected based on the definition of the factors, namely whether it is a quantitative factor or a qualitative factor. For the current industrial case and as shown in Table 12, only quantitative factors are applicable. As the objective of the experiment was to determine whether or not the factor has an effect on the response variable, the size and direction (sign) of the effect, as well as to potentially study the curvature in the response, three levels for each factor were selected. Furthermore, as it was the first time such experiments were performed in this industry, it was required to design and start with a simple model.

After selecting the number of levels, next task is to select values at each level where a factor is set. This requires deep process knowledge of the experimenter, based on a combination of practical experience and theoretical understanding, as well as historical data and/or previous experimental results. Though, even considering all these information, there are still particular situations where the correct identification of levels´ values is hard to accomplish. This might be due to a variety of causes, such as a certain immaturity of the process, a random behavior of the factor levels each time the production is run or even presence of unpredictable noise factors. Similarly, in the current industrial example, after brainstorming with the production and quality managers, it was discovered that values of factor levels are always varying for each setting of the welding machine and it is impossible to clearly identify them with the available tools. Further discussion with the team members reveals that this apparent random behavior is due to the presence of noise factors (e.g. coil properties and other unknown factors) and to the fact that the process might not be completely controlled.

Thus, the best way to address these problems consists in performing pre-experimental runs to identify the best factor levels and their values for these situations. In fact (Czitrom 2003) and (Coleman and Montgomery 1993) have also mentioned this requirement, stating that, if additional information is required on factor levels and their values it is advisable to consider performing pre-experimental runs. An important point to be underlined is that the revision of literature performed, as to the current knowledge, did not explain in detail the process of performing the pre-experimental runs. The guidelines

devised to overcome this problem and the application case where these pre-experimental runs were applied is explained in the following section (Farooq et al. 2015).

5.2.3.1. Development and implementation of Pre-experimental runs

Typically, pre-experimental runs are required in two situations (Farooq et al. 2015):

- When it is not completely known that a quantitative factor will have a linear (2 levels) or a non-linear (3 or more levels) response, as well as in situations where the objective of the experiment is depending on the natural effect of the factor. Generally, two levels are studied if the objective of the experiment is to determine whether or not the factor has an effect (size and direction) on the response. Three or more levels are studied if the objective of the experiment is to study also the full relation with the response;

- When it is not possible to define clearly the values of the levels for quantitative factors and it is required to explore the process behavior over a wide area of factor ranges.

In practice, the selection of factors and their levels, and selection of response variable(s) are done simultaneously or in reverse order, as shown in Table 11. However, if it is required to perform pre-experimental runs, then it is recommended to select response variable(s) as well as to study the measurement system(s) prior to selecting factor levels and their values. This is advisable in order to better understand the process behavior, correctly defining factor levels and their values. Furthermore, it is also recommended to list down all the noise factors before performing pre-experimental runs, noting down their values during the tests. In order to enable a better identification of factor levels and their values, noise factors should be controlled as far as possible, assuring that they will have almost the same values while performing the pre-experimental runs or the designed experiment (Farooq et al. 2015).

The very first step performed to discover the values of factor levels was a brainstorming session conducted with the experts of the production team. This helped in saving some time during pre-experimental runs implementation because it has provided valuable hints

to set the factor around estimated values. The estimated factor values are shown in Table 16. This table is a great baseline to estimate the factor levels as well as to understand the sensibility of knowledgeable people on the shop floor.

Table 16: Control factors and their estimated values

Control factors	Units	Precision	Estimated values		
			Minimum	Average or Standard	Maximum
Overlap	mm	0.05	0.4	0.5	0.6
Welding current	kA	1	225	250	255
Welding force	Kgf	1	45	50	55
Welding speed	m/min	1	55	58	70
Space between welding bodies	mm	0.1	0	1.5	2

Table 17 defines comprehensively the guidelines used for the implementation of pre-experimental runs.

1. Calibration of the selected response variable(s) and measurement system(s);

2. Note down the values for all the possible noise factor(s);

3. Adjust the machine to standard operating condition and start producing the units;

4. Note down the standard values for all control factors when satisfactory units are produced;

5. Increase first control factor from the standard value intermittently until the factor reaches a maximum value while still producing relatively good units by analyzing the response variable(s);

6. Maintain all other factors at the standard values for maximum or minimum values;

7. Note down the value of the factor, this is the factor´s maximum value;

8. Decrease the same control factor from the standard value [*]intermittently until the factor reaches a minimum value while still producing relatively good units by analyzing the response variable(s);

9. Note down the value of the factor, this is the factor´s minimum value;

10. The 2-level of a factor can be defined by low level (minimum factor value) and high level (maximum factor value);

11. The 3-level of a factor can be defined by low level (minimum factor value), center point (standard value) and high level (maximum factor value);

12. Adjust the minimum and maximum values so that the standard value is at the center of both, which is highly recommended. However there are **situations when standard value might not be adjusted at the center, therefore maintain the settings to non-central values.

13. If the factor is required to perform with more than three levels then take more center points between the levels or take points where there is a region of interest;

14. Repeat the steps 5 – 13 to all other selected factors.

[*] Increase the value of control factor by 5%, 10%, … of its value depending upon the objective of the experiment.

** It is dependent on the objective of the experiment.

The noise factors recorded at step 2 of the guidelines are illustrated in Table 18. These noise factors will be recorded each time the experiment is performed and the values will be monitored for any significant variation in the output.

Table 18: Noise factors

Noise factors	Values	Units/comments
Z-bar	0.4	mm
Calibrating tool	OK	By production team member
Cooling fluid (Temperature)	5	°C
Copper wire quality (supplier, batch)	La Farga, 210001785	-
Copper wire profile (diameter)	1.38	mm
Material supplier	Arcelor	mm
Welding rollers diameter (upper)	84.4	mm
Welding rollers diameter (lower)	53.9	mm
Welding rollers profile	OK	By production team member

After successful implementation of the pre-experimental runs for the industrial case, values of levels for all the selected control factors were clearly identified as shown in Table 19. The response variables selected for the pre-experimental runs were only number of leaks that were measured through 100% automatic leak detection system (Wilcomat) and manual waterbath leak detection system because they are online response variables, i.e. the leaks were measured directly and it was required to have the feedback immediately. The sample size in the pre-experimental runs was undefined because the runs were performed until the team was satisfied with the final factor levels.

Table 19: Control factors´ levels

Control factors	Units	Precision	Levels - Estimated values		
			Minimum	Average or Standard	Maximum
Overlap	mm	0.05	0.5	0.5	0.5
Welding current	kA	1	250	254	265
Welding force	Kgf	1	40	43	44
Welding speed	m/min	1	46	58	64
Space between welding bodies	mm	0.1	0.1	2	5.2

Now, the discussion is emphasized on the results of the factor levels if there were any

surprises recorded while performing the pre-experimental runs. First discussion is about overlap that was recorded to be constant at 0.5 mm. This was due to the fact that while reducing or increasing the overlap from the standard value of 0.5 mm to 0.4 mm or to 0.6 mm respectively, the aerosol cans were unable to seam, thus making it impossible to complete the production of cans. As a result, no response variable was measured and therefore overlap must not be considered as a control factor.

Thus, the overlap factor will now be considered as a noise factor, reducing the number of control factors in the DoE analysis from five to four. Also, considering the fact that overlap is an important factor to the problem therefore it was included in the DoE as a response variable, discussed earlier. During each experiment, samples of aerosol cans were taken for overlap measurement to guarantee its accuracy as well as to perform analysis for its significance.

Other important factor is the force that has a very small range of values when compared with the estimated values in Table 16. It was observed that while increasing the force to a value higher than 45 kgf or decreasing the force to a value lesser than 40 kgf, would trigger the occurrence of many bad cans measured through the response variables. Furthermore, while brainstorming with key experts, general consensus about this control factor was that it has a large range of working values and also that one or two unit change in force should not have a large affect in the response variables. Nevertheless, that was not the result of the experiments.

Another important factor is the space between the welding bodies. During brainstorming process with key experts, it was discussed that this factor is always set at 2 mm and there was no idea about the minimum and maximum possible values. The pre-experimental runs performed were helpful in discovering the correct level values and the maximum possible value was found to be 7 mm; however to be on the safe side, the maximum value suggested for the designed experiment is 5.2 mm.

5.2.4. Choose the experimental design

The selection of an appropriate experimental design is a systematic procedure and it is important to keep in mind the objectives of the experiment. This step is relatively easy if

the previous pre-experimental planning steps are followed correctly. The choice of designs is typically based on the number of factors and their levels as well as the number of replicates, and selection of a suitable run order. Once these points are established, it is required to explore if the design can be full factorial, fractional factorial, or orthogonal array (Taguchi Design).

In the case of Microleaks project, the previous pre-experimental planning activities clearly established the number of factors and levels. However when a full factorial or a fractional factorial design was considered, it showed too many experiments to be conducted. Since it was required to perform the experiments on the shop floor, and it was not practically and economically justifiable to spend too many of working hours in an offline testing experience, a Taguchi orthogonal array method was considered the best choice of design. A comparison between the full factorial and Taguchi design is illustrated in Table 20 in terms of the number of experiments required to be performed.

Table 20: Comparison between full factorial and Taguchi orthogonal array method

# of factors	4
# of levels	3
Full factorial design	3^4 = **81** experiments
Taguchi orthogonal array method	**9** experiments

The number of experiments shows a big difference between the two design methods, reason that was decisive for choosing the Taguchi orthogonal array method for the experimental plan. Furthermore, one should consider that reducing the experiments in the Taguchi method has both pros and cons. The results that will be achieved from the Taguchi method are not as complete as those achieved with a full factorial design. The next section, the execution phase, discusses in more detail the time as well as the resources required to perform a single experiment, which justifies the selection of the Taguchi experimental design.

After selecting the Taguchi experimental design, the factors and their levels were entered as input in Minitab software, which provided 9 combinations of factors as shown in Table 21.

Table 21: Combinations of factors from Taguchi orthogonal array method using Minitab

Experiment #	Current (kA)	Force (kgf)	Speed (m/min)	Distance (mm)
L1	250	40	46	0.1
L2	250	43	58	2
L3	250	44	64	5.2
L4	254	40	58	5.2
L5	254	43	64	0.1
L6	254	44	46	2
L7	265	40	64	2
L8	265	43	46	5.2
L9	265	44	58	0.1

The combinations of factors were then rearranged on the basis of, which combinations give the least average setup time. The factor, distance between the welding bodies, takes longer time among all factors to set up. It was proposed to rearrange the combinations on the basis of distance as shown in fifth column of Table 22.

Table 22: Rearranging the combinations of factor on the basis of least average set up time

Run	Experiment	Current (kA)	Force (kgf)	Speed (m/min)	Distance (mm)
L1	250	40	46	0.1
L2	254	43	64	0.1
L3	265	44	58	0.1
L4	254	44	46	2
L5	265	40	64	2
L6	250	43	58	2
L7	265	43	46	5.2
L8	254	40	58	5.2
L9	250	44	64	5.2

The table shows that the settings for factor "distance" have to be changed only for three times, whereas other factors have to be changed approximately every time an experiment is performed. Thus, this combination of factors saves more time and reduces the workload of the operators.

5.3. Execution Phase

In order to conduct the planned experiments, first a team was deployed that consists of the PhD student (myself) leading the process, the production manager, a production team member, a support member from maintenance, and an operator. Then, a meeting was

setup along with the planning department, which estimated a total of 24 shop floor working hours to be required for the entire 9 experiment runs.

It was already mentioned earlier that a single coil was reserved for this analysis and from each coil 60,000 cans could be produced. Had a full factorial design been chosen it would roughly need 9 times more shop floor working hours and one coil would probably not have been enough to complete the array of tests. Another important reason of not selecting full factorial design was that it was the first time DoE analysis was going to be performed in this industry and it is always recommended to start from the simplest model that contains the least number of experimental runs (Montgomery 2008).

Afterwards, the sample size for online response variables for each of the experiment was established at 50 aerosol cans. The online response variables, which were measured during the experiment, are: leaks and conductance measurements. The leaks were measured using (a) 100% automatic leak detection system (Wilcomat); and (b) Manual waterbath leak detection system, while conductance was measured using (c) Welding monitoring system. Since the sample size was very small, therefore waterbath testing functioned in this DoE analysis as an online response variable. The offline response variables, for which aerosol cans were stored for later testing, were: (d) overlap, sample size of 10 aerosol cans / each experiment; and (e) macroscopic and metallographic analysis, sample size of 20 aerosol cans / each experiment.

5.3.1. Working principle of the execution phase

The working principle of the DoE implementation is very simple and straightforward. The 50 aerosol body samples are first measured for the conductance measurement through welding monitoring system. If there are some rejected aerosol bodies through the welding monitoring system, these are recorded and scraped. The accepted aerosol bodies are continued upstream in the production process through necking, flanging, and seaming processes. The test logic of the execution phase is:

- Fifty cans made the conductance test: during this process the automatic rejection from welding monitoring system was enabled, which means that all the cans rejected from this process were recorded and scraped;

- Fifty cans made the Wilcomat test;

- If a can is rejected or accepted at Wilcomat test, then this can will go through the manual waterbath test (rejected can is tested with waterbath for validation only);

- If a can is rejected at waterbath test, then this can will not do any other test;

- If a can is accepted at waterbath test, then this can will be stored in the production facility.

During the process, all the online response variables were recorded. In case of offline response variables, 10 samples of aerosol bodies for overlap and 20 samples of aerosol bodies for microscopic and macroscopic analysis were reserved. The samples for overlap were stored and measured in Colep and the samples for microscopic and macroscopic analysis were sent to INEGI.

Before presenting the recorded data, the next section first discusses the challenges faced by the team, as well as key learning's during the experiments.

5.3.2. Implementation and challenges during experiments

The 9 experiments of DoE matrix were performed in 3 days of 8 working hours/day.

The first and second days of experiments did not accomplish the set targets. The settings of one of the control factor values, the welding current, changed on a daily basis as shown in Table 23. This fact required serious attention in order to understand what went wrong and how could it be fixed. If this problem persisted it would never have been possible to perform the DoE analysis, as it would have required performing all the 9 experiments continuously for 24 hours, not a feasible solution.

Thus, it was required to further analyse the 2-day experiments and the pre-experimental day runs more thoroughly. Finally, the effort of recording the noise factors[4] paid off, as it was noticed that the values of outer welding roller diameter was continuously changing and affecting the welding current. Therefore, in order to reduce the influence of welding

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[4] Appendix I shows recorded noise factors for all the experiment days.

rollers, a consensual decision was made to limit the welding roller diameter at a constant value whenever a DoE analysis was performed.

The outer and inner welding rollers have maximum diameters of $\varnothing 85$ mm and $\varnothing 55$ mm, respectively. The diameters are the variable noise factors that slowly decrease due to wearing out while producing aerosol cans. The welding roller diameters can be set at the constant value in two ways: (1) continue normal production and when the diameter reaches to the baseline value start performing confirmatory runs; and (2) grinding the welding rollers. Production team members used the later method to set the diameters for the 3rd day of experiments, as shown in Table 23. The results were convincing and constant values for welding rollers were achieved.

Table 23: Summary of the experiments performed highlighting variation in the welding current

Type	Welding current levels (kA)			Welding rollers Æ (mm)		Experiments performed
	Minimum	Standard	Maximum	Outer	Inner	
Pre-experimental runs	250	254	265	84.4	53.9	Trials
1st day of experiments	248	250	260	83.9	53.9	1,2,3
2nd day of experiments	235	250	256	82.7	53.9	4,5,6,7,8
3rd day of experiments	235	250	256	82.7	53.9	9,1,2,3

The Taguchi matrix was then revised with the modified baseline values of welding current (Table 24). Following the successful experiment on the 3rd day, it was then decided to consider the revised baseline values of welding current for future reference.

Table 24: Revised Taguchi orthogonal array matrix (baseline values)

Run | Experiment	Current (kA)	Force (kgf)	Speed (m/min)	Distance (mm)
L1	235	40	46	0.1
L2	250	43	64	0.1
L3	256	44	58	0.1
L4	250	44	46	2
L5	256	40	64	2
L6	235	43	58	2
L7	256	43	46	5.2
L8	250	40	58	5.2
L9	235	44	64	5.2

The data collected during experiments as well as detailed statistical analysis are presented in the next section.

5.4.   Statistical Analysis and Recommendation

The objective of statistical techniques is to assist the decision-making process as well as to attach a level of confidence to a statement. If the experiments have been planned and designed correctly as well as performed according to the design, then statistical analysis provide effective and statistically valid inferences. These statistical analyses together with good engineering and process knowledge as well as common sense will lead to significant conclusions (Montgomery 2008).

5.4.1. Statistical analysis of online response variables

The online response variables recoded for the current application case are shown in Table 25.

Table 25: Results of online response variables

Experiment #	Sample size	Online response variables		
		Welding monitoring system rejections (aerosol bodies)	Wilcomat rejections (aerosol cans)	Water bath rejections (aerosol cans)
L1	50	0	0	0
L2	50	1	2	1
L3	50	50	0	0
L4	50	0	0	0
L5	50	6	0	0
L6	50	50	0	0
L7	50	0	1	1
L8	50	40	1	0
L9	50	2	4	6

In order to understand the numbers in the table, let´s take an example of experiment 9 (L9). The values in the row show that during experiment # 9, 2 aerosol bodies were rejected from the welding monitoring system out of 50 (sample size) and were immediately thrown away, 4 aerosol cans were found leaky at the automatic leak detection system (Wilcomat) and 6 aerosol cans were found leaky through manual waterbath.

After collecting the data, it is now required to analyze the results. In a Taguchi orthogonal array design the process robustness is measured using the performance statistic called signal-to-noise ratio (SNR). This statistic combines both the means response and response variability in a single performance measure. Nevertheless, knowing the importance of means, Minitab also generates a separate means response for Taguchi design.

The variance between the factors is analyzed using Analysis of Variance (ANOVA) technique that divides the total variation into variation resulting from main effects, interaction effects and error.

In a Taguchi orthogonal method, it is highly recommended to perform ANOVA for two or more than two response variables. In case of online response variables, two of them measure leaks and one measure conductance. Also, Table 25 shows that welding monitoring system does not correlate with leaks and including it with the other online response variables (leaks) would bias the results due to more rejections from

conductance. Following these reasons, leaks and conductance were separately analyzed for ANOVA.

The ANOVA for leaks did not show any factor as significant for 5% level of significance and therefore the results are not shown here. This might be due to the fact that for the case of Microleaks, Taguchi orthogonal array method is not ideal, and/or sample size of 50 aerosol cans is very small. In order to proceed further with the analysis, it was decided to perform full factorial analysis, which is called confirmatory runs. However, considering the constraints of time and resources on the production shop floor, only two controllable factors can be analyzed because when considering more than two controllable factors, experimental runs will become too many and practically not feasible.

Among the four controllable factors, the two factors selected were welding force and welding current. Distance between welding bodies although is an important factor, it was set at an average value of 2mm, it was already observed that increasing distance beyond certain value would increase the number of leaky cans. Welding speed was set at the highest value of 64m/min, therefore maximizing the productivity. Before discussing the confirmatory runs of full factorial analysis between welding force and welding current, statistical analysis of offline response variables is explained.

5.4.2. Statistical analysis of offline response variables

The offline response variables were measured so that they help in understanding the physics of the problem as well as to go in-depth in understanding what happens in the welding beginning and other important parts of aerosol cans. From statistical point of view, none of the offline response variables found significant. Reasons of insignificance might be due to the fact that the difference in responses between the experiments of an offline variable is so small that it is difficult to infer any statistical significant factors as shown in Table 26.

Experiment #	Offline response variables (average values of 5 samples)					
	Overlap (mm)		Heat affected area (mm)		Thickness (mm)	Extrusion (mm)
	Beginning	End	Beginning	at 3 mm	Beginning	
L1	0.57	0.48	1,4	1,1	0.2612	1.3812
L2	0.57	0.5	1,1	1,0	0.2856	1.0436
L3	0.6	0.5	1,3	1,2	0.2804	1.2986
L4	0.54	0.44	1,3	1,0	0.2412	1.1508
L5	0.5	0.4	1,2	1,1	0.2376	1.223
L6	0.58	0.48	1,2	0,8	0.234	1.1192
L7	0.58	0.48	1,6	1,1	0.2458	-
L8	0.5	0.4	1,6	1,1	0.2456	1.195
L9	0.59	0.5	0,7	0,8	0.2976	0.70175

The values shown in Table 26 for each experiment and response variable are the average of the samples taken and measured. These values were measured at INEGI, spending plenty of hours in preparing, testing, and analyzing the samples.

The offline response variables are not analyzed using the ANOVA method rather simpler graphical analysis is performed. In the following sections, the offline response variables are separately analyzed.

Heat Affected Area:

Heat affected area is measured for each of the experimental run at the beginning and at 3 mm of an aerosol body. Although there is no specific reference to compare these values with, it is understood that large variations or a too high or a too low value in the heat-affected area may have bad consequences later in the production process.

Figure 85 shows the interval plot for each experimental run for a sample size of 5 aerosol bodies. The circle in the middle of each plot represents an average value of 5 samples; the upper line shows the maximum value in a sample whereas the lower line in the plot shows the minimum value in the sample.

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[5] Some example pictures for heat-affected area are presented in the Appendix II Pictures for other response variables are shown in the later sections.

The red color plots in Figure 85 shows those experiments that have leaky cans in the online response variables (Table 25). Overall, and just by analyzing the plot, there is not a clear and significant correlation noticed between the leaky cans and heat-affected area measurements.
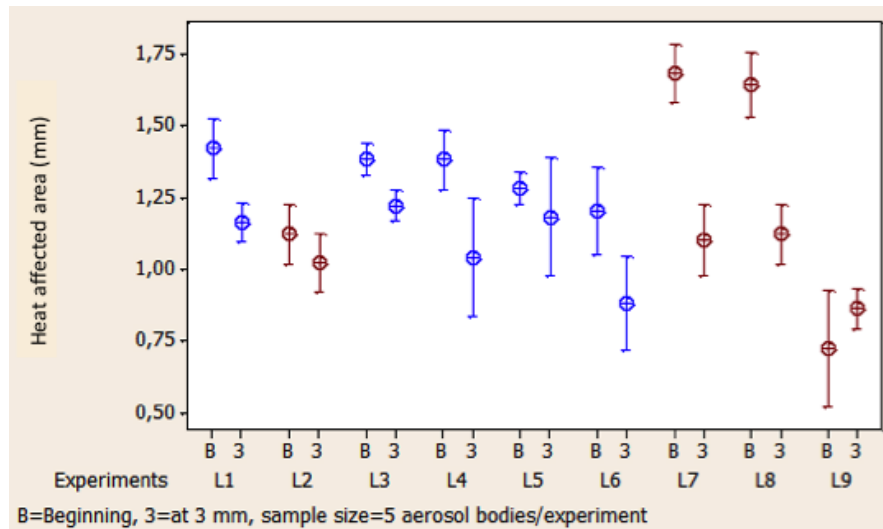
Figure 85: Interval plot of heat-affected area

Plus, the variability of experiments # 4, 5 and 9 is much higher than the others, with experiment # 9 showing the smallest value of all the measurements. It is important to highlight the fact that if the heat-affected area value is too low, it may be very critical for the subsequent processes. The result of experiment # 9 can be compared with the online responses of Table 25, where this experiment has produced most of the leaky cans. It was decided to replicate and investigate experiment # 9 further; therefore during confirmatory runs heat-affected area can also be integrated with this analysis.

Thickness:

The thickness of the welding bead was measured by taking 5 samples in each experiment. Thickness and heat-affected area are somehow correlates, as the common sense says when heat-affected area has a larger value, the thickness should be lower, and vice-versa. The appendix II shows all the individual values (Table 26 only shows averages). There are no reference values to compare these values with. Also, the range of thickness is between 0.22 – 0.3 mm and does not show any serious concern.

Some of the thickness measurements from experiments are shown in Figure 86. It can be seen that thickness highly depends on the extrusion, and vice-versa. Therefore, very large or very small thickness is not desirable like in the case of experiment # 9 or even experiment # 8.

Extrusion:

The extrusion measurements were also recorded for a sample size of 5 aerosol bodies for each experiment. Again there is no established reference value to compare these extrusion measurements. However, the values can be compared among themselves. The Appendix II shows all the individual values (Table 26 only shows averages). Some of the pictures for extrusion measurements are shown in Figure 86.
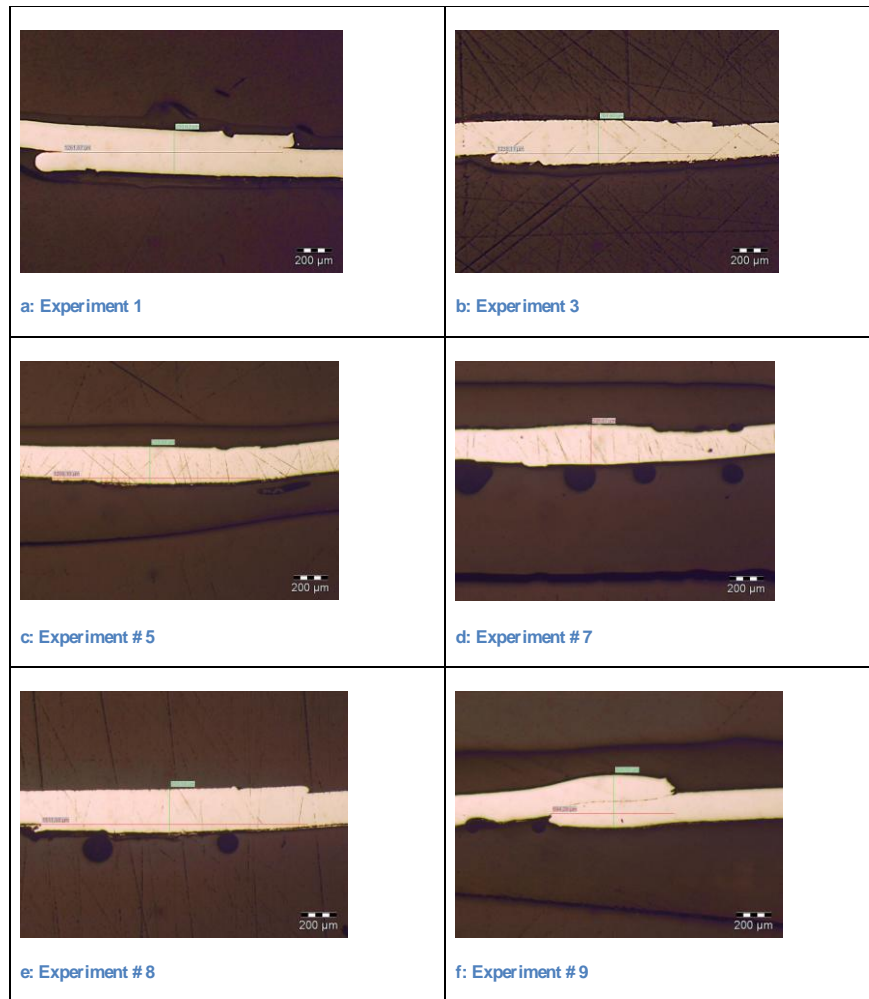
Figure 86: Pictures showing extrusion and thickness measurements as example

Most of the experiments have values between the range of 1 – 1.4 mm, except experiment # 1 that has couple of values around 1.4 mm and especially experiment # 9 that has all the values below 1 mm. In fact, experiment # 9 has been the center of attention for all the response variables, implying that the particular combination of factors should not be setup while running the production.

The pictures in Figure 86 represent almost all kinds of extrusion types that were observed during analysis. Important pictures are those where either the extrusion measurements are very large and unable to measure like for example experiment # 7, or when there are very small cracks like in the case of experiment # 9.

The confirmatory runs are performed in the following section to analyze the welding current and welding force.

5.4.3. Confirmatory runs

The objective of this section is to perform full factorial analysis between the factors welding current and welding force and to explore broader results. The eight steps of DoE were followed, which was defined in Table 11. However, these eight steps will not be explained in that detail as was discussed during first DoE analysis. The discussion starts from choosing the experimental design step and keeping all previous steps as constant.

Choose the experimental design

Table 27 shows the full factorial design of welding current and welding force for the confirmatory analysis. In this design, both factors welding speed and distance between welding bodies were kept constant at 64 m/min and 2 mm respectively.

Table 27: DoE full factorial matrix for confirmatory runs

Run | Experiment	Current (kA)	Force (kgf)
2R1	235	44
2R2	235	43
2R3	235	40
2R4	250	44
2R5	250	43
2R6	250	40
2R7	256	44
2R8	256	43
2R9	256	40

Another combination of factors that was considered to perform for validation in the DoE analysis is shown in Table 28.

Table 28: Validation of experiment for confirmatory runs

Run | Experiment	Current (kA)	Force (kgf)	Speed (m/min)	Distance (mm)
2R10	235	44	64	5.2

The working principle of the implementation phase in the confirmatory runs is slightly different from the previous experiments and is explained in the next step.

Perform the experiment

In order to conduct the planned experiments as well as to reduce variations in the results, the same team conducted these confirmatory runs. Plus, in order to better understand the effect of the controllable factors, the sample size was increased to 420 units and an improved working principle was developed based on the experience of previous experiments.

This working principle first addresses the issue of dividing the 420 samples per type of response variables, i.e. how many aerosol cans will be allocated for each of the response variables. Then, the characteristic of each division is explored per production process stages, i.e. how the procedure is performed.

Cans division per type of response variable tests:

- Cans 1-5 $\rightarrow$ Overlap measurement at Colep
- Cans 6-10 $\rightarrow$ Extrusion measurement at INEGI
- Cans 11-410 $\rightarrow$ Conductance and leak tests
- Cans 411-415 $\rightarrow$ Extrusion measurement at INEGI
- Cans 416-420 $\rightarrow$ Overlap measurement at Colep

Cans division per production process stages:

- Cans 1-5 $\rightarrow$ Only the body is produced (and welded). Body needs 5 mm cut out at the beginning and end to measure overlap
- Cans 6-10 $\rightarrow$ Only the body is produced. Production of body finishes after welding. Stamping operations not done
- Cans 11-410 $\rightarrow$ Cans are produced until the last production process
- Cans 411-415 $\rightarrow$ Only the body is produced. Production of body finishes after welding. Stamping operations not done
- Cans 416-420 $\rightarrow$ Only the body is produced (and welded). Body needs 5 mm cut out at the beginning and end to measure overlap

It is important here to highlight the test logic of the cans from 11-410:

- 100% of the cans made the conductance test: during this process the automatic rejection from welding monitoring system was disabled, which means that all the cans were transported to the subsequent processes;
- 100% of the cans will make the Wilcomat test;
- If a can is rejected or accepted at Wilcomat test, then this can will go through the manual waterbath test (rejected can is tested with waterbath for validation only);
- If a can is rejected at waterbath test, then this can will not do any other test;
- If a can is accepted at the waterbath test, then this can will be stored and will not do any other test.

Statistical Analysis of of Wilcomat and manual waterbath systems

The response variables for Wilcomat as well as for manual waterbath systems were recorded. As it was explained before the rejections from welding monitoring system are not scraped, and will be further analyzed through the subsequent processes. The aerosol bodies, accepted and rejected ones, were later seamed and tested through the Wilcomat machine for detection of leaks. The statistics of the rejected aerosol cans from the Wilcomat machine are shown in Table 29.

The rejected aerosol cans from the Wilcomat machine were validated through the waterbath system. The difference between the original rejections (Z) and after validating the rejected cans from waterbath (X) illustrate that Wilcomat is not consistent in rejecting the leaky aerosol cans. This false positive behavior is already known in the shop floor and one of the possible reasons for this behavior might be the temperature difference of the aerosol can before it is inspected in the Wilcomat machine. If the efficiency of Wilcomat is improved in the future (see chapter 7), then Colep can save money in terms of those good cans that were falsely scraped. A cost analysis is performed in chapter 6 showing the amount of euros that can be saved if Wilcomat doesn't reject false positives.

Table 29: Rejection of aerosol cans through Wilcomat machine

Experiment #	Welding current [kA]	Welding Force [kgf]	Rejections (Z) (measuring through Wilcomat machine only)	Rejections (X) (validation of wilcomat rejections using waterbath)	Total (Y)	% (X/Y)
2R1	235	44	9	8	400	2.00%
2R2	235	43	1	1	400	0.25%
2R3	235	40	14	2	400	0.50%
2R4	250	44	127	116	400	29.00%
2R5	250	43	14	13	400	3.25%
2R6	250	40	5	2	400	0.50%
2R7	256	44	33	26	400	6.50%
2R8	256	43	33	29	400	7.25%
2R9	256	40	3	2	400	0.50%
2R10	235	44	78	52	400	13%

After the Wilcomat process, all the accepted aerosol cans were transported to the manual waterbath system for testing. The statistics of the number of cans rejected through the manual waterbath system are shown in Table 30.

Table 30: Rejection of aerosol cans through Waterbath system

Experiment #	Welding current [kA]	Welding Force [kgf]		Rejections	Total	%
2R1	235	44		52	400	13.00%
2R2	235	43		5	400	1.25%
2R3	235	40		5	400	1.25%
2R4	250	44		56	400	14.00%
2R5	250	43		5	400	1.25%
2R6	250	40		0	400	0.00%
2R7	256	44		14	400	3.50%
2R8	256	43		17	400	4.25%
2R9	256	40		1	400	0.25%
2R10	235	44		121	400	30.25%

The rejections from Wilcomat and manual waterbath systems were combined to build a single table that was later analyzed. The combined rejections are shown in Table 31.

Table 31: Combined rejections from Wilcomat and Waterbath systems

Experiment #	Welding current [kA]	Welding Force [kgf]		Rejections	Total	%
2R1	235	44		60	400	15.00%
2R2	235	43		6	400	1.50%
2R3	235	40		7	400	1.75%
2R4	250	44		172	400	43.00%
2R5	250	43		18	400	4.50%
2R6	250	40		2	400	0.50%
2R7	256	44		40	400	10.00%
2R8	256	43		46	400	11.50%
2R9	256	40		3	400	0.75%
2R10	235	44		173	400	43.25%

ANOVA is performed for the combined leaks generated through the Wilcomat and manual waterbath systems. The ANOVA for SN ratios in Table 32 shows that between the two factors only welding force is significant. This was also clear if one analyzes the Table 31 and applies common sense that welding force at the highest level (44 kgf) generates most of the leaks.

Table 32: Analysis of Variance for SN ratios – Wilcomat and manual waterbath

Sources of variation	Degree of freedom	Sum of squares	Mean square	F-ratio	P-value
Welding current (kA)	2	12.04	6.02	0.08	0.922
Welding force (kgf)	2	1063.19	531.594	7.28	0.046
Residual error	4	91.98	72.994	-	-
Total	8	1367.21	-	-	-

The other important results are Standard error and R-Sq, which also shows comfortable range of the model.

- Standard error for the current model (S) = 8.544
- R-Squared for the current model (R-Sq) = 78.6%

Standard error and R-Sq are the parameters to validate the model. Standard error is the average squared difference of the error in the actual to the predicted values of the data (i.e. the square root of the mean squared error). The smaller the value of S, the stronger the linear relationship exists.

R-sq is a statistical measure of how close the data are to the fitted regression line. It is the percentage of the response variable variation that is explained by a linear model.

ANOVA for means is illustrated in Table 33, where p-value is greater than 0.05 for both the controllable factors. It means that both factors are not significant for means, however in the SN ratios both means and variations are measured – therefore it can be said that welding force is significant for variation.

Table 33: Analysis of Variance for means – Wilcomat and waterbath

Sources of variation	Degree of freedom	Sum of squares	Mean square	F-ratio	P-value
Welding current (kA)	2	2781	1390	0.68	0.558
Welding force (kgf)	2	12419	6209	3.03	0.158
Residual error	4	8199	2050	-	-
Total	8	23398	-	-	-

The main effects plot is analyzed only for SN ratios and for welding force because they are only significant, which is shown in Figure 87. The welding force at the lowest level (40 kgf) produces the maximum signal and least noise or variation. Also, this level produces the least number of leaky cans as it can be witnessed from Table 31.
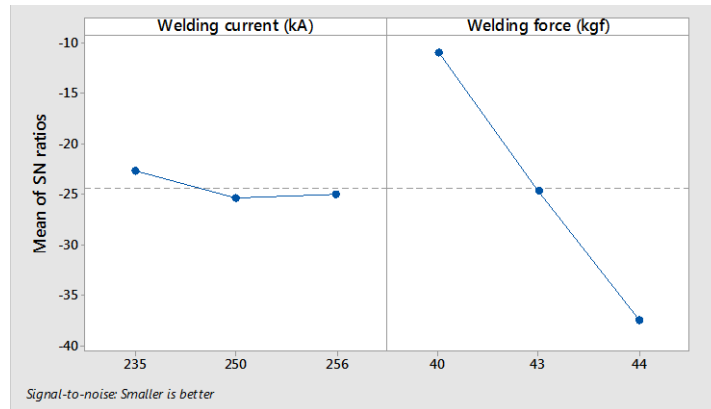
Figure 87: Main effects plot for SN ratios – Wilcomat and Waterbath

The interaction plot is also analyzed only for SN ratios. The plot in Figure 88 shows that both factors have some sort of interaction between them, since the lines are not completely parallel. Furthermore, the signal is maximum or the noise is minimum when welding force is at the lowest level (40 kgf) and welding current is at the standard level (250 kA) also validating the model and the previous results.
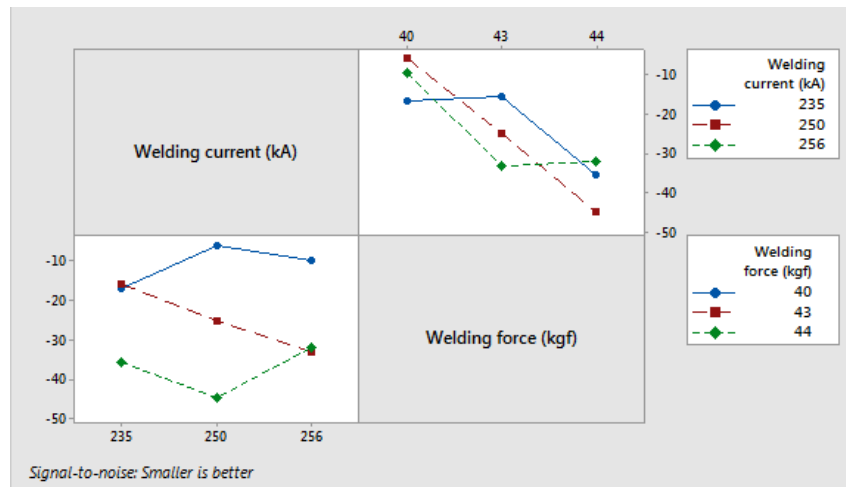
Figure 88: Interaction plot for SN ratios

In order to assess the validity of the model, residuals should:

- Be independent;
- Follow a normal distribution;
- Have constant variance across all factor levels.

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Minitab plotted the residuals for the current analysis in terms of normal probability, histogram, observation number, and fitted value as shown in Figure 89 that confirms the normal behavior of residual.
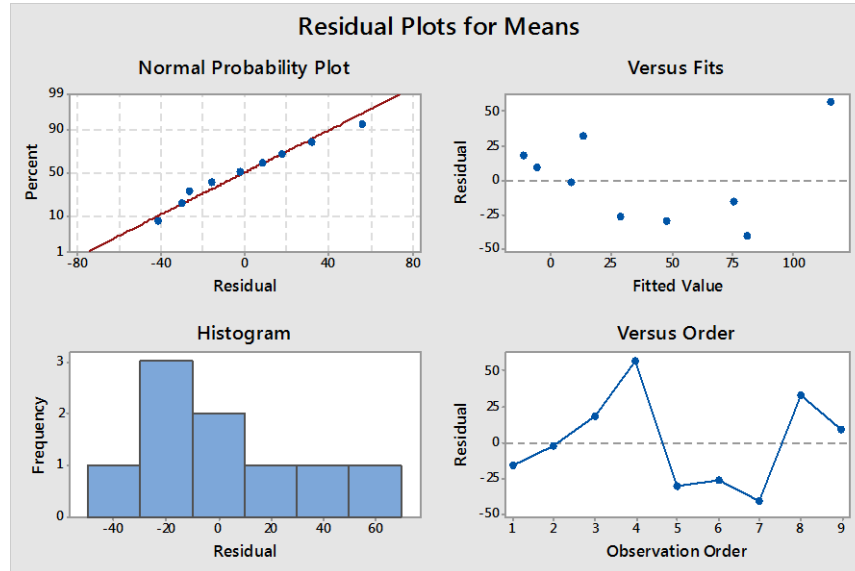
Figure 89: Residual plot for means

In the normal probability plot, residuals are clustered around the red line indicating that the error terms are approximately normal. Furthermore, the plot gives no indication of outliers thus the assumption of normality is valid.

The residual versus fit plot shows that there are approximately half of them are above and half of them are below the zero line indicating that the assumption of error terms having mean zero is valid.

The histogram in this case re-emphasizes the assumption of normality and validates normal distribution of the residuals.

The residual versus order plot is also important in this case because data is a time series and order of the data is important. A clear cyclic pattern indicates that error terms are dependent on the time variable.

- Analyzing experiment # 2R10

The experiment 2R10 that was planned to reiterate in the confirmatory runs to validate the previous results of leaky cans as well as extrusion measurements.

After recording the response variables, it was thought to be a good idea to compare this experiment with experiment 2R1 because all the controllable factors are same except the distance as shown in Table 34. When the distance is varied to 5.2 mm from 2 mm, then the rejections in the total leaks increased by 3 times. This increase in number of rejections is due to the setting of distance between welding bodies at 5.2 mm, which is really close to the limit when aerosol cans start getting leaky.

Table 34: Comparison of results for experiment # 2R10

	Experiment Design						Total leaks (Wilcomat and Water bath)	
Experiment #	Current [kA]	Force [kgf]	Speed [m/min]	Distance [mm]	Sample size		Rejections	%
2R1	235	44	64	2	400		60	15
2R10	235	44	64	5.2	400		173	43

Although, distance is not statistically analyzed nevertheless the results show the importance of distance between the welding bodies. This factor has been the center of concerned for the company and they had already understood its importance to the Microleaks before.

- Graphical analyses of overlap measurements

The overlap measurements were recorded for each experiment at the beginning of the production run (samples 1-5) and at the end of production run (samples 416-420). These samples were analyzed using a box plot diagram shown in Figure 90.

A box plot is a pictorial representation of measurements that shows the maximum, minimum, and average values of a sample. The way box plot is plotted in Figure 90 is on the basis of location (beginning or end of an aerosol body) and type (before or after

production run). Before production means samples of overlap from 1-5 and after production means samples of overlap from 416-420. Lets take an example of experiment 2L1 in Figure 90: where B1 shows sample of overlap measurements that was measured at the beginning of an aerosol body and before production run. Similarly, E2 shows sample of overlap measurements that was measured at the end of an aerosol body and after production run.
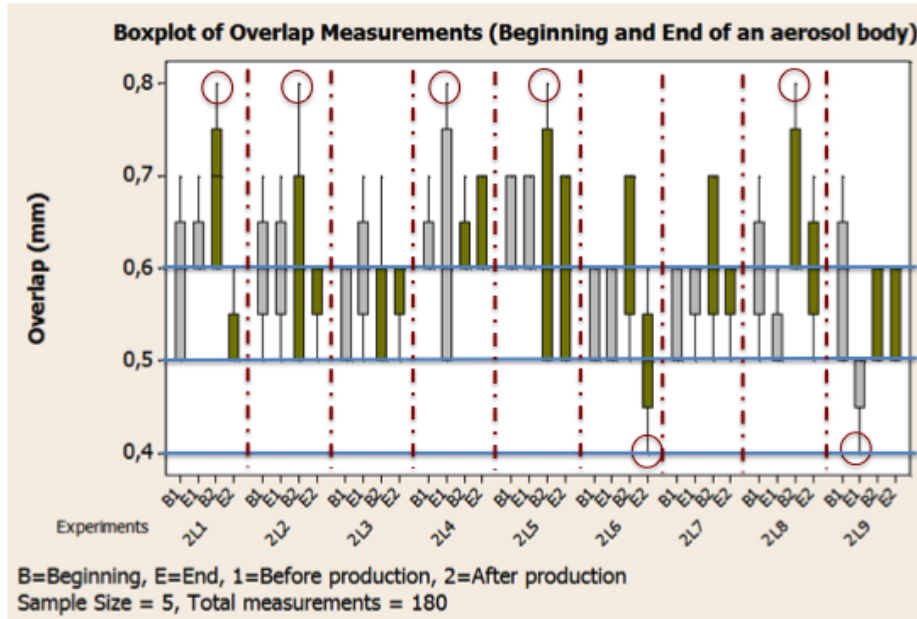
Figure 90: Boxplot of overlap measurements for confirmatory runs # 2

A limit has been marked in the plot with blue line at maximum allowable overlap of 0.6 mm and minimum allowable overlap of 0.4 mm. This range has already been discussed in chapter 3 that the equipment supplier has provided these range and showed confidence if the overlap lies within them.

The box plot does not show convincing results of overlap measurements because majority of the readings are crossing the upper limit. There is no direct correlation noted down from these overlap measurements and the DoE analysis. It can be concluded that the overlap measurements are not stable throughout the experiments. Therefore the overlap might be considered a noise factor, with a considerable effect on the DoE results. Nevertheless no correlation was found between overlap and leaks. Furthermore overlap was never measured underneath 0.4 mm that is really the most critical value of all for

leaks. Also the cans measured with overlap above the upper limit (above 0.6 mm) are all between 0.8 mm and 0.6 mm. Evidence from microscopic analysis shows that although an overlap between 0.8 and 0.6 mm is slightly out of specification, this should not be enough to create a leak mechanism. Therefore it can be said that within the available technology limits, the overlap between 0.4 mm and 0.8 mm is reasonably under control and should not be a cause for leaks or Microleaks. Nevertheless it would be an advantage for the company to install a mechanical system allowing guaranteeing an overlap between 0.4 mm and 0.6 mm for all produced cans.

5.5.   Summary

The Design of Experiments or DoE aimed to analyze the effect of welding factors on the welding beginning of an aerosol can, which is contributing significantly for the generation of leaky cans. In order to achieve this objective, an eight-step methodology for DoE application was followed. Among the eight steps, two steps were identified as critical for the current DoE analyses: (1) Defining and developing response variables; and (2) Identifying factor levels of controllable factors.

Identification of response variable was declared critical because all analyses and results were based on the sensitivity and quality of measurement systems. Both leak detection systems, the 100% automatic (Wilcomat) and the manual waterbath, were the two response variables chosen for measuring direct leaks of the aerosol cans. Furthermore, the response variables that were identified to analyze the physics of welding beginning were heat-affected area, extrusion, and thickness at the beginning of welding bead through performing macroscopic and microscopic analysis.

After selection of the response variables, next step was to select controllable factors. Based on the problem definition, five controllable factors were selected for the DoE analysis. These five factors were analyzed at three levels because of possible curvature behavior of factors. However, while establishing the levels´ values of each factor, the team faced significant challenge because the process was not fully controlled as well as due to the presence of unknown noise factors, factor levels were impossible to identify. In order to overcome this problem, a step-by-step guideline was developed and then

implemented on the shop floor that not only clearly identified the values of factor levels as well as revealed some interesting results. The procedure to accomplish the factor levels is termed as pre-experimental runs and few of the interesting results are:

- The brainstorming process with the key experts revealed that varying force at one or two units would not affect significantly in the generation of leaky cans. However, while performing the pre-experimental runs it was observed that force is greatly affecting the generation of leaky cans.

- The maximum and minimum possible distance between the welding bodies were clearly identified during these pre-experimental runs, which was not evident before.

Following identification of factors and their levels, model was analyzed using Taguchi orthogonal array method. The reason of choosing Taguchi method was because if full factorial analysis were selected then total 81 experiments were required to be performed on the shop floor, while using Taguchi design method only 9 experiments were required. In order to implement 9 experiments, 3 days of 8hrs/day were spent on the shop floor. During the implementation phase, all the planned response variables were recorded for statistical analysis.

The response variables leaks and conductance measurements did not provide any significant controllable factor at a 5% of significance level. This might be due to the Taguchi orthogonal method or the sample size was very small. In order to overcome this issue, full factorial analysis was planned. Among the five controllable factors, welding current and welding force were further considered for analysis while distance between the welding bodies, overlap and welding speed kept constant.

Confirmatory runs:

The objective of the confirmatory runs was to perform full factorial DoE analysis. In these confirmatory runs, following improvisations were made:

- Sample size was increased to 420 aerosol cans;
- Welding speed, overlap, and distance were considered as constant factors at 64 m/min, 0.5 mm, and 2 mm respectively.

- Same noise factors were selected that were recorded during the first experiments. However, diameters of welding rollers were preset at the constant values of: outer welding roller at 82.7 mm and inner welding roller at 53.9 mm.

- An improved working principle was developed for these confirmatory runs after gaining knowledge from the previous experiments;

- The statistical analysis is performed only for leaks (Wilcomat and Waterbath) measurements;

The results from leaks measurements (Wilcomat and waterbath combined) showed that between the two factors only welding force is significant. This was also clear if one analyzes the rejected aerosol cans and applies common sense that welding force at the highest level (44 kgf) generates most of the leaks. However, it was not very clear in the previous analysis whether welding current has significant effect on the leaks or not.

The overlap measurements for these confirmatory runs do not show convincing results because majority of the readings were above the upper limit (0.6 mm). Furthermore, there is no direct correlation noted down from these overlap measurements and the DoE analysis.

Overall, the DoE analysis showed a combination of factors that reduces drastically the Microleaks as well as improves the productivity by 10% (increasing welding speed from 58 m/min to 64 m/min). For the current production setting, the factors should be set at:

Factor	Welding current	Welding force	Welding speed	Overlap	Distance between welding bodies
Level	250 kA	40 kgf	64 m/min	0.5 mm	2 mm

Chapter 6 - Cost of Quality Model

The objective of chapter 6 is to develop cost of quality models in order to analyze different sampling scenarios as well as alternative technologies and leak detection systems, so that the quality of conformance and overall cost of production for a single aerosol can is optimized. First, a general introduction to the cost of quality widely used model Prevention-Appraisal-Failure model is presented.

The next section discusses different inspection strategies and the acceptance-sampling plans currently used by the industry in order to detect the non-conforming lots generated along the manufacturing process. A process based cost model was developed and is described in detail, estimating the cost per piece of a single aerosol can based on the current data received from the industry.

The discussion is focused on the detailed description of the as-is double stage acceptance sampling plan, followed by a proposal of alternative sampling plans including single acceptance sampling, single revised sampling, and no sampling.

Section 6.4 discusses further the development and analysis of alternative technologies, with a special incidence on the trimming technology. A set of experiments that show how this technology can be used to reduce the Microleaks is also presented, as well as cost analysis of the trimming technology, comparing these results with the proposed sampling plans.

Section 6.5 discusses the alternative leak detection systems, which may be integrated with the current Colep´s aerosol production system. In particular, the gas tracer leak detection, where hydrogen and helium gas can be used to detect Microleaks with a very small precision ranging from 10^{-5} to 10^{-3} ml/min, is briefly explained. A cost analysis is also provided comparing different gas tracer leak detection systems.

6.1. Introduction to Cost of Quality

This chapter is the seventh step of the framework presented in chapter 4 and the focus is on the development of cost of quality model. Thus, the focus of this chapter is not only on maximizing the quality of conformance through reduction of Microleaks, but also on minimizing the overall costs. The relation between quality and cost is well explained by the Cost of Quality (CoQ) approach, modeling the quality of a system through the costs incurred in providing that quality. As such, the cost of quality can be identified, measured and improved and should be considered an important metric for any manufacturing industry.

CoQ is better explained as the cost incurred in the design, implementation, operation and maintenance of an organization's quality management system. In other words, the cost committed to continuous improvement processes, cost of system, production and service failures, and non-value added activities and wastage in all its various forms (Pursglove and Dale 1995).

CoQ proposes a breakeven point between maximizing the quality of conformance and minimizing the associated cost. Bottorff (1997) highlighted advantages of having a CoQ system as a system that leads to the development of more advanced performance measures in the areas of customer satisfaction, production and design, to target indirect quality costs better.

Juran was one of the first authors who developed the concept of quality costing, expressing simply that "all the costs would disappear if no defects were produced" (Joseph M. Juran 1951). Feigenbaum, (1956) extended Juran´s concept and studied the quality cost categorization of Prevention-Appraisal-Failure (P-A-F) model. Crosby split the CoQ into conformance costs and non-conformance costs (Crossby 1979). Schiffauerova & Thomson, (2006) made a comprehensive survey on the CoQ models comprising four generic models, as presented in Table 35.

Table 35: Generic Cost of Quality models (Schiffauerova & Thomson, 2006)

Generic model	Cost categories
P-A-F models	Prevention + Appraisal + Failure
Crosby´s model	Conformance + Non-Conformance
Opportunity cost models	Prevention + Appraisal + Failure + Opportunity Tangibles + Intangibles P-A-F (failure costs includes opportunity costs)
Process cost models	Conformance + Non-Conformance
ABC models	Value-added + Non-value-added

Among these models, the classical P-A-F model is the most widely used and will be discussed in detail in the next section.

6.2. Prevention-Appraisal-Failure (P-A-F) Model

Prevention costs refer to all costs incurred to prevent nonconformance, such as the ones due to scheduled equipment maintenance, tool replacement, investments in worker training, and quality improvement programs. Appraisal costs are the costs involved in attempting to detect a non-conformed unit through inspection or testing. Failure costs are further divided into internal and external failure costs: internal failure costs include costs of rework attempts, and scrap when rework is no longer possible, whereas external failure costs occur when a non-conforming unit is mistakenly delivered to the consumer and fails on field. Examples of external failure costs are warranty claims and loss of goodwill and sales.

Williams, Wiele, & Dale, (2000) also classified the P-A-F model in terms of various categories; like system failures can result in obsolete stocks, lost items, production or operation delays, additional work, scrap, rectification, late deliveries, additional transportation costs, poor service. Product or service failures result in warranty, product liability claims, product recall, additional customer service costs, and loss of customer goodwill. Table 36 presents costs that belong to each category in a P-A-F model:

Table 36 Example of type of costs that belong to each category (Zaklouta 2011)

Prevention	Appraisal	Internal Failure	External Failure
Design and development of equipment	Receiving inspection	Scrap	Lost profit/sales
Quality review	Laboratory testing and inspection	Rework and repair	Loss of goodwill
Maintenance and calibration of production and inspection equipment	In-process inspection	Rescheduling due to downtime	Warranty
Quality training (seminars and workshops)	Field testing (performance tests)	Downgrading	Allowances
Supplier quality audits	Final inspection (100%/sampling inspections)	Overtime to cover production losses	Product recalls
Quality improvement programs	Inspection and test equipment		Allowances

It is clear that there has to be a tradeoff between the maximum possible quality with the lowest possible cost and the Lundvall-Juran curve in Figure 91 shows this classical view of CoQ tradeoffs. The picture shows that the non-conformance costs decrease at a decreasing rate and the conformance costs increases at an increasing rate, while the quality of conformance increases. This combined effect results in a parabolic curve with a tradeoff point called the economic quality level (EQL).
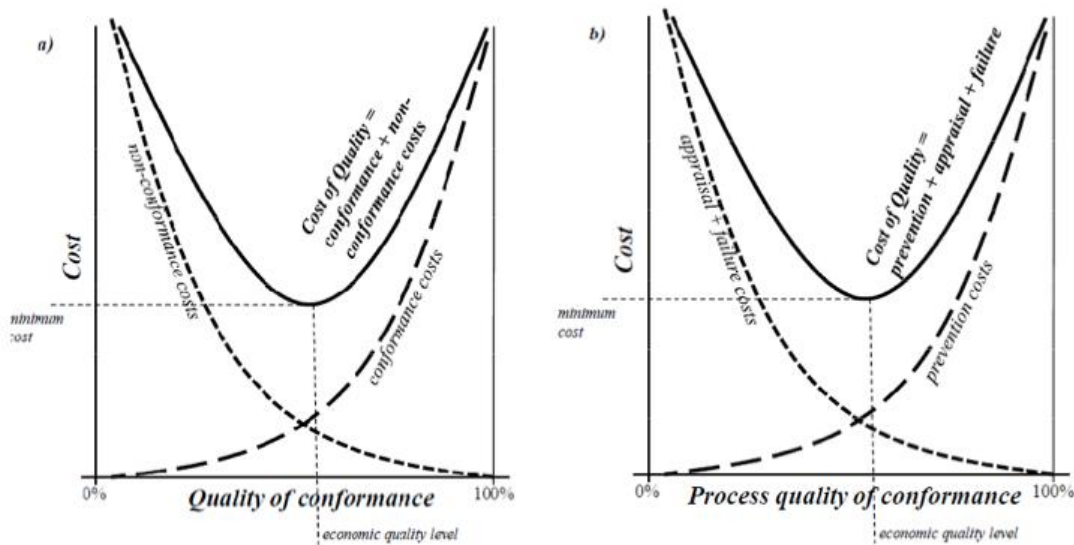
Figure 91: a) Lundvall-juran curve depicting relationship between conformance and non-conformance costs and the tradeoff point (economic quality level) b) P-A-F version of Lundvall-Juran curve.

When putting Figure 91 into the context of the P-A-F model, the Lundvall-Juran curve defines conformance cost as the prevention costs, while the non-conformance cost as the sum of failure and appraisal costs (Joseph.M. Juran, Seder, and Gryna 1962).

The discussions and results achieved in the previous chapters reveal that there are three important areas that need to be further investigated when applying the cost of quality model: (1) analyzing the cost impact of current inspection strategies applied for manual waterbath leak detection systems, propose alternative inspection strategies and compare the overall costs, (2) analyzing the cost impact of trimming technology, and (3) analyzing the cost impact of alternative leak detection systems. These areas are separately discussed in detail in the following sections.

6.3. Analyzing inspection strategies for the industrial application

Inspection is a form of testing the quality of units being produced and one aspect of quality assurance. In chapter 3, two types of inspections performed at Colep were discussed in detail: the first one consists in 100% inspection of aerosol cans through the Wilcomat machine and the second one is based on acceptance sampling through a manual waterbath system. Prior to develop a cost model of the actual system, it is important to investigate the current sampling procedure of waterbath systems as well as to propose alternative sampling procedures, comparing their results.

Acceptance Sampling is one of the important elements in the P-A-F model of CoQ. However, the use of this techniques should not substitute process monitoring and quality improvement methodologies, because acceptance-sampling can´t eliminate all non-conforming units produced by an imperfect manufacturing process. Furthermore, acceptance sampling is usually deployed when it is required to compromise between no inspections at all and 100% inspection, having direct implications on the appraisal and failure costs (Montgomery 2009).

A simple acceptance sampling procedure operates by considering a lot size of S, and taking a random sample of S_n units from the batch. If there are more than a pre-defined number of c defective units in the sample, the whole lot is rejected and scrapped. Thus, a single-sampling plan for attributes is characterized by the sample size S_n and the

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acceptance number c. There are various sampling plans widely known, including single, double, multiple and sequential sampling. Also, there are many schemes to measure the performance of these sampling plans, such as operating characteristic curve (OC) that plots the probability of accepting the batch versus percent defectives (Montgomery 2009). Dodge and Roming defined a scheme, which includes two separate plans for lot tolerance percent defective (LTPD) and average outgoing quality limit (AOQL) (Joseph M. Juran and Godfrey 1998). Other schemes include decision theory schemes (Wetherill 1977) and Bayesian sampling scheme (Chen, Li, and Lam 2007). Harold F. Dodge (Dodge 1943) developed a continuous sampling scheme that begins with 100% inspection, and when a defined quantity of units are free of non-conformities, then the sampling plans are deployed. Similarly, if the number of non-conforming units is more than the defined acceptable limits while sampling, 100% inspection is again resumed.

When sampling takes place and because inspection is never 100% reliable and involves human errors, two errors might always occur, namely the type I and type II errors. 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 92.

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

Figure 92: Type I and type II errors

The type of acceptance sampling procedure applied in Colep at the assembly line 12 and with the, format 65x300 (see chapter 3, section 3.1), is a double stage acceptance sampling. Before developing the COQ model for this double stage sampling procedure, a process based cost model for the assembly line 12 is first developed.

The following sections are organized as follows: first, a Process Based Cost Model (PBCM) is developed, estimating the fixed and variables costs in order to manufacture a single aerosol can. Then, equations are developed for individual processes (welding, seaming, and 100% testing) that will be useful in developing a COQ for all the scenarios. Then, the as-is double stage sampling procedure of the assembly line under analysis is modeled and all formulations related to COQ are developed. Similarly, all relevant formulations for proposed procedures are developed and discussed. The results from these scenarios are only discussed at a later section, where the findings for all the scenarios considered are compared.

6.3.1. Process based cost model for line 12, format 65x300

A general process model for assembly line # 12 is illustrated in Figure 93.
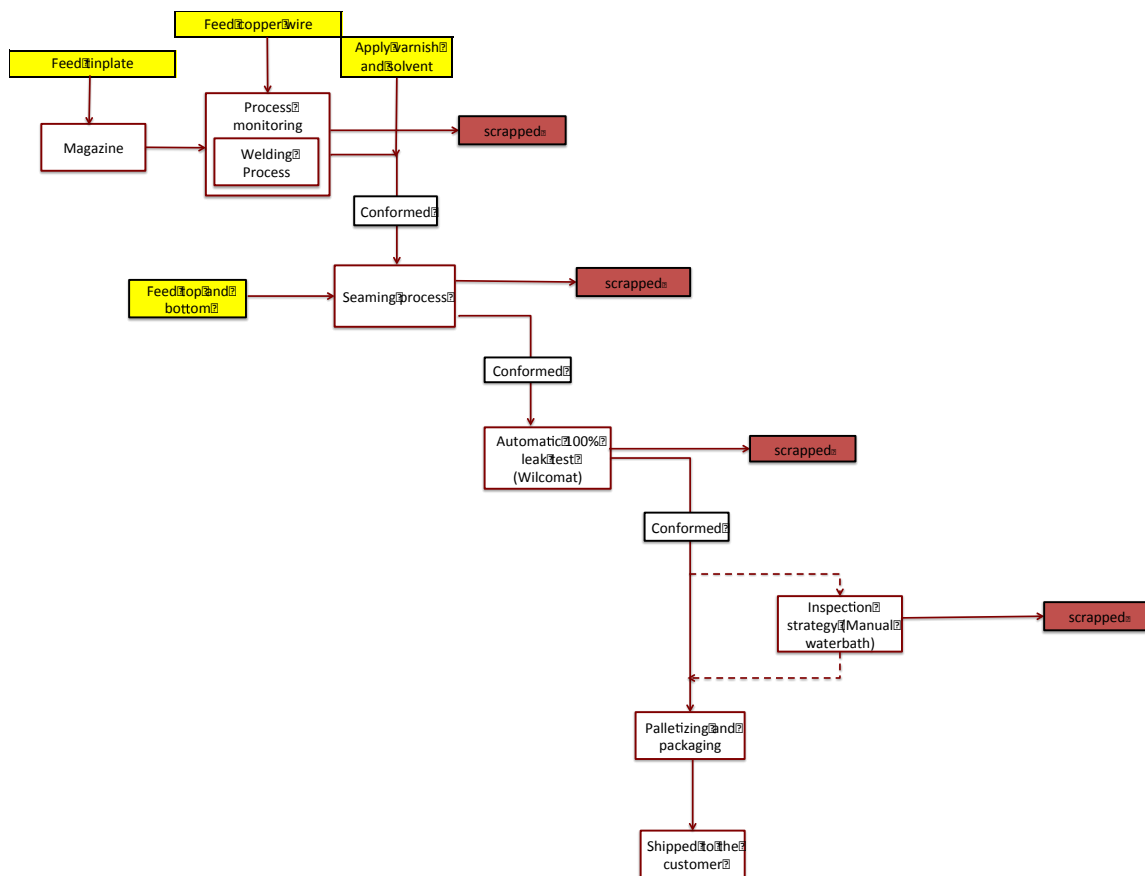
Figure 93: Illustration of process flow for assembly line # 12

The blocks highlighted with yellow color show the input variables to the process and the blocks highlighted with red color represent scrap. The flow diagram also includes the inspection strategy currently in place (manual waterbath system), despite the fact that Colep doesn't include the cost of this system to estimate the final cost per piece, as it is assumed that this cost is marginal when compared to the overall costs. Therefore, the data received from Colep does not include the cost of the inspection strategy (equipment, setup, and scrap). This general model along with the inspection strategy (manual waterbath) will be later used in the section for the development of alternative inspecting strategies, where further details are provided regarding the inspection strategy used for manual waterbath systems.

The PBCM for the assembly line of aerosol cans starts by identifying the relevant cost elements. In this case, there are two major cost categories: (1) Variable cost; and (2) Fixed cost.

Variable Cost: Variable costs are those costs that can be directly associated with the production output of a unit, and whose magnitude (on a per period basis) increases roughly linearly with the total number of units produced (Kirchain and Field 2001). For the case of aerosol cans, variable costs are:

$$C_{variable,Total} = C_{Material} + C_{Energy} + C_{Labor} + C_{Packaging\ \&\ Palletizing}$$

$$C_{Material} = (C_{i,\ Body} + C_{i,\ Bottom} + C_{i,\ Top} + C_{i,\ Copper\ wire} + C_{i,\ Varnish} + C_{i,\ Solvent})^* \ APV$$

$$C_{Energy} = C_{i,\ Utilities} \ ^*APV$$

$$C_{Labor} = (C_{i,\ Direct\ Labor} + C_{i,\ Indirect\ Labor})^* \ APV$$

$$C_{Packaging\ \&\ Palletizing} = (C_{i,\ Packaging} + C_{i,\ Secondary\ Palletizing})^* \ APV$$

Where C is the cost per year; C_i is the unit cost per component, i; APV is the annual production volume.

Fixed Cost:

Fixed costs generally fall into one of two groups: those that are one time capital expenses and those that represent recurring payments related to the quantity of parts produced. Recurring payments, like building rent, are easily annualized or converted to any pertinent time period basis, but one-time payments require adjustments to allocate this cost over the duration of production. Given that capital goods can remain productive for years, or even decades, it is important to factor in the time value of money into this allocation (Kirchain and Field 2001).

For the case of the current application case, the fixed costs for assembly lines represent both groups. Then, we can specify fixed costs as:

$$C_{Fixed,Total} = C_{Machine} + C_{Setup} + C_{Maintenance}$$

The per year fixed costs are:

$$C_{Machine} = (C_{i, Equipments}) * APV$$

$$C_{Setup} = (C_{i, Setup}) * APV$$

$$C_{Maintenance} = (C_{i, Maintenance}) * APV$$

Results:

A cost model was first built in excel spreadsheets to calculate the fixed and variable costs for the assembly line. Input data from the industry was provided in the form of per 1000 units cost, as shown in Appendix IV (cost for assembly line # 12) and, with this information, the cost per unit and the total cost were calculated. As stated earlier, the fixed and variable cost received from Colep doesn't include costs of inspection strategies (manual waterbath) – therefore, the calculations performed in this section doesn't include these inspections costs. However, when calculating the cost of alternative strategies, these inspection costs will be considered.

Based on historical data provided by the company, the annual production volume considered is 32 million pieces/year, produced in three shifts. The results in Table 37 shows that the total cost incurred in manufacturing an aerosol can are only 20.1euro cents.

Table 37: Results of variable and fixed costs

Variable costs	Per piece	Per year (3-shifts)	Percent
Material Cost	€ 0.15753	€ 5,040,960.00	78.26%
Energy Cost	€ 0.00272	€ 87,040.00	1.35%
Labor Cost	€ 0.00814	€ 260,480.00	4.04%
Packaging Cost	€ 0.01772	€ 567,040.00	8.80%
Total Variable Cost	€ 0.19	€ 5,955,520	92.45%

Fixed costs	Per piece	Per year	Percent
Main Machine Cost	€ 0.00406	€ 129,920.00	2.02%
Setup Cost	€ 0.00826	€ 264,320.00	4.10%
Maintenance Cost	€ 0.00287	€ 91,840.00	1.43%
Total Fixed Cost	€ 0.02	€ 486,080	7.55%

Total Fabrication Cost	€ 0.201	€ 6,441,600	100.00%

A sensitivity analysis was performed between production volume, fixed and variables costs, as shown in Figure 94.
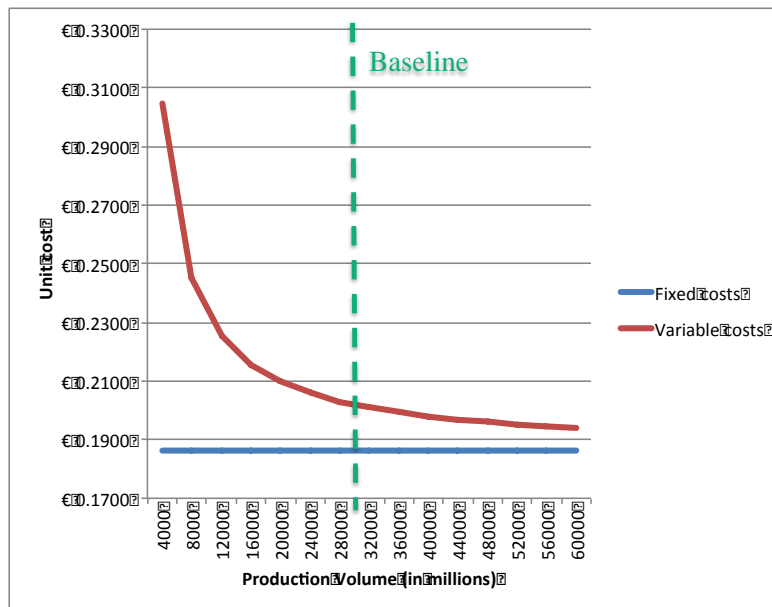
Figure 94: Sensitivity analysis of production volume, fixed and variable costs

The graph shows that when the production volume is too low, then the per piece cost is very high. These costs decrease drastically between the ranges of $8000 - 12000$ million pieces. There is a green doted line marked in the graph that shows the baseline value of the production volume.

Furthermore, it is important to highlight the fact that during peak demand time the production can be ramped up to four shifts and the assembly line can produce up to 43 million pieces/year, thus decreasing substantially the per piece cost.

6.3.2. Process calculations

In the previous section the overall fixed and variable costs were calculated for the entire assembly line, without separating the costs associated with independent process (welding, seaming, and 100% leak testing). In this section fixed and variable costs are formulated for each independent process, which will be later used by each inspection strategy scenario (sections 6.3.3, 6.3.4, 6.3.5, and 6.3.6).

Although the assumptions for the cost calculations are very similar to section 6.3.1, each process has separate inputs and outputs.

Welding Process:

The welding process is the first process of the assembly line. The blank (converted into bodies after the welding process) and copper wire are given as inputs to the process. The height of the blank is 304 mm for format 65x300, a height that is reduced at a later stage when it passes through the deforming processes. The fixed and variable costs for the welding process are:

$C_{i,Total} = C_{i,Variable} + C_{i,Fixed}$

$C_{i,Variable} = C_{i,Blank} + C_{i,Labor} + C_{i,Utility} + C_{i,Copper\ wire} + C_{i,Varnish} + C_{i,Solvent}$

$C_{i,Fixed} = C_{i,Setup} + C_{i,Maintenance} + C_{i,Equipment}$

$TP_{Welding} = TP_{Seaming} * (1 + SR_{Welding})$

Where TP is total pieces required to produce at the defined process; SR is the scrap rate at the defined process.

In order to calculate the costs for an annual production volume, the costs described above can be simply multiplied by the annual production volume (APV).

Seaming Process:

In the seaming process, the top and bottom of an aerosol can is given as input. The fixed and variable costs for the seaming process are:

$C_{i,Total} = C_{i,Variable} + C_{i,Fixed}$

$C_{i,Variable} = C_{i,Bottom} + C_{i,Top} + C_{i,Direct\ labor} + C_{i,Utility}$

$C_{i,Fixed} = C_{i,Setup} + C_{i,Maintenance} + C_{i,Equipment}$

$TP_{Seaming} = TP_{Leak\ testing} * (1 + SR_{Seaming})$

Leak Tesing (Wilcomat):

In the 100% leak testing process, the variable costs comprehend the number of units scrapped, calculated based on the scrap rate of the machine, as well as the cost/component incurred at the seaming and welding processes. The fixed and variable costs for the leak testing process are:

$C_{i,Total} = C_{i,Variable} + C_{i,Fixed}$

$C_{i,Variable} = C_{i,Labor} + C_{i,Utility} + (C_{i,Seaming/component} + C_{i,Welding/component}) * SR_{Wilcomat} *$
$\qquad TP_{Palletizing\ \&\ Packaging}$

$C_{i,Fixed} = C_{i,Setup} + C_{i,Maintenance} + C_{i,Equipment}$

$TP_{Leak\ testing} = TP_{Palletizing\ \&\ Packaing} * (1 + SR_{Seaming})$

Palletizing and Packaging:

The palletizing and packaging is the last process of the assembly line and does not include any scrapping of the material. The fixed and variable costs for the palletizing and packaging process are:

$C_{i,Total} = C_{i,Variable} + C_{i,Fixed}$

$C_{i,Variable} = C_{i,Pallet} + C_{i,Labor} + C_{i,Utility} + C_{i,Secondary\ Packaging}$

$C_{i,Fixed} = C_{i,Setup} + C_{i,Maintenance} + C_{i,Equipment}$

$TP_{Palletizing\ \&\ Packaing} = TP_{Required}$

The formulations developed in this section will be applied to estimate the COQ model for all the sampling scenarios that are discussed in the next sections.

6.3.3. Scenario A - Double stage acceptance sampling procedure

The type of sampling strategy applied in assembly line 12 is a double stage acceptance sampling procedure.

In a double stage sampling, first a sample of units S_{n1} is randomly collected from a batch or lot. A decision is made based on a sampling plan that specifies the non-conforming units d_1 and the acceptance number c_1, among acceptance, rejection or continuing inspection of the batch. If d_1 is greater than c_1, a second sample S_{n2} is taken from the same batch otherwise the batch is accepted and shipped to the customer or to the posterior manufacturing process. If the second sample is taken, the information from both the samples, including non-conforming units d_2 and acceptance number c_2 for the second sample, is combined in order to reach a decision of acceptance or rejection of the lot. A general scheme for the double stage sampling is shown in Figure 95.

Figure 95 Representation of a double stage acceptance-sampling flow diagram

For the case of double stage acceptance-sampling, the following simplifying assumptions are made:

- Units are produced at a very high production rate (e.g. 100 units/min);
- Cost of a unit is very low;
- Cost of testing a unit is low;
- Rejection rate is relatively small;
- External failure cost is relatively high;
- None of the rejected non-conformed units are reworked;
- Batch size or lot size is the same throughout the production year;
- All non-conforming units shipped to the customer are detected non-conformed.

Figure 96 illustrates the procedure of double stage acceptance sampling applied for line 12 in Colep. The type of double acceptance sampling used by Colep is based on the military standard plans, the most widely known acceptance-sampling system (in the present case, for attributes). There are different types of double-sampling schemes, but Colep adapts and slightly alters them according to the customer. An important point to highlight is that, in the second sample, instead of analyzing the all lot, the different pallets

that comprehend the lot of aerosol cans are analyzed one-by-one. As these pallets vary in number as well as in size, a simplifying assumption was made of considering all pallets with average 1000 units. If pallets are found non-conforming, only the pallets are scrapped, instead of scraping the whole lot.
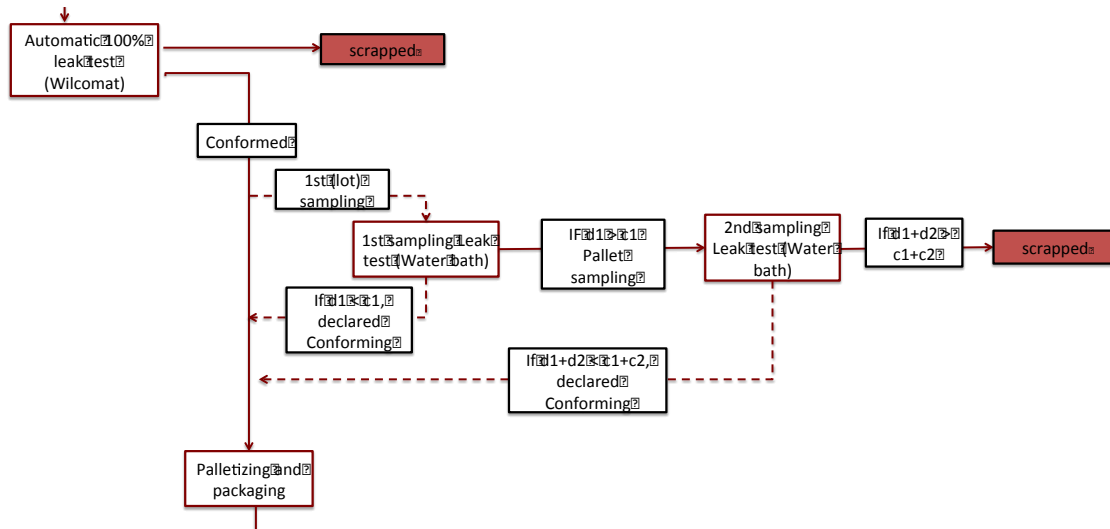
Figure 96: Schematic representation of double stage accepting sampling

First step is to calculate the average number of units sampled, S_n. In this case, the two samples taken are expressed in terms of percentage to the lot or batch size S_b due to limitation of the manual waterbath machine to sample limited aerosol cans. Therefore, these two samples are expressed in terms of percentages rather than a fixed sample size i.e. P_{sn1} and P_{sn2}. For example, if the lot size is 10,000 units and the sample size is 125, then the input data given in the excel sheet was 1.25% for the 1st sample. The maximum % of units sampled by a single manual waterbath leak-testing machine is assumed to be 1.5% of the total production.

The total number of first sample taken in a theoretically finite time is N_p. The probability that the second sample is taken from the same batch is p_r, with a probability of being rejected and scrapped is p_s.

$S_n = M_{n+1} + (N_p * p_s * S_b)$

$N_p = APV/S_b$

Where M_{n+1} is the total units produced at the post manufacturing process; APV is the annual production volume.

The Inspection cost ($C_{Inspection}$) has two components, first is the fixed cost (C_{Fxed}) that is the cost of the testing equipment ($C_{Equipment}$) and the second is the variable cost ($C_{Variable}$) that is the cost of testing the sample ($C_{Testing}$) plus cost of scrapping the lot (C_{Scrap}).

$C_{Inspection} = C_{Fixed} + C_{Variable}$

$C_{Fixed} = C_{Equipment} = PMT$ (interest rate, payment periods, present value)

$C_{Variable} = C_{Testing} + C_{Scrap}$

$C_{Testing} = ((S_n * P_{sn1}) + (p_r * N_p * P_{sn2})) * C_{i,Testing}$

$C_{scrap} = p_s * N_p * S_b * C_{i,Scrap}$

Where C_i is the unit cost

The probability of taking the second sample, assuming that the number of rejected units in the sample follows a binomial distribution is:

$p_r = 1 - \sum_{d1=0}^{c1} p_{d1}{}^{d1} \frac{S_n!}{d!(S_n - d1)!} (1 - p_{d1})^{S_n - d1}$

The probability of rejecting and scrapping the batch is

$p_s = p_r * (1 - \sum_{d2=0}^{c2} p_{d2}{}^{d2} \frac{S_n!}{d!(S_n - d2)!} (1 - p_{d2})^{S_n - d2})$

Where p_{d1} is the percent defective on the lot for the first sample, p_{d2} is the percent defective for the second sample.

6.3.4. Scenario B - Single stage acceptance sampling procedure

The first alternative sampling procedure proposed is the single stage acceptance sampling, i.e. a single-sampling plan, where a sample of units S_n is randomly drawn from a batch/a lot of size S. Based on the number of observed defectives in the sample, a decision is made between acceptance and rejection of the all batch. If the number of non-

conforming units d is greater than the acceptance number c, the all batch is rejected; if the number of non-conforming units is less than or equal to d, the lot is accepted. A declared conformed batch is shipped directly to the customer or to the post manufacturing process, whereas a non-conformed batch is rejected and scrapped. A general scheme for single stage acceptance sampling is shown in Figure 97.
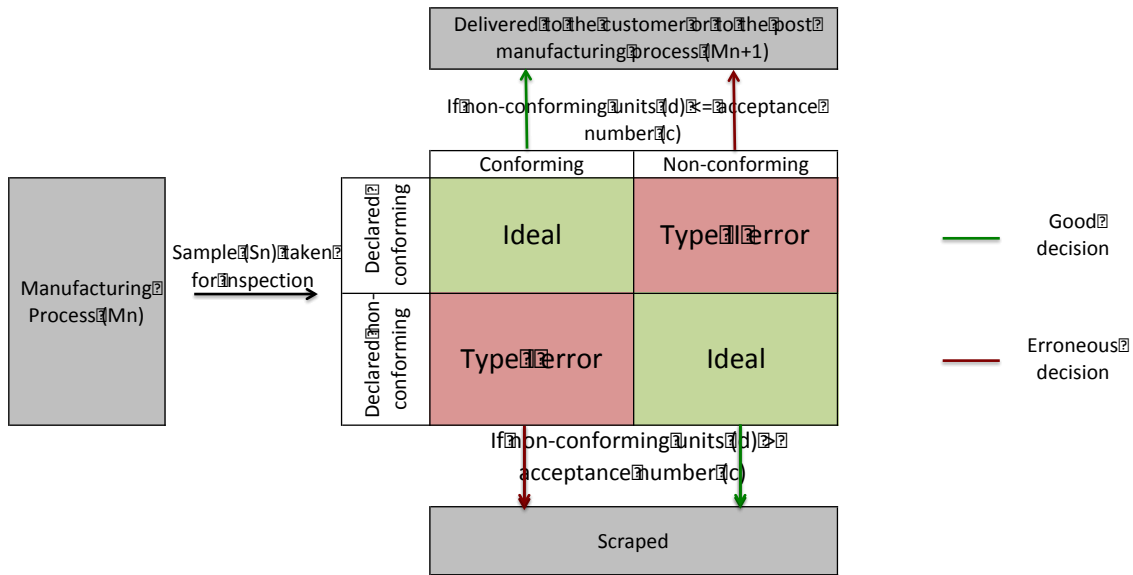
Figure 97: Representation of a single stage acceptance sampling flow diagram

In the current study, several simplifying assumptions are made in order to arrive to an expression:

- Units are produced at a very high production rate (e.g. 100 units/min);
- Cost of a unit is very low;
- Cost of testing a unit is very high;
- Rejection rate is relatively high;
- External failure cost is high;
- None of the rejected non-conformed units are reworked;
- Batch size or lot size is same through out the production year;
- All non-conforming units shipped to the customer are detected non-conformed.

Figure 98 illustrates the procedure of the single stage acceptance sampling proposed for line 12 in Colep.
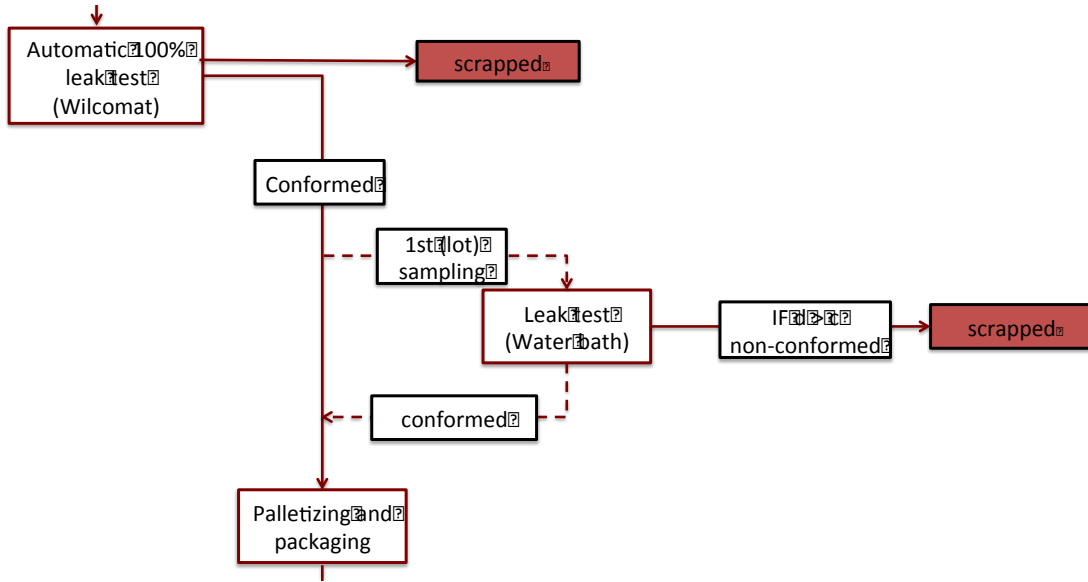
Figure 98: Schematic representation of single stage acceptance sampling

The average number of units sampled S_n is essential in formulating an expression for costs. For a single acceptance sampling strategy, S_n depends primarily on the total units produced at the post manufacturing process (M_{n+1}), number of samples taken throughout the production period (N_s), probability of rejecting and scrapping the batch (p_s), batch size (n_b), and percent of units measured per batch (p_b):

$$S_n = M_{n+1} + (N_s * p_s * n_b * p_b)$$

The Inspection cost ($C_{Inspection}$) has two components: the first is the fixed cost (C_{Fxed}) that is the cost of the testing equipment ($C_{Equipment}$), and the second is the variable cost ($C_{Variable}$), that is the cost of testing the sample ($C_{Testing}$) plus the cost of scrapping the lot (C_{Scrap}).

$$C_{Inspection} = C_{Fixed} + C_{Variable}$$

$$C_{Fixed} = C_{Equipment} = PMT \text{ (interest rate, payment periods, present value)}$$

$$C_{Variable} = C_{Testing} + C_{Scrap}$$

$$C_{Testing} = N_s * n_b * p_b * C_{i,Testing}$$

$$C_{Scrap} = N_s * p_s * n_b * p_b * C_{i, Scrap}$$

Where C_i is the unit cost

The probability of scrapping a lot with a percent defective in the lot (p_d) is

$$p_s = 1 - \sum_{d=0}^{c} p_d{}^d \; \frac{S_n!}{d!(S_n-d)!} \; (1 - p_d)^{S_n-d}$$

If the acceptance number c is very small and the percentage defective p_d is relatively high, the standard single acceptance sampling may not always be a good approach for a low cost product with a high production rate. It is evident in this case that many lots will be rejected and scrapped, thus increasing the overall costs. Therefore, in order to find a better alternative solution, a revised single sampling plan is proposed that only rejects the non-conforming units in the sample rather than the complete batch. It is important to note that this method would not be named as an acceptance-sampling plan, as it is not taking any judgment of the lot quality based on the sample.

6.3.5. Scenario C - Single stage revised sampling procedure

Similar to single stage acceptance sampling, a sample of units S_n is randomly drawn from a batch or a lot of size S. However, in this revised case only a unit from the sample is either declared conforming or non-conforming following the inspection process. A declared conforming unit is shipped directly to the customer or to the post manufacturing process, whereas only the non-conforming units in the sample are rejected and scrapped, instead of scraping the complete lot. A general scheme for this single stage revised acceptance sampling is shown in Figure 99.

For the revised single acceptance sampling following simplifying assumptions are made:

- Units are produced at a very high production rate (e.g. 100 units/min);
- Cost of a unit is very low;
- Cost of testing a unit is relatively high;
- Rejection rate is relatively small;
- External failure cost is relatively high;
- None of the rejected non-conformed units are reworked;
- Batch size or lot size is same through out the production year;

- All non-conforming Units shipped to the customer are detected non-conformed;

- Only non-conformed unit is rejected from the sample not the whole lot.
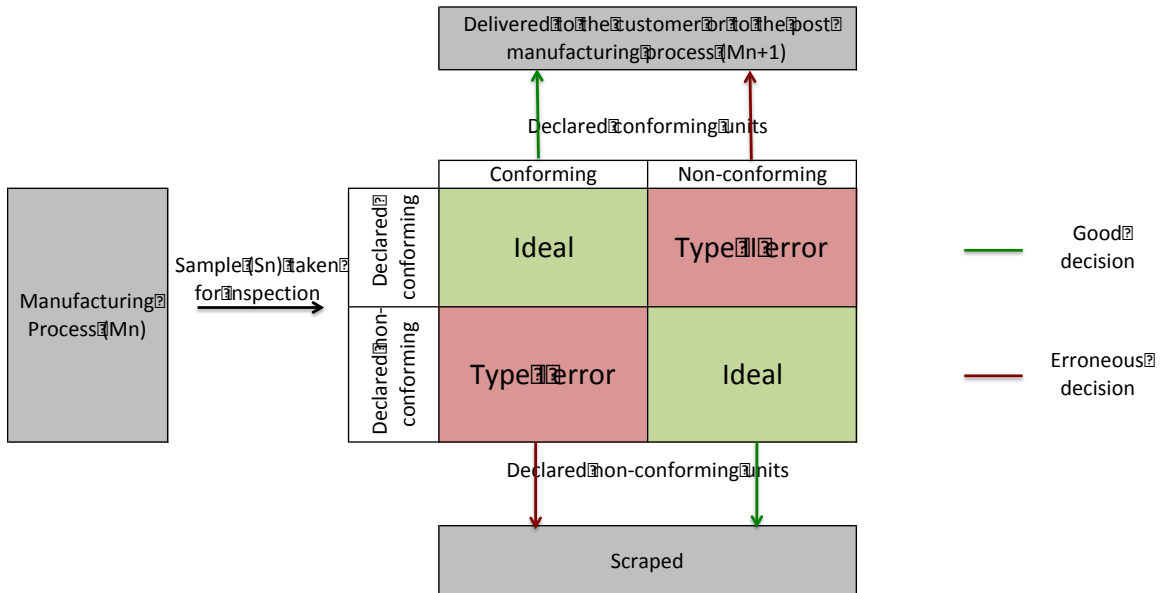
Figure 99: Representation of a single stage revised acceptance sampling flow diagram

Figure 100 illustrates the procedure of single stage revised sampling applied for line 12 in Colep.
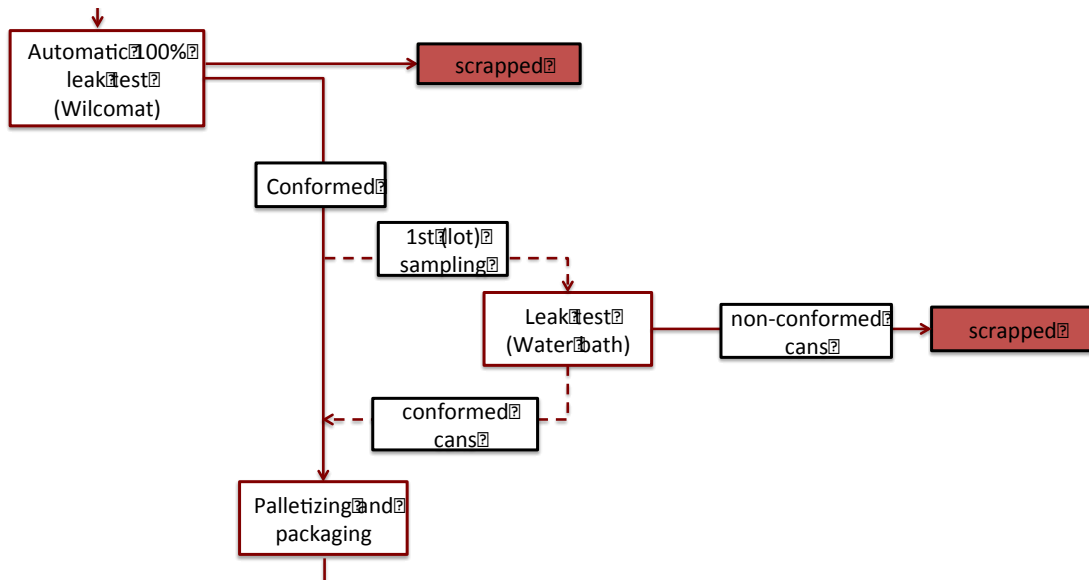
Figure 100: Schematic representation of single stage revised acceptance sampling

Similar to the procedure followed in single stage acceptance sampling, first it is depicted the number of units sampled and the expression that calculates the costs. For a revised single acceptance strategy, S_n depends primarily on the total units produced at the post manufacturing process (M_{n+1}), number of samples taken throughout the production period (N_s), percent defective in the lot (p_d), batch size (n_b), and percent of units measured per batch (p_b):

$$S_n = M_{n+1} + (N_s * p_d * n_b * p_b)$$

$$C_{Inspection} = C_{Fixed} + C_{Variable}$$

$$C_{Fixed} = C_{Equipment} = PMT \text{ (interest rate, payment periods, present value)}$$

$$C_{Variable} = C_{Testing} + C_{Scrap}$$

$$C_{Testing} = N_s * n_b * p_b * C_{i,Testing}$$

$$C_{Scrap} = N_s * p_d * n_b * p_b * C_{i,Scrap}$$

6.3.6. Scenario D - No waterbath inspection strategy procedure

When no inspection is performed apart from the 100% testing at Wilcomat, then the process flow is simple and straightforward as shown in Figure 101. Also, there is no need to develop any cost formulations for this scenario.
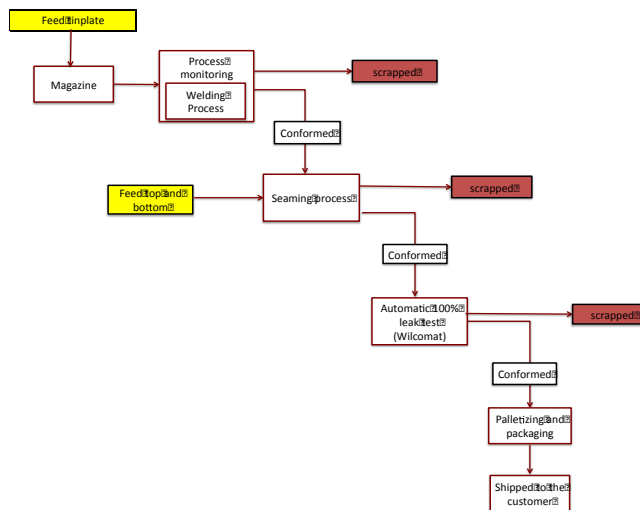
Figure 101: Process flow when no waterbath inspection is performed

6.3.7.   Defining quality of conformance rates and external failure costs

Prior to presenting the final results of this analysis, it is necessary to discuss the concept of quality of conformance and non-conformance rates, as well as external failure costs. The flow diagram of Figure 102 introduces these concepts.
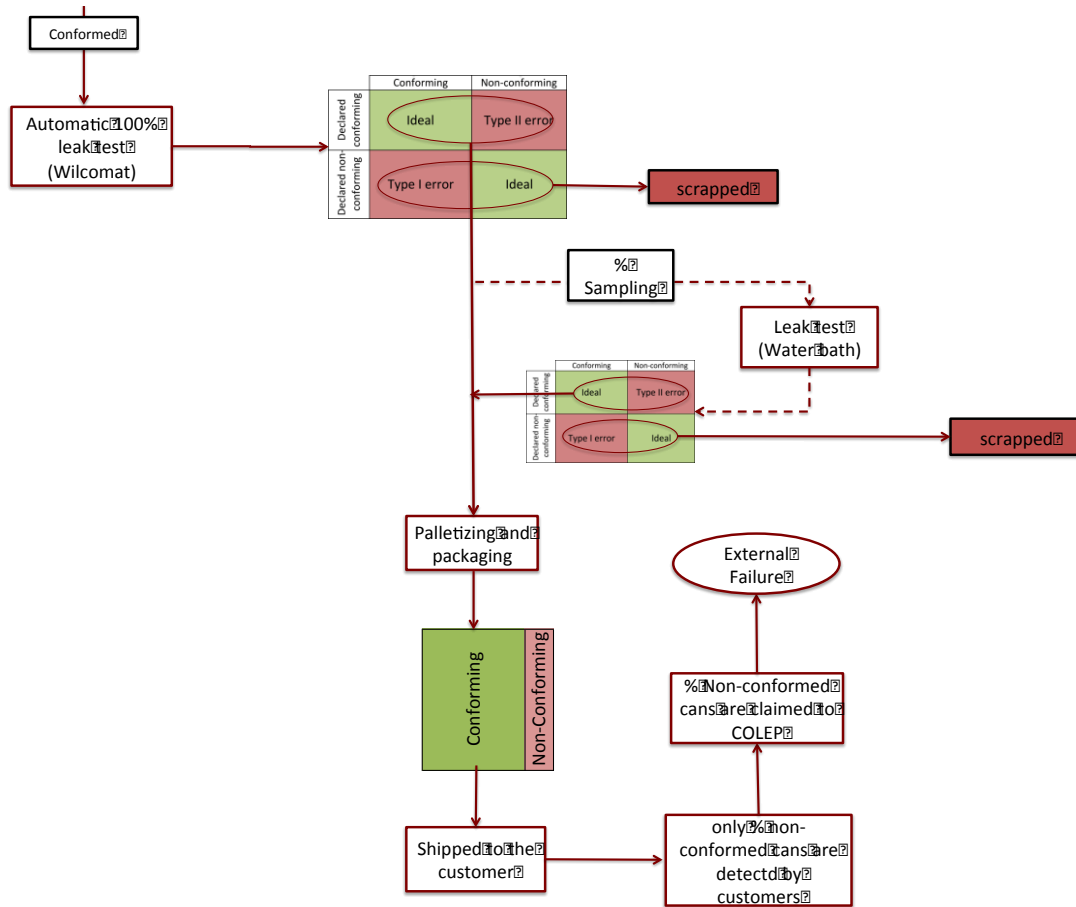
Figure 102: Explaining external failure, quality of conformance and non-conformance rates

Quality of Conformance rates for 100% Leak Testing (Wilcomat):

In summary, following 100% testing of the aerosol cans, there are two possible paths: either the cans are declared non-conforming and immediately scrapped, or declared conforming to standards and sent to the next production process (Figure 102).

Declared Non-Conforming rates:

In the case of declared non-conforming cans at either stage, there is a possibility that the testing machine results in false positives (type I error) and, despite the fact that aerosol cans are good, they are nevertheless scrapped. As a final result, material costs are increased.

Currently, neither the leaky aerosol cans nor the false positives at assembly line # 12 are counted, which makes the estimation of the non-conformance rate quality difficult. A reference value was taken from the DoE results achieved in Chapter 5, Table 29 also revisited here in Table 38, showing a range of false positives (or type I error) between 0% - 86% with an average of 26% (Column A). The maximum value of 86% shows an outlier that might have happened due to the reason that Wilcomat was not properly calibrated. Although, it is difficult to choose any single number from this table because it is not known which combination of factors the assembly line 12 works, after discussing with the team members as well as analyzing the table results, a range of 10% - 20% of false positive (column A) looks appropriate.

Table 38: False positive analysis of Wilcomat machine

Leak measurements (Wilcomat machine)					
Experiment #	X -Rejections (measuring through Wilcomat machine)	Y - Rejections (validation of wilcomat rejections using waterbath)	Z – total sample size	1 - Y/Z % Conformance	A = Y/X % False positives or type I error
2R1	8	7	400	98.25%	12.50%
2R2	1	1	400	99.75%	0.00%
2R3	14	2	400	99.50%	85.71%
2R4	127	116	400	71.00%	8.66%
2R5	14	13	400	96.75%	7.14%
2R6	5	2	400	99.50%	60.00%
2R7	33	26	400	93.50%	21.21%
2R8	33	29	400	92.75%	12.12%
2R9	3	2	400	99.50%	33.33%

The numbers in Table 38 (column A) draw serious attention of the production managers, being evident that by taking the necessary actions (recommended in chapter 7), a lot of money can be saved, as shown in Table 39 – column E.

Table 39: Cost calculations - Scrapping false positives

Experiment #	B = X/Z Total % rejections	C = A*B % Rejections only false positive from total	D = C * 32 million False positives scrapped per annum	E = D * 0.201 Cost incurred in scrapping false positive per annum
2R1	2.00%	0.25%	80000	€ 16,080
2R2	0.25%	0.00%	0	€ 0
2R3	3.50%	3.00%	960000	€ 192,960
2R4	31.75%	2.75%	880000	€ 176,880
2R5	3.50%	0.25%	80000	€ 16,080
2R6	1.25%	0.75%	240000	€ 48,240
2R7	8.25%	1.75%	560000	€ 112,560
2R8	8.25%	1.00%	320000	€ 64,320
2R9	0.75%	0.25%	80000	€ 16,080

An average of € 71,000 can be saved yearly by only analyzing and improving the process of false positives, proposing methods that can reduce the number of false positives. Note that the savings are only an estimate from a very small sample size of 400 aerosol cans.

Declared conforming rates:

Similarly, for declared quality of conformance rates, the conformed aerosol cans from the 100% leak testing (Wilcomat) need to be evaluated: how many cans are shipped as being conforming, that are in fact non-conforming cans (or type II error). Again, a reference is taken from the results of DoE and the rejections of manual waterbath presented in Chapter 5, Table 30 are revisited here in Table 40.

Table 40: Rejections from the Waterbath machine

Experiment #	Rejections	Total	%
2R1	52	400	13.00%
2R2	5	400	1.25%
2R3	5	400	1.25%
2R4	56	400	14.00%
2R5	5	400	1.25%
2R6	0	400	0.00%
2R7	14	400	3.50%
2R8	17	400	4.25%
2R9	1	400	0.25%

Table 40 shows a range of rejections from 0% - 14% with an average of 4.3% and a median of 1.25%. By analyzing these rejections as well as discussing with the team members, a consensus about the appropriate value for the quality of declared

conformance that is actually non-conforming units sent to the customer was set at 0.25% - 1.25%.

A summary of the quality of conformance and non-conformance rates is presented in Table 41. In the table, a fixed value rather than a range is considered for further calculations. Later, a sensitivity analysis that shows a wider range of conformance and non-conformance values is presented and discussed (see for example, Figure 106 and Figure 107).

Table 41: Quality of conformance and non-conformance states for 100% leak test (Wilcomat machine)

Declared state / True state	Conforming	Non-conforming
Conforming	99.5 %	0.5 %
Non-conforming	15 %	85 %

Quality of Conformance rates for manual waterbath leak tests:

The current claims data available to Colep are very limited and it is not possible to correlate these claims with the internal production data, exploring further the values of conformance rates for manual waterbath tests. A discussion session was conducted between the production team members, and a consensus was reached around the values shown in Table 42.

Table 42: Quality of conformance and non-conformance states for waterbath leak test

Declared state / True state	Conforming	Non-conforming
Conforming	99.95 %	0.05 %
Non-conforming	0.01 %	99.99 %

The chances of finding a conformed aerosol can (type I error), after it has been declared non-conformed is very low, and its value was estimated to be 0.01%.

External Failure:

External failure occurs when a declared conforming aerosol can fail on the field or at the customer facility, as shown in Figure 102. Furthermore, the non-conforming cans that are declared conforming are not always detected by the customer. However, data concerning the number of non-conforming cans sent to the customer and the number of non-

conforming cans detected by the customer is not known. Analyzing this data limitation, an assumption is made in the calculations that all the non-conforming cans (type II error) sent to the customer which were declared as good parts, will be detected by the customer's detection systems. As a result, the overall cost per piece will increase slightly, but the comparison among the different scenarios is still valid and conclusive.

The excel model is designed in a way that for any given period of time, Colep discovers the values of non conforming cans sent to/detected by the customer; it is very easy to update the model and generate again the results.

When an aerosol can fail on the field there are two types of costs involved in it: tangible and intangible costs. Tangible costs are material, transportation, labor, production, and testing of the product at the customer facility. In other words, it is the cost per piece plus transportation and testing costs. Intangible costs are loss of goodwill, company image, and customer dissatisfaction.

Tangible costs are easier to estimate than intangible costs, because it is evident that intangible costs are not measureable. Furthermore, for the particular case of the Microleaks and considering its crucial importance to Colep, intangible costs overshadowed the tangible costs. Thus, in order to consider the impact of intangible costs in the cost of the quality model, a higher external failure value must be considered. After discussion, the initial value was estimated to be €12, which is 60 times more than the cost per piece (20.1 cents). The value for an external failure is only an estimate and it is recognized that finding an exact value requires extensive market research. Therefore, for an external failure, a sensitivity analysis is performed to assess the impact of different external failure values on the scenarios (see Figure 105 and Figure 107).

The quality of conformance rates and external failure costs estimated in this section are the baseline values for all the subsequent four scenarios.

6.3.8. Results, discussions and comparison among the scenarios

The equations developed in section 6.3.2 were applied in the COQ model to estimate the costs for welding, seaming, 100% testing, and packaging processes for all the scenarios. These cost estimations were combined with the cost estimations developed for each case of sampling procedure. The baseline data was mainly supplied by the company, and, in the case of missing information assumptions were made in Appendix IV.

The baseline data consisted for the complete assembly line, related to data for equipment´s, labor, setup, and energy costs (Appendix IV– cost for assembly line 12). In order to estimate the costs of individual processes, it was required to do a brainstorming with the key industrial experts to estimate the percent contribution of each process from the overall costs (Appendix IV– % contribution).

A first breakdown of the costs enables a comparison between the four scenarios (Figure 103) and several conclusions can be drawn:

- Among the four scenarios, scenario C that rejects only the non-conforming units in the sample, minimizes the overall costs per piece due to relatively high savings in the external and internal (scrap) failure costs, and appraisal (inspection) costs;
- All the four scenarios have a strong focus on appraisal costs, internal and external failure costs, the breakdown costs due to packaging and palletizing, Wilcomat (leak testing), seaming process, and welding process are almost constant;
- **External failure:** in all the four scenarios, scenario A minimizes the external failure as it re-inspects the rejected batch. Contrary to Scenarios B and C, which only performs single inspection;
- **Appraisal and internal failure:** in all the four scenarios, scenario D minimizes the appraisal and internal failure costs because in this scenario there is no manual waterbath testing procedure, therefore resulting in the maximum external failure costs.

The difference in total cost per piece among the four scenarios is only notable at the fourth decimal, so it is hardly significant; this can be due to the fact that the cost of a

single aerosol can is very small and only appraisal costs, internal and external failure costs are being affected by the current analyses.

	Scenario A	Scenario B	Scenario C	Scenario D
■ External failure	€ 0.07381	€ 0.07390	€ 0.0739	€ 0.0750
■ Packaging and palletizing	€ 0.0221	€ 0.0221	€ 0.0221	€ 0.0221
■ Appraisal and Internal failure	€ 0.0009	€ 0.0012	€ 0.0007	€ 0.0000
■ Wilcomat	€ 0.0065	€ 0.0065	€ 0.0065	€ 0.0065
■ Seaming process	€ 0.0529	€ 0.0529	€ 0.0529	€ 0.0529
■ Welding process	€ 0.1220	€ 0.1219	€ 0.1220	€ 0.1220
Total	**€ 0.2783**	**€ 0.2786**	**€ 0.2782**	**€ 0.2785**
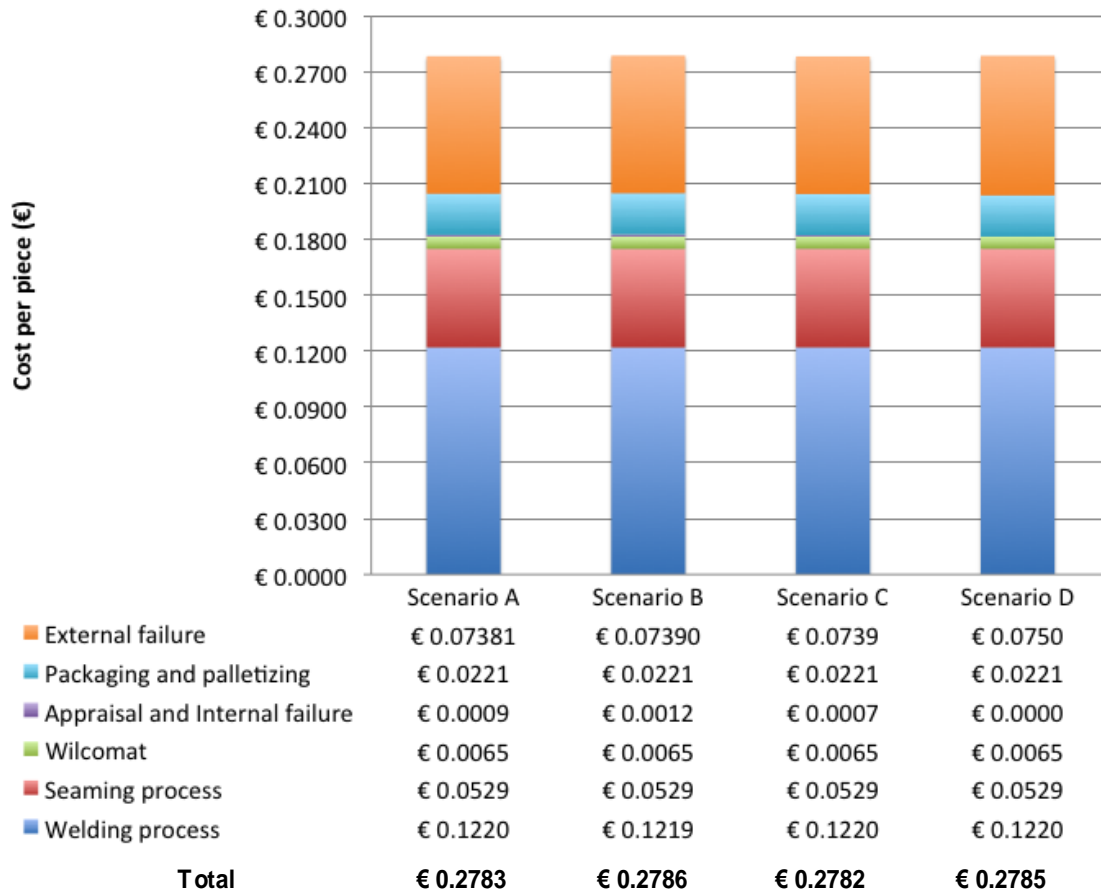
Figure 103: Breakdown cost comparison among the scenarios

The previous analyses showed that appraisal costs, internal and external failures costs are the main driving parameters. Therefore, Figure 104 shows the breakdown cost comparison for all the four scenarios focusing only on the appraisal, internal and external failure costs. This figure is just an extraction from the big picture of breakdown costs presented in Figure 103.
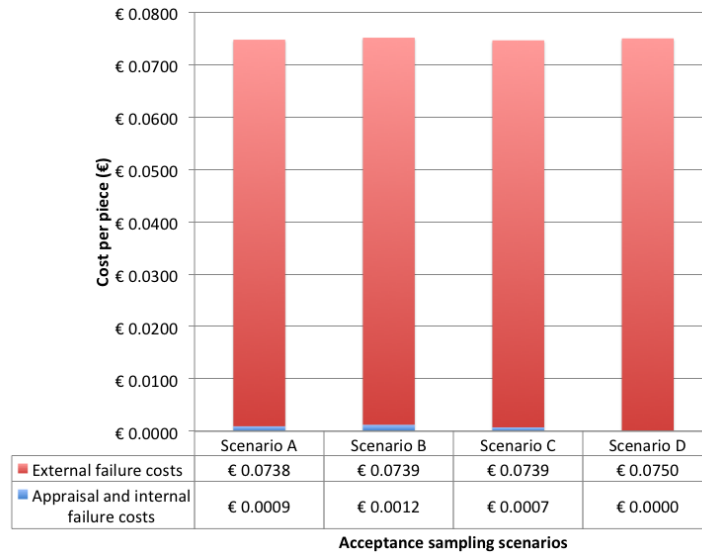
Figure 104: Breakdown cost comparison for appraisal, internal and external failure costs among the sampling scenarios

The small difference among the per piece cost can be analyzed through analyzing the cost savings from each scenario for a time period of one year. As a result, a cost savings comparison table is prepared taking scenario A (double sampling – as-is condition) to be the reference to all the other scenarios (Table 43).

Table 43: Cost savings comparison table

Scenarios	Scenario A	Scenario B	Scenario C	Scenario D
Cost per piece	€ 0.2783	€ 0.2786	€ 0.2782	€ 0.2785
Cost savings compared with A				
Per piece	-	-€ 0.0003	€ 0.0001	-€ 0.0003
% Per piece	-	-0.1%	0.04%	-0.10%
1000 cans	-	-€ 0.35	0.12	-€ 0.27
Per Year (32 million cans)	-	-€ 11,056	3,783	-€ 8,563

Thus, for the current baseline values, on average Colep could save €4,000 by following scenario C rather than scenario A. However, as the differences are very small and in order to better understand the impact of the different baseline values, a sensitivity analysis will be performed for the annual cost savings for each of the four scenarios, with the following set of parameters:

- Additional external failure premium;

- % Conformance (fraction non-conforming) shipped to the customer.

Sensitivity analysis of cost savings per piece and additional external failure premium:

For this analysis of the cost savings per year, only the additional external failure premium is varied, while all the discussed parameters are kept at their baseline values. As discussed, the baseline for external failure premium is set at €12, which gives scenario C as the procedure that minimizes the total cost per piece (shown in Figure 105).
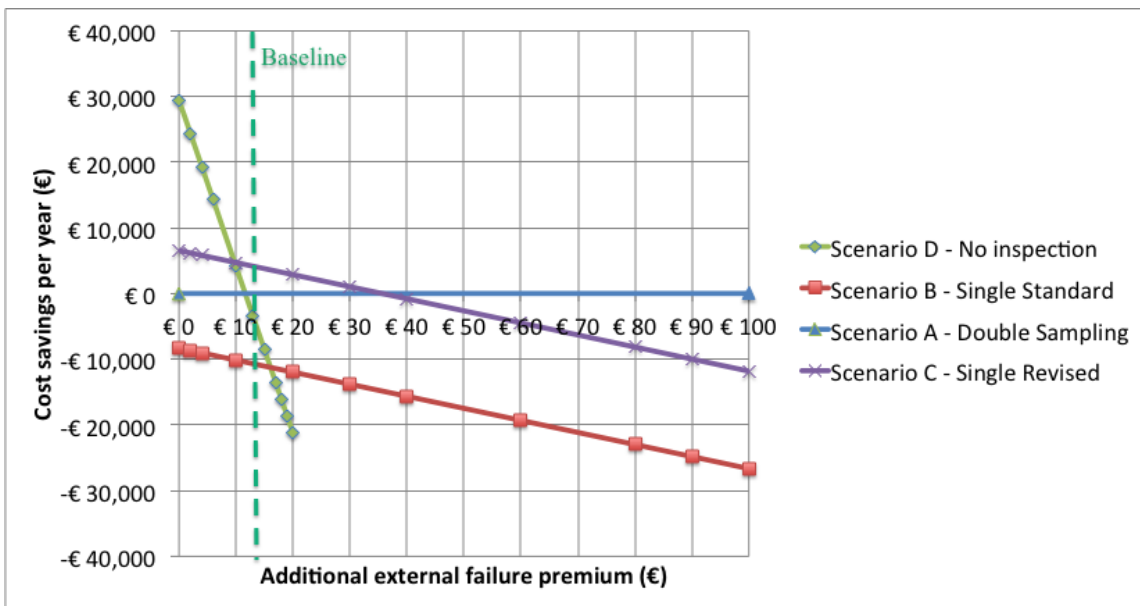
Figure 105: Cost savings versus additional external failure premium

All the scenarios show linear function to the external failure premium where slopes are equal to the respective probability of the occurrence of external failure. Scenario A that was set as a reference to all other scenarios is fixed at €0. Scenario D has the highest magnitude of slope, which makes sense because while no manual waterbath inspection in-place, increasing the external failure premium would increase drastically the overall cost per piece. Scenarios B and C have approximately the same slope, showing different cost savings per year, which also makes sense because scenario C was adapted for this particularly case and the number of non-conforming units that are scraped is much lower. If the acceptance number for scenario B is increased then it will give the same result as scenario C however practically it is not possible to implement scenario B with higher

acceptance number due to lower defective rates and therefore scenario C come into play an important role here.

Concluding the sensitivity analysis of additional external failure premium, one can say that for the current baseline value of €12, scenario C looks appropriate. However, this baseline value is merely an estimate and the exact value is hard to achieve without extensive market research. Therefore, adding to this conclusion, if the external failure premium would lie within the range of €0 - €10, then scenario D would be the one that minimizes the overall costs. If the external failure premium lies between the range of €11 - €35, then scenario C minimizes the overall costs. For a value of the external failure premium above €35, scenario A would be the most appropriate, minimizing the overall costs.

The excel model was built considering that the external failure premium and all the baseline values are variables that can be easily altered, every time Colep requires a model update.

Sensitivity analysis of cost savings per piece and percentage conformance (fraction non-conforming) shipped to the customer:

Similarly to previous analysis, only the percentage conformance (fraction non-conforming) shipped to the customer is varied to evaluate its effect on the cost savings per year, while all the other parameters are kept at baseline values. In this analysis, conformance rates are considered only for the 100% leak testing equipment (Wilcomat) and the conformance rate is incrementally increased from an initial value of 98.6% to 99.8%. The baseline for conformance rate was estimated at 99.5 %, as shown in Table 41. The results, as shown in Figure 106, validate the previous conclusion that scenario C minimizes the overall cost per piece.
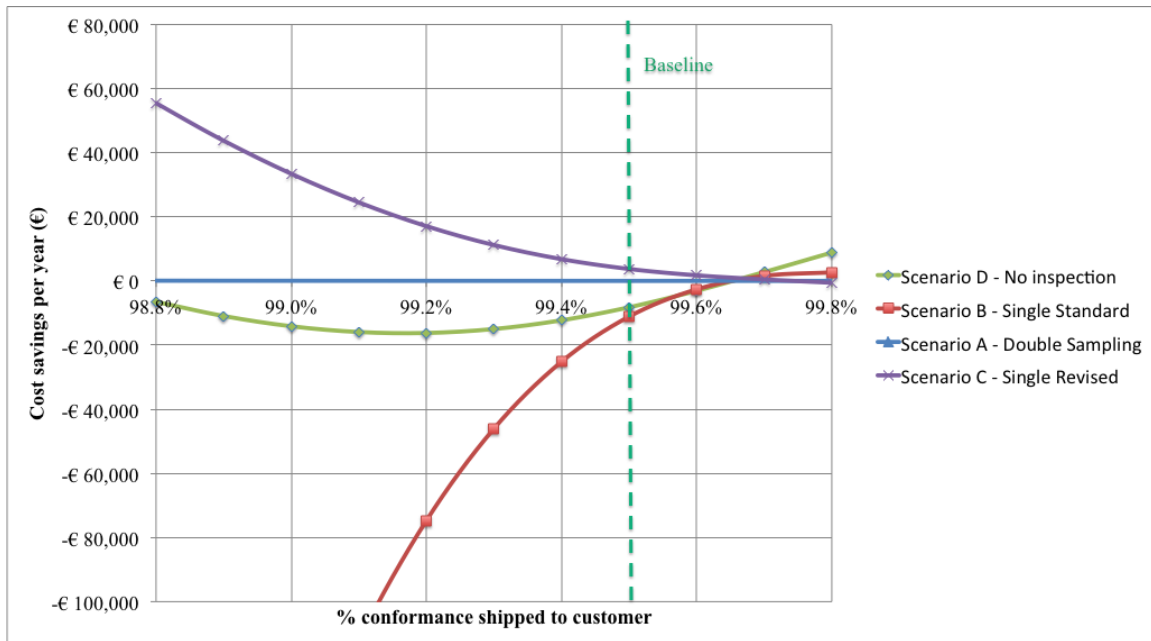
Figure 106: Cost savings versus % conformance (fraction non-conforming) shipped to the customer

Scenario B is the most sensitive while scenario D is the least sensitive to changes in the conformance rates. At higher levels of conformance rates, difference in cost savings becomes very small among all the scenarios. This might be due to the fact that most of the units are according to specifications, being less likely to scrap any batch or perform extra sampling procedure, making scenario D (no inspection) the ideal one. Similarly, scenario C is optimal when conformance rates are lower due to less scrapping and less sampling of units. These conditions may change, while increasing or decreasing the external failure value.

From the analysis of Figure 105 and Figure 106, scenario B is the only scenario that never achieved an optimal condition (looking throughout the range of external failure costs and conformance rates). Whereas, for all the other scenarios (A, C, and D) somewhere in the graphs leads to an optimal condition. Therefore, in order to investigate the behavior of the two parameters (conformance rates and external failure costs) together along with the three scenarios (A, C, and D) a 3D-contour plot was developed, as shown in Figure 107.
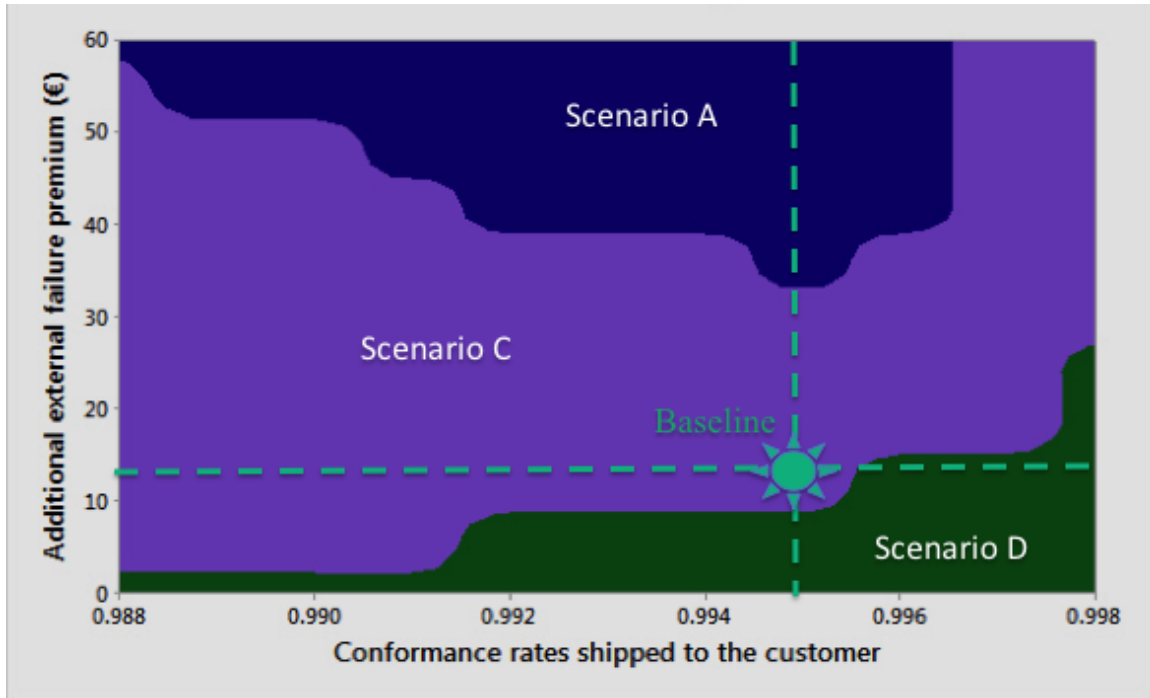
Figure 107: Contour plot of scenarios A, C and D

The contour plot is a representation of the previous two sensitivity analyses in 3-D, plotting conformance rates on the x-axis and external failure premium on the y-axis. The contour plot allows understanding the sensitivity of both the parameters, drawing a boundary around all the scenarios. The current as-is condition of assembly line 12, scenario A, can be justified as an optimal procedure if the external failure cost is very high, when the range of conformance is between 98.8% - 99.65%. For higher conformance rates than 99.65%, scenario C becomes ideal, this might be due to lower appraisal (sampling) and internal failure (scrapping) costs of this scenario when compared with scenario A.

If the external failure costs are too small like, for example, between €0 – €10 then no inspection becomes ideal for most of the rates of conformance, because sampling and scrapping units increases the overall costs, making scenario A and C not appropriate anymore. Overall, Scenario C dominates the contour plot especially at the mid values of external failure premium.

6.4.   Alternative technology – Trimming process

Following the identification of welding beginning as the critical location for Microleaks in chapter 3, a possibility of trimming the welding beginning was briefly reviewed. In this section, the working principle and as the cost analysis of this trimming process is discussed in detail.

6.4.1.   Working principle

The task of studying, understanding, and analyzing the trimming process was performed by one of the TME students (Valente 2013) in collaboration with LTI student. The trimming process is a well-known process in the aluminum can-making industries, where extrusion process is used to produce aluminum cans and it passes through a series of processes. Figure 108 shows the series of production processes for aluminum cans including the trimming process.

FROM A SOLID   EXTRUSION   TRIMMING...   MULTI-STAGE   AND DIE
"SLUG" OF   TO A CAN   DIE   CURLING.
ALUMINIUM...   WITH A   NECKING...
                DOMED END...
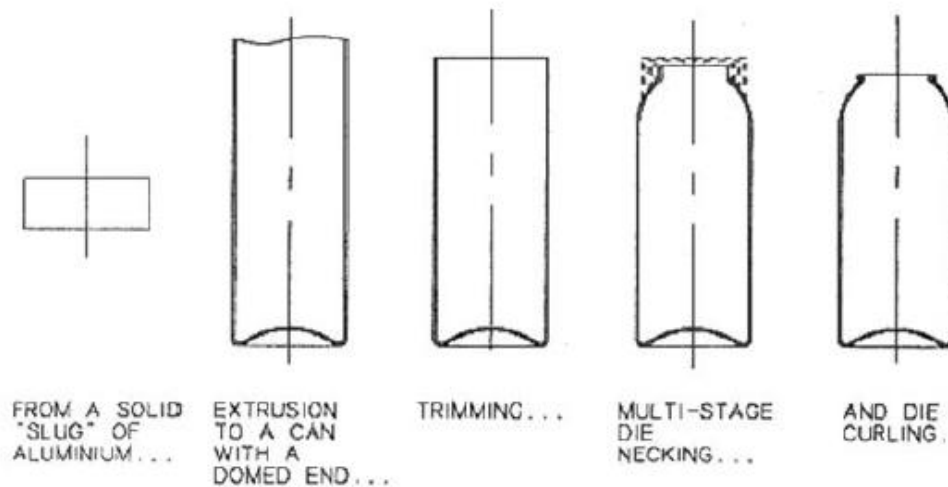
Figure 108: Series of production processes for aluminum cans (Valente 2013)

A similar concept is adapted for trimming the welding beginning of aerosol cans. Thus, in order to analyze whether trimming process method also works for aerosol cans, a set of experiments were performed. Since Colep does not have a trimming technology to perform trimming process at the welding beginning of aerosol cans, a specialized company was contacted only for the trimming activity.

The assembly line # 27 and format 49x185 were selected for the experiments. The welding direction of this assembly line is from bottom to top. Figure 109 shows the location of the trimming process in the standard production processes of aerosol cans.
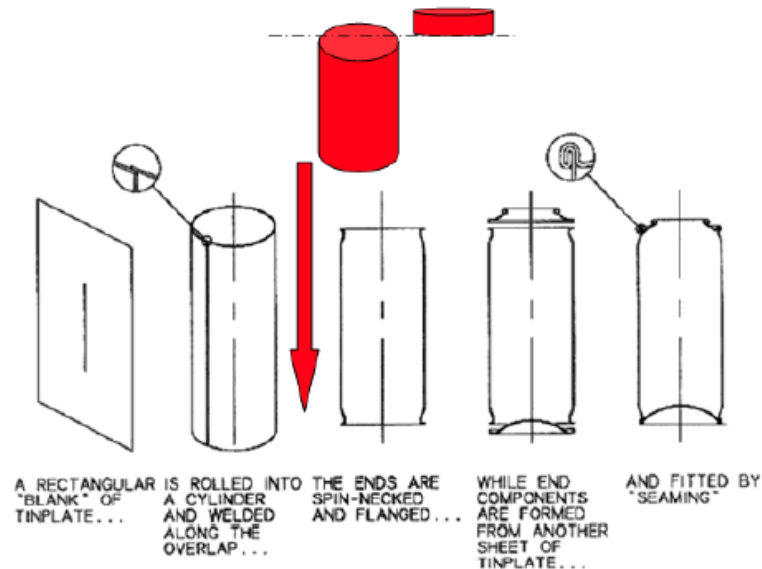
Figure 109: Addition of trimming process in the production of aerosol cans (Valente 2013)

In order to compare the addition of the trimming process in the assembly line with the standard production of Colep, 100 aerosol cans were selected for the analysis. Fifty aerosol cans were passed through the trimming process while the remaining 50 aerosol cans followed through the standard production processes, without any additional trimming process. Experiments were performed in the following sequence:

- First, all the 100 cans were welded with the same parameters. The welding parameters were intentionally set at a level where it is highly likely that Microleaks are generated;

- Fifty aerosol cans were selected, which do not require the trimming process. They followed the standard production processes, inspected for leaks in the 100% leak testing and manual waterbath machines and then the leaks were recorded, as shown in Table 44;

- The remaining fifty aerosol cans were selected, which require the trimming process. They were sent to the specialized company for trimming process where all of them

were cut out 3mm from the welding beginning and sent back to Colep. In Colep, they followed the standard production processes, inspected for Microleaks in the 100% leak testing and manual waterbath machines and then the leaks were recorded, as shown Table 44.

Table 44: Results of experiments for trimming process

	Without trimming process	With Trimming process
Sample size	50	50
Leaks/Microleaks	22	0
% Leaky	44%	0%

The results shown in Table 44 look interesting because 44% of the leaks/Microleaks were generated when no trimming was performed, while adding the trimming process eliminates leaky cans totally for this sample. In other words, addition of trimming process in the standard production processes would possibly eliminate the welding beginning problem. However, other factors should be taken into account, such as: required investments on new trimming technology, increased material costs, land costs, adaption of this new technology for the long production run of aerosol cans, as well as shop floor availability. These factors are further discussed in the next section.

6.4.2. Cost Analysis

The cost analysis has been performed for assembly line 12 and format 65x300, so that a comparison can be made for the total cost per piece between the current and previous analyses. The addition of the trimming process in the standard production processes of aerosol cans for assembly line 12 is shown in Figure 110. It is assumed that by adding the trimming process the need of manual waterbath inspection is eliminated.

In order to calculate the total cost per piece while adding a trimming process in the assembly line, only the equations for the trimming process are done, keeping all the assumptions constant (section 6.3.2). The fixed and variable costs for the trimming process are:

$C_{i,Total} = C_{i,Variable} + C_{i,Fixed}$

$C_{i,Variable} = C_{i,Body} + C_{i,Labor} + C_{i,Utility}$

$$C_{i,Fixed} = C_{i,Setup} + C_{i,Maintenance} + C_{i,Equipment}$$
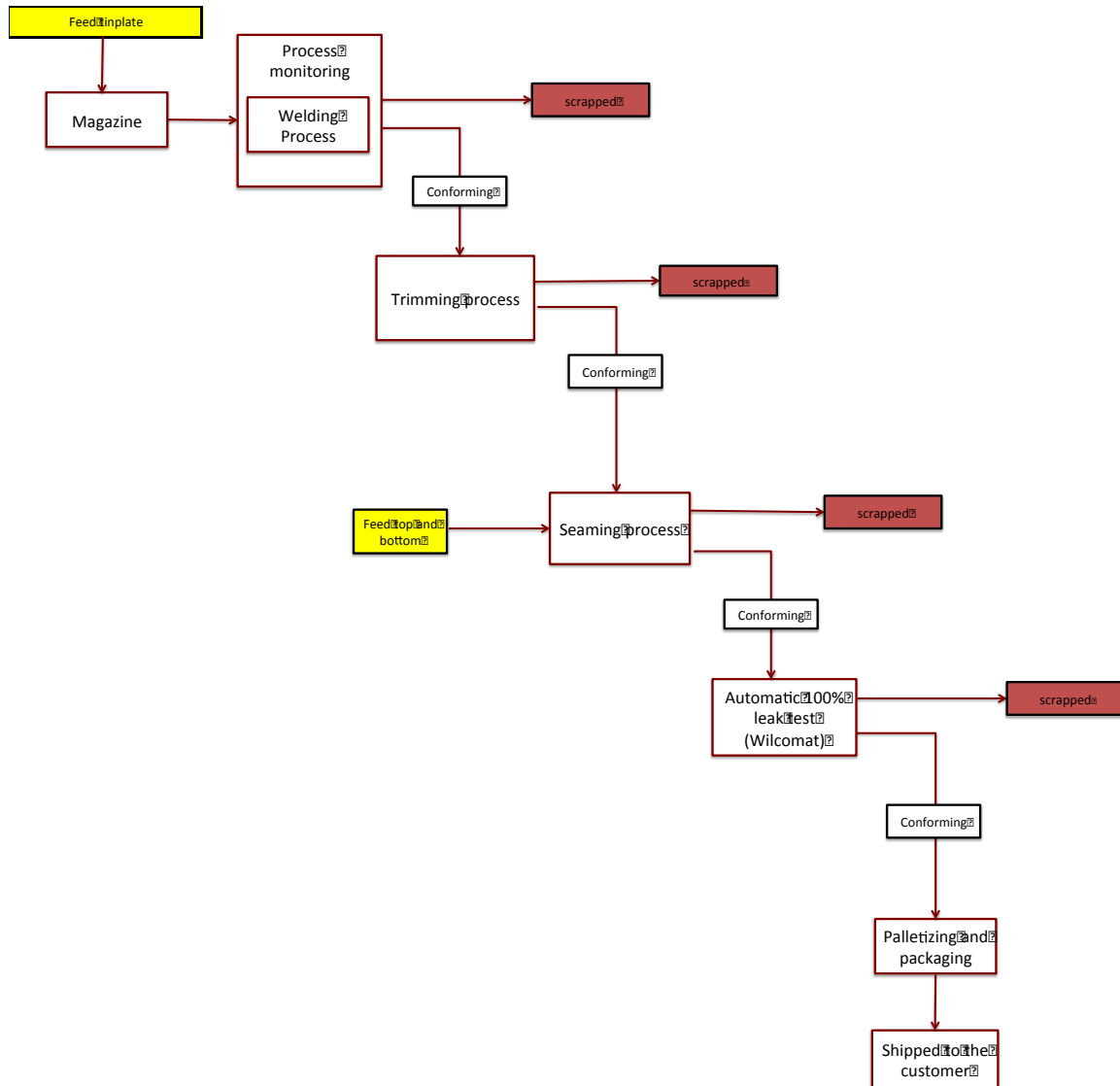
Figure 110: Production flow block diagram of assembly line 12 including trimming process

In the case of the trimming process, every aerosol can needs to be trimmed 3mm from the beginning therefore the blank, which is fed initially in the form of a tinplate, should have an additional height of 3mm from a standard height of 304mm. As a result of this requirement, material cost is increased and the cost of blank for 3mm was added to the cost that was given as input previously (Appendix IV - Cost for assembly line 12).

Since the trimming process is quite new to this industry, the information is scarce. So, most of the data presented in Appendix IV (trimming process input data assumptions) is

based on the best possible assumptions at the time the analysis was performed. The cost of a single equipment was provided by one of the equipment's supplier and, in order to calculate $C_{i,Equipment}$, the PMT function of excel was used that calculates the payment for a loan based on constant payments and a constant interest rate. Although being very important factors for the cost analysis, the values of land, availability of space, adaptation of trimming for the aerosol manufacturing industry, as well as installation costs, were unable to estimate. In order to take into compensate for the missing information, the Cost of equipment ($C_{i,Equipment}$) was multiplied by a scale factor of 5. In the future, if Colep is able to find the exact values or best assumption of these factors, it will be easy to update the model and generate new results.

The costs of energy, labor, setup, and maintenance are assumed to be the same as the ones used for previous analyses. Furthermore, following a trimming process, it is also assumed that the non-conformed cans sent to the customers are reduced by 65%, as welding beginning contributes at least with a value of 65% to the total Microleaks (see chapter 4, section 4.5). The non-conformance rate assumed in the previous analyses when no trimming process was in place was 0.5%, while after the trimming process the non-conformance rate is reduced to 0.18% [(100-65)*0.5)].

Similar to the previous sampling scenarios, an excel model was built for the trimming process scenario. The results for the cost breakdown in Figure 111 show that the external failure costs have been greatly reduced while investing in the trimming process development. Moreover, following the implementation of the rimming process, manual waterbath testing is not considered as part of the assembly line for cost analysis, because it might not be beneficial for the reduction of the non-conforming cans anymore.

	Cost breakdown
■ External failure	€ 0.0270
■ packaging and palletizing	€ 0.0221
■ Wilcomat	€ 0.0075
■ Seaming process	€ 0.0529
■ Trimming process	€ 0.0448
■ Welding process	€ 0.1230
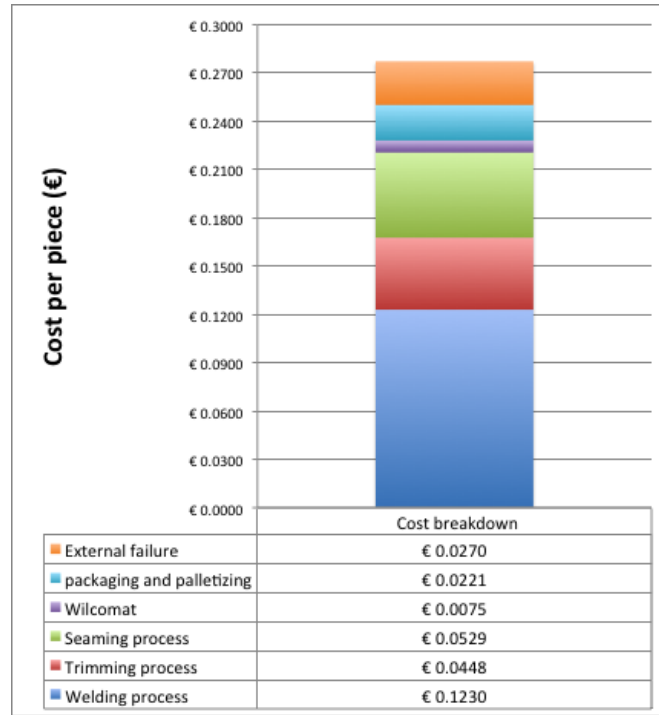
Figure 111: Cost breakdown of trimming process scenario

A cost comparison table between the trimming process scenario and the scenarios previously analyzed is shown in Table 45.

Table 45: Cost comparison for all scenarios including trimming process

Type of scenario	Cost per piece (€)	External failure costs (€)
Scenario A	0.2783	0.07381
Scenario B	0.2786	0.07390
Scenario C	0.2782	0.0739
Scenario D	0.2785	0.0750
Scenario Trimming process	0.2773	0.0270

Although the trimming process scenario greatly reduces the external failure, the difference in cost per piece is quite small. Furthermore, implementing the trimming scenario requires a lot of investments, modifications in the infrastructure and further validation processes. It is important to reiterate again that the results for the trimming process scenario are achieved based on many feeble assumptions, but those were the best possible assumptions at the time of the analysis. Particularly in what concerns the

assumptions made with land cost, adaptability, and availability of space that play a significant role in the overall costs.

6.5. Leak detection systems

The type of leak detection systems investigated in this thesis is based on the technology of gas tracer leak detection. The idea is to use gases that exist at a low concentration in the atmosphere for detecting leaks generated in the aerosol cans. The sensitivity of gas tracer technologies is very high, ranging between 10^{-3} ml/min – 10^{-5} ml/min depending on the type of gas being used. The working principle of the gas tracer technology is briefly described in this section.

First, the sample is pressurized at a certain pressure and temperature with the tracer gas. Then, the sensor that can detect the tracer gas is placed at critical locations of the aerosol cans. For the case of Microleaks detection, a sensor can be placed at the welding beginning of the sample. This sensor emits a signal whenever it detects a tracer gas flowing through any cavity generated in the aerosol can. A general type of gas tracer leak detector is shown in Figure 112.

Leak detector (probe)

GAS H₂ N₂ (95%)
SUPPLY

Aerosol
Can

omponents, it is important to handle it with care

e sensor (sniffer) to all types of solvents, oils,
ors that destroy irreparably.
immerse the sniffer!

Gas cylinder
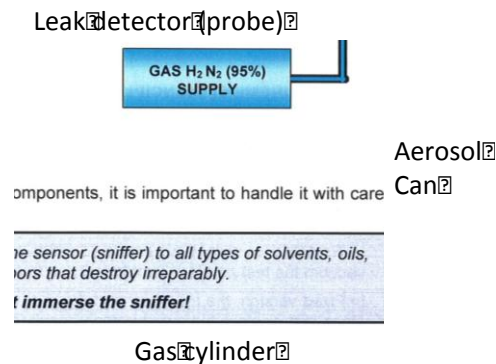
Figure 112: Type of gas tracer leak detector (ATEQ 2015)

Although the use of gas tracer technology looks simple at a first glance, it requires strict conditions and standards to be followed. The important parameters that must be fine-tuned are the temperature, pressure, and time of detection. It is important to highlight the fact that time plays an important role for the case of Microleaks, because the gas tracer leak detection systems are manual and it takes some time to provide results – a drawback of this technology. Another drawback is due to contamination problems, problems that

appear when an aerosol can has already been detected with a leak using any tracer gas. In this case, the environment is more likely contaminated and the subsequent aerosol can might be falsely detected as being defective, while being a good one, i.e. a false positive. Integrating vacuum with this technology and eliminating the doubt of tracer gas presence in the environment can solve this problem of contamination.

The types of tracer gases typically used are (Teixeira 2013):

- Helium (He): it is an inert gas that contains very small molecules – high diffusion rates allows it to penetrate through cavities that may exist. The sensitivity of this gas is 10^{-7} ml/min;
- Hydrogen (H): it is a cheap gas but also very hazardous at concentrations above 4%. It has a sensitivity of 10^{-3} ml/min – 10^{-5} ml/min.

The types of gas tracer leak detection equipment´s investigated in this thesis are:

- Gas tracer leak detection without vacuum;
- Gas tracer leak detection with vacuum.

6.5.1. Gas tracer leak detection – without vacuum

This type of gas tracer leak detection is similar to the one depicted in Figure 112, and the tracer gas that can be used is a hydrogen gas 5% in nitrogen gas. The PhD student has made some experiments with the equipment at a specialized company. The technology has a range of sensitivity from 10^{-5} to 10^{-3} ml/min. This equipment does not have a built-in vacuum technology.

First, a sample of 100 aerosol cans were tested with this technology. The first leaky aerosol cans were easily detected by the gas tracer detection system. However, because of existent leaks in the aerosol cans, hydrogen gas was released and contaminated the environment. As a result, the aerosol cans that were tested afterwards were falsely detected leaky. Following these experiments, it was then concluded that this kind of technology is not suitable for detecting mass quantities of leaky cans, due to this contamination problem.

Nevertheless, by integrating vacuum in this technology the problem of contamination might be solved and the technology could then be used for the purpose of detecting leaks in the production of aerosol cans. As a consequence of these tests, another technology was assessed that might solve the contamination problem: the gas tracer leak detector with built-in vacuum system, which is discussed in the next section.

6.5.2. Gas tracer leak detection – with vacuum

This type of gas tracer leak detector (Figure 113) is used to test the air-tightness of parts on production lines. It is specially adapted for automatic or semi automatic stations. However, it can be used also in a manual station, allowing localization of the leak. The gas to be used for this technology is Hydrogen (H2) gas. The equipment was not available at the specialized company for experiments and all the description provided here is based on discussions and available equipment´s documents.
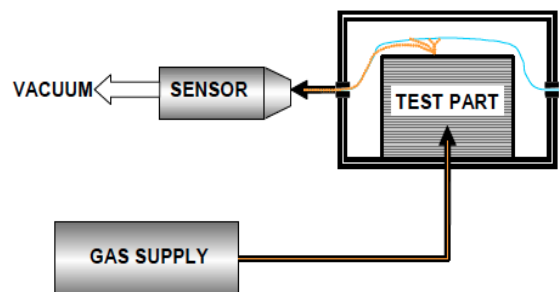
Figure 113: Gas tracer leak detector with vacuum (ATEQ 2015)

The working principle of the equipment (as shown in Figure 114) is the following:

- Coupling: first, the sealing connections are made to the test part;
- Vacuum test: then, the test part is vacuumed. At the end of the vacuum time, the instrument checks the vacuum level;
- Fill: the test part is filled with Hydrogen gas to the required pressure level;
- Fine test: the suction valve is opened, allowing airflow from the valve to the detector (with probably some leaking gas), the concentration of "Hydrogen" gas is measured;
- Purge: the gas in the test part is dumped to a remote location (outside the factory), and the part is vacuumed to extract the maximum gas as possible;

- Cleaning: the sensor is put back to the atmospheric pressure. At this time the sensor and probe are cleaned using full vacuum in order to limit pollution effect for the next cycle.
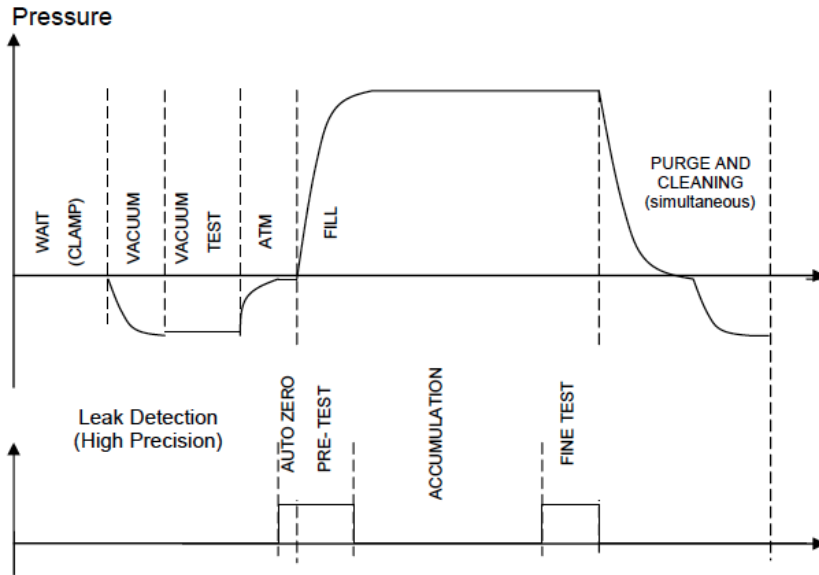
The measurement cycle consists of 6 phases:

	1	2	3	4	5	6	
			Fill				
Start	Coupling	Vacuum Test	Pre-Test	Accumulation	Fine Test	Purge and Cleaning	Cycle end

Figure 114: Description of the test cycle (ATEQ 2015)

The number of companies that have developed gas tracer leak detection systems is scarce and only two of those companies were contacted for systems quotation. A comparison of the costs is shown in Table 46. These costs does not include cost of vacuum pump and any other installation costs, as most of the gas tracer systems with built-in vacuum technology are manual and require integrating into the aerosol production system for online inspection.

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Table 46: Cost comparison for gas tracer leak detection systems

Type of equipment	Cost of a single equipment (€)	Adaptability to aerosol can production system	Testing time
Company A - Gas tracer leak detection with vacuum (manual)	€ 10,300	Slow speed; can only be used as a manual detection system	Approx. 1 aerosol can / min
Company B- Gas tracer leak detection without vacuum (manual)	€ 29,465	Relatively high speed; can only be used as a manual detection system	-
Company B - Gas tracer leak detection without vacuum (Hi speed)	€ 18,223	Very high speed; can be integrated with vacuum; can be adapted as an online detection	Approx. 30 aerosol cans/min without vacuum

A preliminary test was performed at a company B site in Sweden using Hi-Speed gas tracer leak detection system. The results showed that 30 aerosol cans in a minute can be tested using this Hi-speed technology, when there is no vacuum system. Integrating vacuum into the system would likely increase the testing time. In the future, more tests can be performed if Colep borrows the equipment along with vacuum technology. Also, another possibility of integrating this technology with 100% leak detection system (Wilcomat) can be studied.

Figure 115 shows the current standing of the gas tracer leak detection systems in Colep´s aerosol production system. The investments in gas tracer technologies would likely pull Colep to detect leaky cans with higher precision. However more experiments are required to validate if these technologies really work for online detection of aerosol cans.
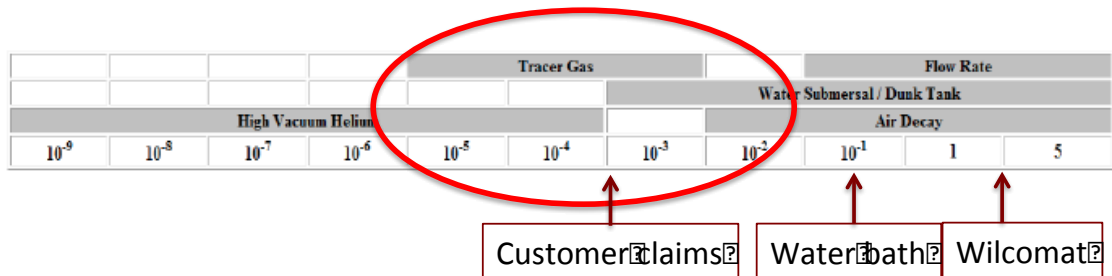
Figure 115: Current standing of tracer gas detection systems in the aerosol production system (Teixeira 2013)

6.6.   Summary

The chapter has successfully developed and discussed cost of quality model for the three-piece tinplate aerosol can. First, a process based cost model for assembly line 12 format 65x300 was developed. The results showed that for the yearly demand of 320 million aerosol cans, cost per piece was estimated to be at 20.1euro cents.

The chapter has developed also formulations for all the processes of the assembly line as well as for all the sampling scenarios. When comparing the results of the sampling scenarios, it showed that single stage revised sampling scenario optimized the overall cost of quality. The results were based on the data received from the industry. A sensitivity analysis was performed to investigate the impact of variation from the input data on the cost of quality. The results showed that if the external failure cost is very high e.g. 60 euros, then the optimized solution is the double stage sampling plan. If the external failure cost is very low, e.g. 2 euros, then the optimized solution is no sampling. If the external failure cost is at a mid range, e.g. $10 - 40$ euros, then the optimized solution is single stage revised sampling plan.

Another approach used in this chapter to optimize the cost of quality is to study the application of alternative technologies. Particularly, trimming technology has been discussed in this chapter, consisting in cutting the welding beginning of the aerosol body in order to eliminate the Microleaks. A cost of quality model for the trimming technology was developed and the results were compared with the previous sampling plans. The results showed that, however trimming technology has greatly reduced the external failure costs, the difference in cost per piece with the previous sampling plans is very small. This is because trimming technology required huge investments in equipment´s, modification in the infrastructure, and adaption of the technology to the aerosol manufacturing.

Another possibility of detecting Microleaks is discussed through investing in the leak detection systems. The technology discussed was gas tracer leak detection, where hydrogen or helium gas is used to detect very small leaks with a precision ranging from 10^{-5} to 10^{-3} ml/min. Due to lack of time, the number of experiments performed by the

PhD student to explore the possibility of integration of this technology into aerosol can production system was scarce, and no final conclusions could be achieved.

CHAPTER 7 - Conclusions and Recommendations

The chapter briefly discusses the results obtained throughout the research, followed by the proposed general methodology, implications of the research, recommendations, and future work.

7.1.   Summary of the Results

The goal of the thesis was to improve the final product quality for a consumer goods and packaging industry. In particular, the industry had serious quality problems concerning one of its products, having received in recent year's significant customer claims. The customer claims are mostly related to Microleaks in the aerosol cans. Being Microleaks a common problem to most of the consumer goods and packaging industries, a solution to this problem inherently implies a competitive advantage over the competitors.

Occurrence of Microleaks in the final product is a consequence of non-conformities generated along the production line of a manufacturing process. Therefore, through identifying, modeling and analyzing these non-conformities systematically, the common causes behind the variability that generates Microleaks can be revelead. To achieve this, the research is based on the hypotheses that non-conformities can be determined with a high degree of reliability and their analyses allow correctly inferring about the final product quality. In order to analyze further the non-conformities, a systems engineering tool was used to model them systematically, highlighting key and critical areas of the manufacturing process. These key areas will then be analyzed using quality improvement tools enabling a better elicitation of the problem, optimizing the production process.

A review of contributions from systems engineering, evolution of quality control and improvement, quality improvement methodologies and design structure matrix, as a systems engineering tool has been performed. Although all of these contributions showed that there are abundant methodologies for improving the final product quality, having a holistic and systematic approach to these types of problems is still difficult. Yet, the existing methods provide a sufficient basis to develop a holistic methodology based on systems engineering approaches, supporting effectively quality improvement of manufacturing systems.

The very first research question was responded in this thesis by developing a Systems Engineering methodology for quality improvement of manufacturing systems. The methodology, resulting from the development of a novel non-conformity matrix tool is structured into 10 steps, that can be followed sequentially. In the first step of the methodology, the problem was clearly stated, project scope was defined and the project team was chosen. In the project scope, based on historical data analysis, a single assembly line and a single format were chosen for further investigation.

A multidisciplinary team was selected to achieve the goals of the Microleaks project. This included, the project leader, the project manager, master students, experts and researchers, and professors.

The methodology further emphasizes on the development of novel NCM tool, which was the response of the second research question and was discussed in chapter 4, it allows systematic modeling and analysis of the NCs. The phases involved in the implementation of the NCM tool were: collection of all the NCs generated in the manufacturing system, filtering the NCs and selecting only those that are relevant to the Microleaks, applying mathematical operations to the NCs and highlighting key manufacturing areas for further investigation. In the case of Microleaks, the NCM highlighted four key areas of interest: (1) Output quality parameters (Leaks); (2) Flanging and seaming; (3) Secondary cutting; and (4) Varnishing and printing.

The output quality parameters were further decomposed into four critical locations: leakage in welding area at the beginning and end of an aerosol can; leakage in seaming area at the beginning and end of an aerosol can. The results showed that more than 65% of the Microleaks occur at the welding beginning of an aerosol can. Following this achievement, the Microleaks team focused all its attention at the welding beginning. A brainstorming session with the key responsible of the process identified several methods that can be applied for further investigation.

One of the optimization tools that were implemented in the thesis for in-depth analysis of the welding beginning was Design of Experiments. Eight steps were followed for the successful implementation of DoE. In order to identify efficiently the levels of each

controllable factor in the presence of noise factors, an innovative pre-experimental run method was developed. Due to limitation of time and resources, a Taguchi orthogonal array method was used, reducing the number of total experiments from 81 to only 9 experiments.

The Taguchi method did not prove successful in identifying the significant factors for the welding beginning problem. Thus, a full factorial analysis was planned between the two most important factors - the welding current and the welding force - whereas the other three factors were kept at a constant value. The results from the full factorial analysis showed that even by increasing the speed 10% it is still possible to reduce drastically the Microleaks.

The results and recommendations were then analyzed through the implementation of Cost of Quality models that economically investigated the feasibility of the various proposals. Cost of Quality model was developed in detail in chapter 6, responding to research questions 3 and 4. The implementation of CoQ model was done two fold: (1) First, the acceptance sampling plans that function with the manual waterbath system to inspect leaky cans were economically explored; (2) Second, alternative technologies and leak detection systems that could become part of the assembly line to reduce the Microleaks were also economically investigated.

The results showed that among the four acceptance sampling plans, including the as-is double acceptance sampling plan, the revised single sampling plan optimized the overall results. Results from the alternative technology, particularly trimming technology, showed that implementing this technology could reduce drastically the external failure costs, although the overall costs due to investments in the technology rise. Nevertheless, when comparing trimming technology with the acceptance sampling plans, the former provided optimum results.

In the case of leak detection systems, the gas tracer leak detection system provided better precision than the current technologies. This technology can measure leaks up to 10^{-5} ml/min and should be further investigated for adaptation into the online system.

7.2.   General Systems Engineering methodology

A general Systems Engineering methodology for quality improvement of manufacturing systems has been developed with the purpose of being easily implemented to other assembly lines, formats, or even other manufacturing areas and systems. The major phases of the synthetized methodology are:

1. Define clearly the project scope, problem to be analyzed and identify the team;
2. Develop a complete process mapping and identify the quality control points relevant to the problem identified;
3. Identification of all elements along the production line of a product and collection of all relations between them;
4. Transfer all data to a DSM, parsed by manufacturing process;
5. Apply mathematical operations to DSM and evaluate and characterize the final DSM;
6. Use the most adequate quality improvement tools to further refine the critical quality characteristics and areas previously identified;
7. Perform cost of quality analysis to enable an informed choice;
8. Improve the manufacturing process according to the results;
9. Evaluate again the relations of elements, deleting the elements that were eliminated and update the DSM;
10. Standardize the results and refine the model over time.

7.3.   Contributions and Implications of the thesis

The research supports and contributes to the field of Systems Engineering, and Quality Engineering and Management. The important contributions are the following:

- Development of a Systems Engineering methodology: for complex manufacturing problems where there are multidisciplinary fields involved, the proposed methodology of Systems Engineering for quality improvement of manufacturing systems emerges to be a useful methodology;
- Development of a NCM as a novel tool: for the first time, an application of a DSM in a different context, related to quality control of manufacturing systems is

demonstrated. NCM has been proved successful in modeling the entire manufacturing system systematically and innovatively, allowing a deeper and quicker analysis of the critical areas of manufacturing systems;

- New approach of pre-experimental runs in the DoE can be useful for both research and industrial practitioners who are dedicated to large DoE projects, with unknown factor interactions and when the operational levels are not completely defined.

The implication of the thesis can be regarded either from a research or an industry perspective. From an industry perspective, the industrial engineers can use a novel methodology to assist them in performing a systematic analysis of the entire manufacturing system. Also, the methodology allows the industrial practitioners to analyze existing processes for possible improvements, by investigating the interactions and relations between the important components of the manufacturing systems.

From a research perspective, although it is unequivocal that a lot of quality improvement methodologies exist, it is not easy to identify one that provides a systematic and holistic perspective of the entire system. This research attempted to develop a novel methodology, integrating contributions from the field of systems engineering and quality control and improvement.

In fact, and according to the literature review, applications of System Engineering tools in quality improvement problems has not been attempted so far, being one of the research gaps that this work attempts to address. Although Systems Engineering tools are designed for very complex systems, it is believed that integrating this approach in the new context of quality problems and exploring the benefits that might be achieved is a new avenue of research.

Based on the achievements and results throughout the thesis, the following recommendations are proposed:

7.3.1. Optimization of the welding process

One of the greatest achievements of the DoE analysis is the identification of factor combinations that reduce drastically the Microleaks, as well as improving the

productivity by 10%. For the current production setting, the factors should be set at the following combinations:

Factor	Welding current	Welding force	Welding speed	Overlap	Distance between welding bodies
Level	250 kA	40 kgf	64 m/min	0.5 mm	2 mm

However, it is important to note that these factor combinations were only attained for specific conditions that were met in the current DoE analysis, like, for example, keeping the outer welding roller at 82.7 mm. Therefore, a more general recommendation is presented below, where factors are set at their minimum (-), standard (0), and maximum (+) levels.

Factor	Welding current	Welding force	Welding speed	Overlap	Distance between welding bodies
Level	Standard (0)	Minimum (-)	Maximum (+)	Standard (0)	Standard (0)

When implementing these results to other conditions or formats or assembly lines, it is important first to define the levels of these factors by implementing the pre-experimental runs developed in this thesis.

7.3.2. Controlling parameters through welding rollers diameters

The DoE analysis revealed that welding rollers diameters have a direct affect on the values of welding current, therefore directly affecting conductance values. It is easy to understand that the welding roller is a variable, as its diameter constantly varies due to wearing out while producing aerosol cans. Therefore, throughout the experiments and in order to minimize this noise effect, the diameter of the welding rollers was kept constant. As this method showed convincing results, it is recommended to use the same method to other formats and assembly line for future DoE analysis.

7.3.3. False rejections from the 100% leak testing machine (Wilcomat)

During the analysis it was recorded that a significant percentage of aerosol cans are falsely rejected from the Wilcomat machine. As a result, loss of revenues in terms of scrap, production time, and energy is incurred. Therefore it is recommended to study in depth the problem and how can it be reduced or eliminated. The first step towards

analyzing any problem is to monitor it for a period of time: currently the Wilcomat rejections are not recorded neither the rejected aerosol cans are further validated for false rejections. In fact, results from cost of quality models showed that, on an average, €70,000 can be saved if false rejections could be completely eliminated.

7.3.4. Cost of Quality

There are two types of recommendations provided in the cost of quality chapter: the first doesn´t imply a major investment, whereas the second recommendation requires huge investments. The recommendations that can be in-effect immediately are changes in the acceptance sampling plans, provided the industry estimates correctly the external failure costs and the conforming units sent to the customer. In this case, a better sampling scenario could be chosen in order to optimize the cost of quality. This recommendation won't reduce the external failure costs drastically; however, by selecting a different acceptance-sampling scenario the current condition could be optimized.

The second type of recommendation, requiring huge investments, consists of two possibilities. The first possibility to reduce external failure is to implement the trimming technology in all lines. Nevertheless this technology requires significant investments and is not completely mature. The second possibility is to invest in gas tracer leak detection systems, with a word of caution, as this system still requires further experimentation and validation process.

7.4. Directions of future research

There are three areas that can be additionally explored in the future to further improve the final product quality and strengthen the Systems Engineering methodology: (1) updating the corrected NCM with new knowledge acquired during the implementation phase of the methodology; and (2) applying the general methodology of Systems Engineering for quality improvement of manufacturing systems to other types of industries.

7.4.1. Updating the corrected NCM with the new knowledge acquired

During the implementation phase of the Systems Engineering methodology, many new NCs were recorded – in particular NCs related to the welding process. As a future work,

these NCs can be added to the corrected NCM and the subsequent steps could be followed for revealing new relations and interactions between the NCs, following a cyclic improvement process.

7.4.2. Application of systems engineering methodology to other manufacturing systems

The methodology discussed in the thesis was specific to the Microleaks project. However, there was an attempt to create a general methodology, which still requires further validation through a more vast application to other manufacturing systems and industries.

The recommended manufacturing systems where the Systems Engineering methodology can be applied range from consumer goods and packaging industry to automotive industries to chemical and plastic industries to electronic industries to semiconductor industries to pharmaceutical industries to wood and paper industries.

References

(INCOSE), International Council on Systems Engineering. 2006. *Systems Engineering Handbook*. Edited by Cecilia Haskins. Third.

AG, Wilco. 2015. "Wilco AG - Leak Detection - Pressure Decay Combined with High Pressure Test, Aerosol Cans."

Aichouni, Mohamed. 2012. "On the Use of the Basic Quality Tools for the Improvement of the Construction Industry : A Case Study of a Ready Mixed Concrete Production Process." *International Journal of Civil & Environmental Engineering* 12 (5): 28–35.

Andersson, Roy, Henrik Eriksson, and Håkan Torstensson. 2006. "Similarities and Differences between TQM, Six Sigma and Lean." *The TQM Magazine* 18 (3): 282–96.

Antony, J, M Kumar, and M K Tiwari. 2005a. "An Application of Six Sigma Methodology to Reduce the Engine-Overheating Problem in an Automotive Company." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 219 (8).

Antony, J., 2011. Six Sigma vs Lean: Some perspectives from leading academics and practitioners. *International Journal of Productivity and Performance Management*, 60(2), pp.185–190.

Antony, J., Kumar, M. & Tiwari, M.K., 2005a. An application of Six Sigma methodology to reduce the engine-overheating problem in an automotive company. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 219(8), pp.633–646.

Antony, J., Kumar, M. & Tiwari, M.K., 2005b. An application of Six Sigma methodology to reduce the engine-overheating problem in an automotive company. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 219(8), pp.633–646.

ATEQ. 2015. "ATEQ Measurement Systems." www.ateq.com (accessed on July, 2015).

Bamford, David R., and Richard W. Greatbanks. 2006. "Article Information :" *International Journal of Quality & Reliability Management* 22 (4): 376–92.

Batallas, Diego, and Ali Yassine. 2006. "Information Leaders in Product Development Organizational Networks: Social Network Analysis of the Design Structure Matrix." *Engineering Management, IEEE …* 53 (4): 570–82.

Bertels, Thomas. 2003. *Rath & Strong's Six Sigma Leadership Handbook*. John Wiley & Sons.

Black, Ken, and Lee Revere. 2006. "Six Sigma Arises from the Ashes of TQM with a Twist." *International Journal of Health Care Quality Assurance* 19 (3): 259–66.

Bottorff, Dean L. 1997. "COQ Systems: The Right Stuff." *Quality Progress vol.30 no.3*.

Brady, James E., and Theodore T. Allen. 2006. "Six Sigma Literature : A Review and Agenda for Future Research." *Quality and Reliability Engineering International* 22: 335–67.

Browning, T.R. 2001. "Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions." *IEEE Transactions on Engineering Management* 48 (3): 292–306.

Carrascosa, Maria, Steven D. Eppinger, and Daniel E Whitney. 1998. "Using the Design Structure Matrix to Estimate Product Development Time." In *ASME Design Engineering Technical Conferences*. Atlanta, Georgia, USA.

Chen, Jianwei, Kim-Hung Li, and Yeh Lam. 2007. "Bayesian Single and Double Variable Sampling Plans for the Weibull Distribution with Censoring." *European Journal of Operational Research* 177 (2): 1062–73.

Coleman, David E, and Douglas C Montgomery. 1993. "Industrial Experiment A Systematic Approach to Planning for a Designed Industrial Experiment." In *Technometrics*, Vol 35:1:1–12.

Crossby, Phillip B. 1979. "Quality Is Free." New york, NY: McGraw-Hill.

Czitrom, Veronica. 2003. "Guidelines for Selecting Factors and Factor Levels for an Industrial Designed Experiment." In *Handbook of Statistics*, Volume 22, 22:3–32.

Deming, Edward. 1986. *Out of the Crisis*. *MIT Press eBooks*.

Deshmukh, Abhijit V, Joseph J Talavage, and Moshe M Barash. 1993. "Analysis of Static Complexity." In *Complexity in Manufacturing Systems*, 32.

Dodge, Harold F. 1943. "A Sampling Inspection Plan for Continuous Production." In *Bell Telephone Laboratories, New York*.

Duffy, G. L., S. Laman, P. Mehta, G. Ramu, N. Scriabina, and K. Wagoner. 2012. "Beyond the Basics – Seven New Quality Tools Help Innovate, Communicate and Plan." *Quality Progress*.

Dusharme, Dirk. 2006. "Six SIgma Survey." *Quality Digest*. http://www.qualitydigest.com/feb03/articles/01_article.shtml.

Farooq, Arsalan, António Araújo, S M O Tavares, and Henriqueta Nóvoa. 2013. "Evaluation of a Non-Conformity Matrix Complexity Using Components Modularity Metrics." In *15th International Dependency and Structure Modelling Conference, DSM.*, 19–25. Melbourne: Carl Hanser Verlag GmbH & Co. KG.

Farooq, Arsalan, S M O Tavares, Henriqueta Nóvoa, and António Araújo. 2014. "An Application of Knowledge Management in Design Structure Matrix for a Process Improvement Phase." In *16th International Dependency and Structure Modelling Conference, DSM.* Paris: Carl Hanser Verlag GmbH & Co. KG.

Farooq, Muhammad Arsalan, Henriqueta Nóvoa, António Araújo, and Sergio M.O. Tavares. 2015. "An Innovative Approach for Planning and Execution of Pre-Experimental Runs for Design of Experiments." *Journal of European Academy of Management and Business Economics* 21 (1).

FEA. 2015. "European Aerosol Federation - How the Aerosol Works." Accessed April 22. http://www.aerosol.org/about-aerosols/aerosol-s-functioning.

Feigenbaum, By Armand V. 1956. "TOTAL QUALITY CONTROL." *Harvard Business Review, Vol. 34 No. 6, P. 93*, 93–102.

Folaron, Jim. 2003. "The Evolution of Six Sigma." *ASQ*.

Fowlkes, William Y, and Clyde M. Creveling. 1996. "Engineering Methods for Robust Product Design: Using Taguchi Methods in Technology and Product Development." *Journal of Product Innovation Management* 13 (3): 279.

Freeman, Linton C. 1978. "Centrality in Social Networks Conceptual Clarification." *Conceptual Clarification, Social Networks* 1: 215–39.

Gershenson, J. K., G. J. Prasad, and Y. Zhang. 2010. "Product Modularity: Measures and Design Methods." *Journal of Engineering Design* 15 (1): 33–51.

Gogue, Jean-marie. 2005. "Before the Deming ' S 14 Points for Management." *The French Deming Association*.

Hahn, G. J. 2005. "Six Sigma: 20 Key Lessons Learned." *Quality and Reliability Engineering International* 21 (3): 225–33.

Hahn, Gerald J., Necip Doganaksoy, and Roger Hoerl. 2000. "The Evolution of Six Sigma." *Quality Engineering* 12 (3): 317–26.

Hoerl, Roger W., and Ronald D. Snee. 2013. "Identifying the Right Improvement Methodology." *Quality Progress*.

Hommes, Qi D. 2008. "Comparison and Application of Metrics That Define the Components Modularity in Complex Products." In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conferences*, 1–10. Brooklyn, New York.

Javorsky, Joseph, Matthew Franchetti, and Hongyan Zhang. 2014. "Determining the Optimal Parameters of Bonding Polyvinylchloride to Stainless Steel in Automotive Applications with the Use of Full Factorial Design of Experiment." *CIRP Journal of Manufacturing Science and Technology* 7 (2). CIRP: 151–58.

Juran, Joseph M. 1951. *Quality-Control Handbook*. 1st editio. McGraw-Hill, New York, NY.

Juran, Joseph M., and A. Blanton Godfrey. 1998. *Juran´s Quality Handbook*. Fifth edit. McGraw-Hill, New York, NY.

Juran, Joseph.M., Leonard A. Seder, and Frank M. Gryna. 1962. *Quality-Control Handbook*. 2nd editio. McGraw-Hill, New York, NY.

Kirchain, R, and F R Field. 2001. "Process-Based Cost Modelling: Understanding the Economics of Technical Decisions." *Encyclopedia of Materials Science and Engineering* 2: 1718–27.

Kreimeyer, Matthias F. 2009. "A Structural Measurement System for Engineering Design Processes." Technishe Universitaet Muenchen.

Kumar, U. Dinesh, David Nowicki, José Emmanuel Ramírez-Márquez, and Dinesh Verma. 2008. "On the Optimal Selection of Process Alternatives in a Six Sigma Implementation." *International Journal of Production Economics* 111 (2): 456–67.

Lanzoni, B Y Massimo, and Mirko Salomoni. 2010. "Seam Welding Monitoring System Based on Real-Time Electrical Signal Analysis - A New Approach to in-Line Seam Welding Quality Evaluation Is Presented." *Welding Journal* 89 (October).

MacCormack, Alan, John Rusnak, and Carliss Y. Baldwin. 2006. "Exploring the Structure of Complex Software Designs: An Empirical Study of Open Source and Proprietary Code." *Management Science* 52 (7): 1015–30.

Melo, Pedro. 2013. "Improvement of the Integrity of Aerosol Cans - Material Analysis." University of Porto.

Montgomery, Douglas C. 2008. *Design and Analysis of Experiments*. 7th Editio. Wiley, New york.

Montgomery, Douglas C. 2010. "A Modern Framework for Achieving Enterprise Excellence." *International Journal of Lean Six Sigma* 1 (1): 56–65.

Montgomery, Douglas C. 2009. *Introduction to Statistical Quality Control*. 6th Editio. John Wiley & Sons, Inc.

Montgomery, Douglas C., J. Bert Keats, Leonard a. Perry, James R. Thompson, and William S. Messina. 2000. "Using Statistically Designed Experiments for Process Development and Improvement: An Application in Electronics Manufacturing." *Robotics and Computer-Integrated Manufacturing* 16 (1): 55–63.

Montgomery, Douglas C., and William H. Woodall. 2008. "An Overview of Six Sigma." *International Statistical Review* 76 (3): 329–46.

Paliska, G, D Pavletic, and M Sokovic. 2007. "Quality Tools – Systematic Use in Process Industry." *Journal of Achievements in Materials and Manufacturing Engineering* 25 (1): 79–82.

Pande, Pete, and Larry Holpp. 2000. *What Is Six Sigma?* McGraw-Hill, New York, NY.

Pursglove, A.B., and B.G. Dale. 1995. "Developing a Quality Costing System: Key Features and Outcomes." *Omega 23, 567-575*.

Schiffauerova, Andrea, and Vince Thomson. 2006. "A Review of Research on Cost of Quality Models and Best Practices." *International Journal of Quality & Reliability Management* 23 (6): 647–69.

Schilling, Edward G, and Paul R Garvey. 2008. *Acceptance Sampling in Quality Control*. 2nd editio. Taylor and Francis Group.

Sharman, David M., and Ali a. Yassine. 2004. "Characterizing Complex Product Architectures." *Systems Engineering* 7 (1): 35–60.

Sharman, David M., Ali a. Yassine, and Paul Carlile. 2002. "Characterising Modular Architectures." In *Design Engineering Technical Conferences and Computer and Information in Engineering Conferences*, 1–14. Montreal.

Shewhart, Walter. 1931. *Economic Control of Quality of Manufactured Product*. New York: D. Van Nostrand Company Inc.

Snee, Ronald D. 2008. "W. Edwards Deming's 'Making AnotherWorld.'" *The American Statistician* 62 (3): 251–55.

Snee, Ronald D. 2010. "Lean Six Sigma - Getting Better All the Time." *International Journal of Lean Six Sigma* 1 (1): 9–29.

Sokovic, M, D Pavletic, and Kk Pipan. 2010. "Quality Improvement methodologies–PDCA Cycle, RADAR Matrix, DMAIC and DFSS." *Journal of Achievements in …* 43 (1): 476–83.

Sosa, Manuel E, Steven D Eppinger, and Craig M Rowles. 2007. "A Network Approach to Define Modularity of Components." *ASME Transactions* 129.

Steven D. Eppinger, and Tyson R. Browning. 2012. *Design Structure Matrix Methods and Applications*.

Subulan, Kemal, and Mehmet Cakmakci. 2011. "A Feasibility Study Using Simulation-Based Optimization and Taguchi Experimental Design Method for Material Handling—transfer System in the Automobile Industry." *The International Journal of Advanced Manufacturing Technology* 59 (5-8): 433–43.

Tague, Nancy. 2005. "Pareto Chart Analysis (Pareto Diagram)." *ASQ*. http://asq.org/learn-about-quality/cause-analysis-tools/overview/pareto.html.

Tari, Juan Jose, and Vicente Sabater. 2004. "Quality Tools and Techniques: Are They Necessary for Quality Management?" *International Journal of Production Economics* 92 (3): 267–80. doi:10.1016/j.ijpe.2003.10.018.

Tavares, S M O, Arsalan Farooq, António Araújo, and Henriqueta Nóvoa. 2013. "Application of Non-Conformity Matrix to Predict System Interactions in Complex Quality Problems." In *Flexible Automation Integrated Manufacturing (FAIM)*, 839–50. Porto: Springer.

Teixeira, Raquel. 2013. "Improvement of the Integrity of Aerosol Cans - Detection Systems." University of Porto.

Tjahjono, B, P Ball, V I Vitanov, C Scorzafave, J Nogueira, J Calleja, M Minguet, et al. 2010. "Six Sigma: A Literature Review." *International Journal of Lean Six Sigma* 1 (3): 216–33.

Valente, Renato. 2013. "Improvement of the Integrity of Aerosol Cans - Welding and Forming Processes." University of Porto.

Warfield, John N. 1973. "Binary Matrices in System Modeling." *IEEE Transactions on Systems, Man, and Cybernetics* 3 (5): 441–49. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4309270.

Wetherill, G Barrie. 1977. *Sampling Inspection and Quality Control*. 2nd editio. Springer science business media.

Whitney, Daniel E, Qi Dong, Jared Judson, and Gregory Mascoli. 1999. "Introducing Knowledge-Based Engineering into an Interconnected Product Development Process." In *1999 ASME Design Engineering Technical Conferences*. Las Vegas, Nevada.

Williams, A R T, A Van Der Wiele, and B G Dale. 2000. "Quality Costing : A Management Review." *International Journal of Management Reviews* 1 (4): 441–60.

Wynn, David C, David F Wyatt, Seena M T Nair, and P John Clarkson. 2010. "An Introduction to the Cambridge Advanced Modeller." In *International Conference on Modeling and Management of Engineering*, 19–20. Cambridge.

Zaklouta, Hadi. 2011. "Cost of Quality Tradeoffs in Manufacturing Process and Inspection Strategy Selection." Massachusetts Institute of Technology.

Appendix I
Description of noise factors

Z-bar: Z-bar determines the overlap. The center of z-bar should be 0.4mm above the wire of the lower welding roller. If z-bar is too low, than leading end of seam will not be welded. If z-bar is too high, than trailing end of seam will not be welded. An illustration of the concept of z-bar is shown in Figure 116 (position A).
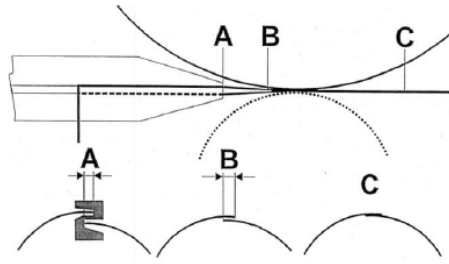
Figure 116: Z-bar settings (Valente 2013)

Cooling fluid, Copper wire profile, and Welding rollers profile: These factors are noted during the experiments and are usually recorded at a constant value. The cooling fluid must be 5°C, copper wire profile must be 1.38mm and welding rollers profile has no specific value however must be checked each time experiment is performed.

Calibrating tool: During the welding process, the calibrating tool guides the aerosol body. It plays an important role in the overlap of the body and influences welding. The parallelism of overlap is influenced by position of calibrating tool in feed direction.

All the noise factors for design of experiments are presented in Table 47.

Table 47: Defining noise factors

Defining Noise Factors					
Noise factors	Pre-experimental day	1st day	2nd day	3rd day	Units/comments
Z-bar	0.4	0.4	0.4	0.4	mm
Calibrating tool	OK	OK	OK	OK	By production team member
Cooling fluid (Temperature)	5	5	5	5	°C
Copper wire quality (supplier, batch)	La Farga, 210001785	La Farga, 210001785	La Farga, 210001785	La Farga, 210001785	-
Copper wire profile (diameter)	1.38	1.38	1.38	1.38	mm
Material supplier	Arcelor	Arcelor	Arcelor	Arcelor	mm
Welding rollers diameter (upper)	84.4	83.9	82.7	82.7	mm
Welding rollers diameter (lower)	53.9	53.9	53.9	53.9	mm
Welding rollers profile	OK	OK	OK	OK	By production team member

Appendix II
Results of offline response variables

Overlap Measurements:

		Overlap	
		Beginning	End
L1	Average	0.57	0.48
	1	0.6	0.5
	2	0.6	0.5
	3	0.5	0.4
	4	0.55	0.5
	5	0.6	0.5
L2	Average	0.57	0.5
	1	0.6	0.5
	2	0.6	0.5
	3	0.5	0.5
	4	0.6	0.5
	5	0.55	0.5
L3	Average	0.6	0.5
	1	0.6	0.5
	2	0.6	0.5
	3	0.6	0.5
	4	0.6	0.5
	5	0.6	0.5
L4	Average	0.54	0.44
	1	0.5	0.4
	2	0.6	0.5
	3	0.5	0.4
	4	0.5	0.4
	5	0.6	0.5
L5	Average	0.5	0.4
	1	0.5	0.4
	2	0.5	0.4
	3	0.5	0.4
	4	0.5	0.4
	5	0.5	0.4
L6	Average	0.58	0.48
	1	0.5	0.4
	2	0.6	0.5
	3	0.6	0.5
	4	0.6	0.5
	5	0.6	0.5
L7	Average	0.58	0.48
	1	0.6	0.5
	2	0.6	0.5
	3	0.6	0.5
	4	0.5	0.4
	5	0.6	0.5
L8	Average	0.5	0.4
	1	0.5	0.4
	2	0.5	0.4
	3	0.5	0.4
	4	0.5	0.4
	5	0.5	0.4
L9	Average	0.59	0.5
	1	0.55	0.5
	2	0.6	0.5
	3	0.6	0.5
	4	0.6	0.5
	5	0.6	0.5

Extrusion and Thickness Measurements:

Experiment number	Grinding	
	Extrusion	Thickness

	Grinding (0.8 mm)	
	1.4	0.277
	1.28	0.251
L1	1.38	0.267
	1.326	0.266
	1.52	0.245
Average	1.3812	0.2612

	Grinding (0.8 mm)	
	1.1	0.291
	1.08	0.286
L2	1.038	0.289
	1	0.28
	1	0.282
Average	1.0436	0.2856

	Grinding (0.8 mm)	
	1.28	0.286
	1.323	0.277
L3	1.25	0.275
	1.3	0.277
	1.34	0.287
Average	1.2986	0.2804

	Grinding (0.8 mm)	
	1.2	0.257
	1.17	0.255
L4	1.114	0.238
	1.19	0.229
	1.08	0.227
Average	1.1508	0.2412

	Grinding (0.8 mm)	
	1.169	0.237
	1.27	0.237
L5	1.21	0.223
	1.265	0.255
	1.201	0.236
Average	1.223	0.2376

	Grinding (0.8 mm)	
	1.12	0.223
	1.18	0.242
L6	1.21	0.225
	1.026	0.251
	1.06	0.229
Average	1.1192	0.234

	Grinding (0.8 mm)	
	-	0.236
	-	0.223
L7	-	0.277
	-	0.245
	-	0.248
Average		0.2458

	Grinding (0.8 mm)	
	1.12	0.242
	-	0.24
L8	-	0.22
	-	0.253
	1.27	0.273
Average	1.195	0.2456

	Grinding (0.8 mm)	
	0.6	0.3
	0.835	0.3
L9	0.69	0.304
	0.682	0.302
	-	0.282
Average	0.70175	0.2976

Heat Affected Area:

Experiment number	Heat affected area (in mm)	
	Beginning	at 3mm

L1	1.5	1.2
	1.4	1.1
	1.4	1.2
	1.3	1.1
	1.5	1.2
Average	1.42	1.16

L2	1	0.9
	1.1	1
	1.2	1.1
	1.1	1
	1.2	1.1
Average	1.12	1.02

L3	1.4	1.2
	1.3	1.2
	1.4	1.2
	1.4	1.3
	1.4	1.2
Average	1.38	1.22

L4	1.5	1.2
	1.3	1.2
	1.4	1
	1.4	1
	1.3	0.8
Average	1.38	1.04

L5	1.3	0.9
	1.3	1.2
	1.2	1.3
	1.3	1.2
	1.3	1.3
Average	1.28	1.18

L6	1.3	0.8
	1.2	0.8
	1.3	0.8
	1.2	1.1
	1	0.9
Average	1.2	0.88

L7	1.7	1
	1.6	1
	1.7	1.1
	1.8	1.2
	1.6	1.2
Average	1.68	1.1

L8	1.6	1.1
	1.6	1.2
	1.6	1
	1.6	1.1
	1.8	1.2
Average	1.64	1.12

L9	0.5	0.8
	0.9	0.9
	0.6	0.8
	0.8	0.9
	0.8	0.9
Average	0.72	0.86

a: Experiment # 1 (magnification 50x)

b: Experiment # 1 (magnification 50x)

c: Experiment # 7 (magnification 10x)

d: Experiment # 8 (magnification 10x)

e: Experiment 9 (magnification 10x)

f: Experiment # 9 (magnification 50x)
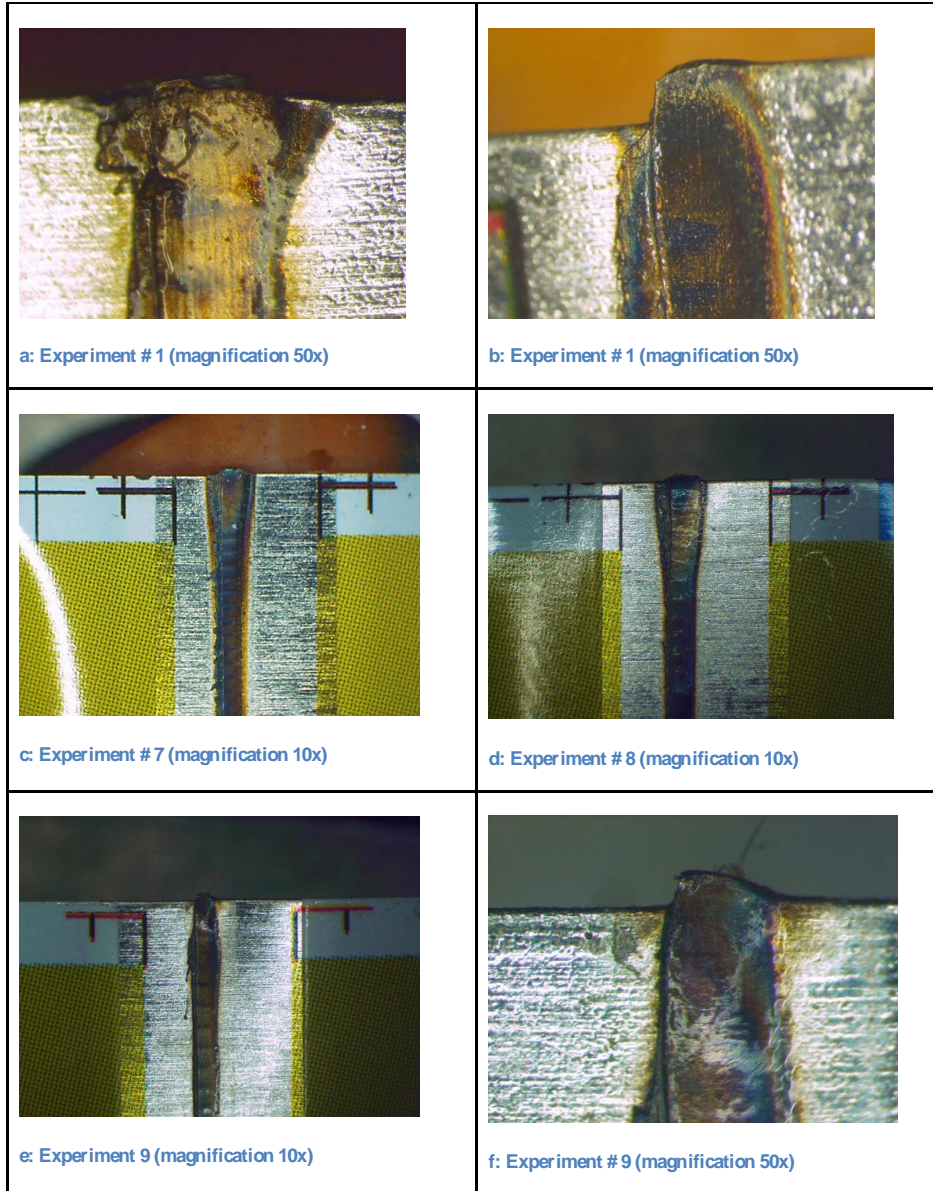
Figure 117: Some of the examples taken from experiments showing heat affect areas

Appendix III
Components of an ANOVA table:

Source - indicates the source of variation, either from the factor, the interaction, or the error. The total is a sum of all the sources.

DF - degrees of freedom from each source. If a factor has three levels, the degrees of freedom is 2 (n-1). If you have a total of 30 observations, the degrees of freedom total is 29 (n - 1).

SS - sum of squares between groups (factor) and the sum of squares within groups (error)

MS - mean squares are found by dividing the sum of squares by the degrees of freedom.

F - calculate by dividing the factor MS by the error MS; you can compare this ratio against a critical F found in a table or you can use the p-value to determine whether a factor is significant.

P - use to determine whether a factor is significant; typically compare against an alpha value of 0.05. If the P-value is lower than 0.05, then the factor is significant.

Standard error (S): S is the average squared difference of the error in the actual to the predicted values of the data (i.e. the square root of the mean squared error). The smaller the value of S, the stronger the linear relationship exists.

R-squared (R-Sq): R-squared is a statistical measure of how close the data are to the fitted regression line. It is the percentage of the response variable variation that is explained by a linear model. Or:

R-squared = Explained variation / Total variation

R-squared is always between 0 and 100%:

0% indicates that the model explains none of the variability of the response data around its mean.

100% indicates that the model explains all the variability of the response data around its mean.

Residuals: The difference between an observed value and its corresponding fitted value is called residuals. They are especially useful in regression and ANOVA procedures because they indicate the extent to which a model accounts for the variation in the observed data.

Appendix IV
Inputs for the Cost of Quality model

Aerosol design		
Type	**Dimension**	**Units**
Aerosol can thickness	0.18	mm
Aerosol can diameter	65	mm
Aerosol can length	300	mm

Exogenous data		
Type	**Dimension**	**Units**
Annual Production Volume (2014-3 shifts)	32000000	(/yr.)
Annual Production Volume (2014-4 shifts)	43000000	(/yr.)
Product Life	2	Yrs.
Direct Wages (w/ benefits)	€ 7.48	/hr
Working Days	264	Days/yr.

Cost for Assembly Line # 12		
Type	**Costs**	**Units**
Set-up cost	€ 8.26	/1000 units
Equipment's	€ 4.06	/1000 units
Direct Labor	€ 7.88	/1000 units
Indirect Labor	€ 0.26	/1000 units
Maintenance	€ 2.87	/1000 units
Utilities	€ 2.72	/1000 units
Body (Blank)	€ 105.633	/1000 units
Bottom	€ 17.216	/1000 units
Top	€ 27.852	/1000 units
Copper wire	€ 1.86	/1000 units
External side seam varnish	€ 0.42	/1000 units
Solvent	€ 0.09	/1000 units
Pallet 1200x800x135	€ 5.49	/1000 units
Secondary packaging	€ 12.23	/1000 units

Constant Scrap Rates	
Process	**Percentage**
Welding process	1.50%
Seaming process	0.00%
Leak testing (Wilcomat)	2.00%

% Contribution					
	Welding process	**Seaming process**	**Leak testing (Wilcomat)**	**Packaging and palletizing**	
Machine costs	45%	33%	15%	7%	Total equipment
Maintenance cost	35%	25%	15%	5%	Total maintenance
Set-up cost	65%	20%	1%	14%	Total set-up
Labor per station	33%	17%	17%	33%	/station
Energy requirement	60%	12.5%	20%	7.5%	Total utilities

Aerosol leak testing machine (Waterbath)		
Cost of water bath (leak testing) or present value	€ 10,000	/machine
Cycle time	0.1666	Min/can
Set-up time	0.2	Min/can
Accounting life of machine or number of periods	10	Yrs.
Interest rate	0%	
% Of the cans that can be measured from a single machine	1.5%	

Scenario A		
% Of cans measured from the batch (1st sample)	1.25%	Aerosol cans/batch
Batch size	10000	Aerosol cans
Accept the 1st sample when NC	0	Unit
Nr of pallets for second sample	1	Pallets
Nr of units each pallet has	1000	Units
Accept the second sample when NC	2	Unit
% Of cans measured from the pallet (2nd sample)	8.00%	Aerosol cans/pallet

Scenario B		
% Cans measured from the batch	1.50%	
Accept the 1st sample when NC	3	Unit(s)

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Scenario C		
Pallet (batch) size	1000	Aerosol cans/batch
% Of cans measured from the batch	20%	Aerosol cans

External Failure Costs	
External failure cost per unit (cost of additional failure premium)	15 Euros

Trimming Process Input Data Assumptions		
Equipment + Conveyors + Post trimming equipment	€ 1,000,000	/equipment
Accounting life of machine	10	Yrs.
Discount rate	20%	
Constant scrap rate	0.5%	
Maintenance cost	30%	Total maintenance
Set-up cost	30%	Total set-up
Labor per station	33%	/station
Energy requirement	40%	Total utilities
Quality of conformance for 100% testing (Wilcomat)	99.82%	