Quality Improvement of Magnetron in Company T Based on Six Sigma

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Abstract

Purpose – The purpose of this study is to improve the magnetron quality in Company T by identifying the nonconforming defect, adjusting the factors affecting the leakage of the magnetron tube core, and determining the optimal parameter values of these factors.

Deign/methodology/approach – A case study method is used to present the quality improvement of magnetron tube core. The DMAIC (Define, Measure, Analyze, Improve, and Control) framework is applied in the case study as well as several Six Sigma tools.

Findings – The results show that Ag-W thickness, Ag-W installation state and furnace entry interval are significant factors on the leakage of magnetron tube core, and the optimum settings for these factors are 0.055mm, offset by 1mm from the outer edge, and 5cm, respectively.

Research limitations/implications – The main limitation of this study is that it was carried out on a small number of production processes. The authors would like to analyze more case studies on the improvements of after-sales quality and supplier quality.

Practical implications – This research could be used in magnetron manufacturing process as a tool for managers and engineers to improve product quality, which can also be extended to similar manufacturing systems.

Originality/value – In this case study, the Six Sigma approach has been applied for the first time to solve magnetron manufacturing problems by improving the quality of magnetron production process. It can help the quality engineers be more familiar to the deployment of Six Sigma and effective tools.

Keywords Six Sigma, DMAIC, Failure mode and effect analysis, Design of experiments, Magnetron production

Paper type Case study

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1. Introduction

In fierce market competition, the improvement of product quality and the quick respond to customer needs become more important for the organizations to gain a strategic competitive advantage (Yadav *et al.*, 2019). Company T mainly produces the magnetrons which are supplied for household electrical appliance industry. To improve the quality of magnetrons can not only meet the daily usage needs of end customers, but also enhance brand recognition and increase market competitiveness. This relies on the significantly reduction of the production defects or the process variability (Sánchez-Rebull *et al.*, 2020) with the utilization of a customer-centric management philosophy (Tsarouhas and Sidiropoulou, 2024). Six Sigma is such a philosophy that pursues excellence and provides reliable products or services to achieve customer satisfaction (Sánchez-Rebull *et al.*, 2020).

Six Sigma, originally proposed by Motorola in 1980s, is a well-structured methodology for reducing variation and improving the quality of processes within an organization (He *et al.*, 2017; Alcaide-Muñoz and Gutierrez-Gutierrez, 2017). It is powerful to identify and remove the defects and the sources of faults or failures using a data-driven approach (Srinivas and Sreedharan, 2018; Ninerola et al, 2020). As it developed, Six Sigma has been deemed as a philosophy that pursues excellence and provides reliable products or services (Sánchez-Rebull *et al.*, 2020) and a business strategy that allows companies to drastically improve their performance (Park, 2000). Six sigma aims at the continuous process improvement related to the critical characteristics that are relevant for the customers (Yadav et al., 2019). The adoption of Six Sigma will have a significant effect on financial benefit (Oprime *et al.*, 2021), especially on free cash flow, EBITDA and asset turnovers (Foster Jr., 2007).

In this paper, Six Sigma has been applied in a magnetron manufacturing company. It is a first attempt to employ Six Sigma for improving the quality of magnetron in magnetron manufacturing company in China. Magnetron is assembled using high-temperature technology and manufactured using vacuum technology. Its product implementation process is relatively complex, and quality management is difficult. Any quality defects that occur during this production process are generally scrapped and cannot be reused, making it difficult to reduce quality costs. Therefore, how to control the quality of magnetron production process and reduce quality costs will become the key to whether the magnetron production enterprises can win in fierce competition. Therefore, it is necessary to reduce the magnetron defects in the manufacturing process.

The rest of this study is structured as follows: Section 2 discusses the literature review of Six Sigma and its case studies, and the research methodology is illustrated in Section 3. Section 4 outlines the background of the Six Sigma case study in Company T. Next, Section 5 presents the case study of Six Sigma application in the quality improvement of magnetron tube core. The lessons learned and the implications are discussed in Section 6, and some conclusions are provided in Section 7.

2. Literature review

Six Sigma as a philosophy aims at the continuous process improvement, which requires the top-down implementation of projects with a clear goal by systematically using some specific tools and techniques. Therefore, Six Sigma is also a project-driven approach (Büyüközkan and Öztürkcan, 2010), selecting projects is sensitive in the deployment of Six Sigma (Antony *et al*., 2007; Gijo and Rao, 2005), and several project selection methods (Büyüközkan and Öztürkcan, 2010; Wei and Cheng, 2020; Pakdil *et al*., 2021) have been developed to find the suitable Six Sigma projects. Meanwhile, Six Sigma projects that employ specific challenging goals result in a greater magnitude of improvement (Linderman *et al*., 2003).

Six Sigma projects are carried out with five basic phases: define, measure, analyze, improve, and control, which can be symbolized by initials as DMAIC (Büyüközkan and Öztürkcan, 2010; Srinivasan *et al*., 2016). Many useful tools and techniques have been developed and provided for the deployment of Six Sigma, which are classified and discussed based on functionality or qualitative-quantitative distinction (Tague, 1995; Pande *et al*., 2002; George *et al*., 2005; Antony and Desai, 2009; Uluskan, 2016). Therefore, because of the rich available tools, it is even argued that Six Sigma is a toolset, not a management system (Raisinghani *et al*., 2005).

Six Sigma through DMAIC is widely applied in industries (Srinivasan *et al*., 2016), such as manufacturing sectors (Zhang *et al*., 2015; Gijo *et al*., 2011), service sectors (Altuntas *et al*., 2020; Chen and Chen, 2016), and unconventional sectors (Sánchez-Rebull *et al*., 2020; He *et al*., 2014). Sharma *et al*. (2018) employed the DMAIC methodology to identify and eliminate the sources of variations in the anodizing process of a portable amplifier production process, and finally improve the sigma level of the anodizing process to 3.91 from base sigma level 3.62 in short term. Costa *et al*. (2019) applied the DMAIC structured method to reduce the defective units in the process of pins insertion in printed circuit boards. For the friction welding of tube-to-tube plate using the external tool (FWTPET) process, Padmarajan and Selvaraj (2021) implemented the DMAIC technique to find the optimum values and range of values using Six Sigma tools such as Analysis of Variance, Response Surface Methodology, and control charts. Other Six Sigma applications include reducing the defects in a rubber gloves manufacturing process (Jirasukprasert *et al*., 2014), and improving the bag production process while analyzing the reliability, availability and maintainability based on DMAIC approach (Tsarouhas, 2021). Yadav et al. (2019) studied the application of Six Sigma to minimize the defects in glass manufacturing industry, where the overall yield of a car windshield achieved to 93.57% from the historical yield 88.4%. Tsarouhas and Sidiropoulou (2024) applied the Six Sigma DMAIC approach in a packaging olives production system, and, as a result, the yield of the production process was improved by 8.24%. Uluskan and Oda (2020) analyzed and decreased the oven door-panel alignment defects in a household appliances company's plant using the Six Sigma DMAIC approach.

Six Sigma has mostly been applied in many large-sized organizations which do not face scarcity of money and human resources (Soundararajan and Janardhan, 2019). However, recently the successful applications of Six Sigma through DMAIC in small and medium enterprises (SMEs) have also been reported in literatures. Soundararajan and Janardhan (2019) reported a case study which improves the quality of guide wheel only using DMAIC phases in a SME. C.R. and Thakkar (2019) presented a successfully deployed study in a medium-scale industry, where DMAIC is used to identify the root cause and reduce the rejections of a telecommunication cabinet door manufacturing process. Desai and Prajapati (2017) adopted the DMAIC approach to reduce the critical defects to improve the quality of injection molding process. It is worth noting that the belt-based training infrastructure is always a major pillar of Six Sigma for large-sized or small- and medium-sized organizations (Soundararajan and Janardhan, 2019). Moreover, data collection is a major issue for implementing the DMAIC method in SMEs (Desai and Prajapati, 2017), which should attract the attentions of enterprises.

In summary, it is obvious from above research studies that the deployments of Six Sigma DMAIC approach are efficiency and lead to the improvement of quality in many industrials or different enterprises. However, it is the first attempt to apply Six Sigma in magnetron production process, where the magnetron cannot be reused once it has quality defects. Thus, it is essential to improve the quality of magnetron production process and reduce the magnetron defects.

3. Methodology

A case study method is adopted here, which entails the detailed and intensive analysis of a single case to get a close in-depth and first-hand understanding of it (Bell et al. 2018; Sunder and Kunnath, 2020). A single case can be a single organization, a single location or a single event. Though it is claimed that the extent to which generality from a single case study is limited, each case adds to the sum of knowledge available by documenting case experiences (Sunder and Antony, 2015), which is indeed valuable for future academicians, researchers and practitioners. According to Sunder and Antony (2015) and Sunder and Kunnath (2020), the case study methodology is preferred over other research methodologies due to the reasons including a) the case study method offers flexibility in design through mixed qualitative and quantitative methods and application which are more sensitive to the complexities of organizational phenomena, b) case study offers a means of investigating complex programmes consisting of multiple variables, and c) case study has proven particularly useful for studying evaluating programs like Six Sigma.

In a single case study, it is critical to appropriately decide the unit of analysis, i.e., the phenomenon under study (Lee, 1999). In this article, a case study is designed to study the underlying problem of the leakage of magnetron tube core that leads to the low quality of magnetron within the process. As part of the case study, the well-structured DMAIC problem-solving scheme was applied to improve the magnetron quality. Six Sigma tools, such as supplier-input-process-output-customer (SIPOC) model, gauge R&R, cause-and-effect (C&E) matrix, failure mode and effect analysis (FMEA), design of experiments (DOE), etc., are used to analyze the process and the related causes in order to achieve the objectives of each phase.

4. Background of Six Sigma Case Study in Company T

Company T is a joint venture and currently has 6,609 employees. The Magnetron Division was established in 2002, with strong technical development and production capabilities, has an annual production capacity of more than 12 million units, meeting domestic and overseas markets. Company T adheres to the business philosophy of "creating value for customers", and the principles of "quality is the life of the enterprise". It continuously optimizes the production and service system, and improves the quality of products. It has established a good brand image in the market and occupied a favorable market competitive position. It has maintained an average annual growth rate of 42% for many years and has become an important white home appliance production base in Tianjin and even in the north of China.

Company T realized the importance of carrying out the Six Sigma, and determined a set of methods and processes to promote Six Sigma, including the introduction stage, the expansion stage, and the deepening stage. Up to now, Six Sigma was regarded as the most important improvement method in company T. Combined with the annual business plan, the structured Six Sigma approach with DMAIC is continuously implemented in the scope of various business activities such as quality, production, procurement, development, and materials. Therefore, Six Sigma improvement can be achieved in the entire business scope.

Improving the quality level and reducing the cost of quality are particularly important for enhancing the competitiveness of enterprises. The defective rate of magnetron in company T is maintained at around 3.2%, which has no obvious competitive advantage in the industry, and the quality loss cost exceeds one million RMB per month. This has seriously affected the achievement of the development strategy of company T. Therefore, it is necessary to resolve the quality problem and improve the quality level as soon as possible. At the same time, company T produces more than 10 million magnetrons per year. Effective reduction of the defective rate can save a lot of money and make a considerable contribution to the company's strategic goals. Thus, as Six Sigma is a project-driven method, the project in the application of Six Sigma is selected as the improvement of magnetron quality in Company T.

5. Case Study: Magnetron tube core Quality Improvement

In the Six Sigma project of magnetron quality improvement, the well-structured Six Sigma DMAIC framework has been followed for improving the magnetron quality.

5.1 Define

5.1.1 Definition of CTQ

In order to effectively define the scope of the project, the SIPOC model is used to analyze the project to identify the main manufacturing processes and related functions, as shown in Table I. The magnetron is a kind of vacuum diode, and the vacuum state of the magnetron tube core must be ensured to guarantee its normal operation. The magnetron tube core, which is the key component in magnetron, cannot be reworked if it is leaked within the process. The vacuum degree of the magnetron tube core is a necessary condition to ensure the normal emission of electrons, and is required to reach 8×10^{-7} Torr in engineering applications. In this project, the vacuum degree of the magnetron tube core is selected as the key quality characteristic or critical-to-quality characteristic (CTQ).

[Insert Table I here]

5.1.2 Definition of nonconforming defect

Engineering data show that the leakage of the magnetron tube core mainly results in that the vacuum of the tube core cannot meet the requirements, leading to that the magnetron cannot work normally. Tube core leakage refers to a leakage phenomenon caused by a leakage point during the assembly process of the magnetron tube core. Once the leakage defect occurs, it cannot be repaired and can only be scrapped directly, resulting in a considerable cost of quality loss. Moreover, the leakage defect was primary among all the defects of magnetron. For example, the nonconforming rate of magnetron in October 2018 was 32000PPM, of which the leakage rate was 15,380 PPM, accounting for 49%. The Pareto analysis is applied to find the main leakage causes leading to the leakage defect of tube core. As shown in Figure 1, the key causes were the three leakage points of the magnetron tube core, i.e., the leakage points in the top of ceramic A, ceramic F, and the bottom of ceramic A. Thus, the nonconforming defect was defined as the leakage rate of the magnetron tube core in this project, and the leakage rates of the top of ceramic A, ceramic F, and the bottom of ceramic A are denoted by y_1, y_2, and y_3, respectively. It is planned to reduce the leakage rate of magnetron and achieve the purpose of saving quality loss costs.

[Insert Figure 1 here]

5.1.3 Goal of the project

The current leakage rate in company T is 15,380PPM, and the best level of leakage rate in this industry is around 7,000PPM. In order to reduce the quality cost between company T and the target company, the target leakage rate is set at 7,800PPM. A 50% improvement rate is a very challenging task for the project team, which greatly improves the cost competitive advantage. Through the implementation and improvement of this project, it is expected to obtain benefits in two aspects. The first is tangible financial benefits, that is, the financial income benefited from the improvement project. The second is intangible benefits, that is, the improvement in several areas, including corporate culture, quality awareness, employees' Six Sigma skills, and corporate competitiveness.

5.1.4 Team Members

Company T formed a cross-departmental Six Sigma team to proceed this project of reducing the leakage rate. The Six Sigma team contains 8 members. The first 3 members include a Champion, a project leader, and a mentor, who are all Black Belt and responsible for overall planning and resource support, overall responsibility, and methods and tools guidance, respectively. The other 5 members are all Green Belt, and responsible for quality data collection and analysis, process improvement analysis, and supplier product test, respectively.

5.2 Measure

5.2.1 Measurement System Analysis

Before collecting and analyzing data, it is necessary to evaluate the measurement system and correct any issues to ensure the validity of the measurement data. For the validation, two operators were chosen to measure 20 samples where each sample is measured twice. The 20 samples include 10 conforming products and 10 nonconforming products. The measurement results are then analyzed using the attribute agreement analysis. As shown in Table II, all the assessment agreements meet the requirements, including those about within appraisers, between appraisers, each appraiser vs standard, and all appraisers vs standard. These results indicated a gauge of 100% in repeatability and in reproducibility which means that there is no discrepancy between the different measurements made by them. This was greater than the judgment standard, 90%. Therefore, the measurement system is valid. The current measurement system was considered adequate to collect data and did not require further improvement.

[Insert Table II here]

5.2.2 Process Capability Analysis

To analyze the process capability analysis (PCA), during 30 days since late October 2018, 30 samples with sample size 300 were randomly sampled from the product records. It is calculated that the process capability is Z=2.147, as shown in Figure 2. This implies that there is still a big gap to be improved while compared with the Six Sigma level, Z=4.5.

[Insert Figure 2 here]

5.3 Analyze

5.3.1 Factors selected

In this project, the defect is the leakage of the magnetron tube core, including the leakage in the top of ceramic A, ceramic F, and the bottom of ceramic A. The cause-and-effect diagram is carried out to find the main factors that may lead to the tube core leakage, which is shown in Figure 3. Finally, 23 potential factors are identified considering human, machine, material, method, and environment elements.

[Insert Figure 3 here]

Then, a C&E matrix is applied to show the relationship between these 23 potential factors and the defects, which is tabulated in Table III along with their weighted score in the last column. Among these potential factors, 10 factors (denoted in bold in Table III) with total score equal or greater than 90 are deemed to be key factors influence the defects.

[Insert Table III here]

Next, FMEA is used to analyze these 10 key factors, as shown in Table IV. There are 6 key factors (highlighted in bold in Table IV) whose risk priority number (RPN) is greater than 200. Among these factors, proficiency and casual work can be immediately corrected through a simple and quick improvement scheme. Furthermore, Jig state, Ag-W thickness, Ag-W installation state, and furnace entry interval will be further analyzed in this section and improved by the Six Sigma tools in the next section.

[Insert Table IV here]

5.3.2 Quick Improvement

Following the simple and quick improvement scheme, the proficiency and the casual work are quickly improved by strengthening the familiarity of operators with the operating standards and adding the assessment system, respectively. Specifically, in order to ensure the proficiency, the standard operating qualification assessment is added before the operators work into the production line, and at least 1 year of working experience is needed for the tube core assembly workers. On the other hand, to reduce the risk of deviating from the standard operating process, the defective product traceability system is adopted and the reward and punishment measures are implemented. Then a second FMEA for these two factors is analyzed, as shown in Table V. It is easily seen that the RPN values of these two factors are all below 200. After the implementation of the quick improvement, the leakage rate has reduced from 15,380PPM to 12,300PPM.

[Insert Table V here]

5.3.3 Analysis scheme

The effects of Jig state, Ag-W thickness, Ag-W installation state and furnace entry interval on the leakage of the tube core are analyzed using the two-proportion test, as shown in Table VI.

[Insert Table VI here]

1) *Effect of Jig state*. Jig is a tooling mold, which fixes the parts in its specific mold. It is used to keep the parts stay in the correct link position when they enter the Br. furnace for high-temperature welding. The two-proportion test is used to analyze the effects of Jig state with a completeness of 90% and 60% on the leakage. The results illustrate that Jig state have no significant effect on the leakage because the p value is 0.785, greater than 0.05.

2) *Effect of Ag-W thickness*. Ag-W is a silver gasket that is used as a solder during the assembly process of the magnetron tube core. The effect of Ag-W with thicknesses of 0.055mm and 0.04mm on the leakage was analyzed. The results show that the Ag-W thickness has a significant effect on the leakage of the tube core since the p value is 0.014, smaller than 0.05.

3) *Effect of Ag-W installation state*. The installation state of Ag-W will affect the flow direction of Ag after melting. When the Ag-W is placed correctly, it will be offset by 1mm from the outer edge, and the deviation will be large when placed incorrectly. The influence of the Ag-W installation state with 1mm and 3mm deviation from the outer edge on the leakage is analyzed. The p value of the Ag-W installation state is 0.014, smaller than 0.05. This implies that the installation state of Ag-W has a significant impact on the leakage of the tube core.

4) *Effect of furnace entry interval*. The interval between entering the furnace refers to the distance between parts on the strips. The effect of furnace entry interval with 5cm and 0cm on the leakage is analyzed as well. As shown in Table V, the p value of the furnace entry interval is 0.03, smaller than 0.05. Thus, the furnace entry interval significantly affects the leakage of the tube core.

5.4 Improve

In the improve phase, the main task is to further analyze the effect of Ag-W thickness, Ag-W installation state and furnace entry interval on the leakage of magnetron tube core and to find out the optimal settings of these key factors to obtain the minimization of the leakage rate using the design of experiments (DOE). Here, we will adopt a full factorial design with three factors at two levels with three center points. The experiments were run according to the run order in Table VII, and the results were recorded. Due to the leakage rate is a discrete response variable that cannot be directly calculated like continuous data. Therefore, the logistic exchange, $y = \ln(p/(1-p))$, is used to convert the leakage rate into a continuous variable, which is also listed in Table VII. As shown in Table VIII, the three main effects and the interaction between Ag-W thickness and Ag-W installation state are significant. After deleting the insignificant interactions in the model, the reduced model is shown in Table IX. It can be clearly seen from Table IX that the main effects and the interaction are all significant. Also, there is no curvature and lack of fit of the model. Residual analysis validates the appropriateness of the model.

[Insert Table VII here]

[Insert Table VIII here]

[Insert Table IX here]

Optimization is then used to find the best values of Ag-W thickness, Ag-W installation state and furnace entry interval. Based on the optimized values of these parameters, the Ag-W with thickness 0.055mm is used and placed correctly (i.e., offset by 1mm from the outer edge), and furnace entry interval with 5cm are tested to observe if the leakage rate of magnetron tube core reaches the target of leakage rate. The converted leakage rate under this experimental setting is -5.1269, which is 5,935PPM, much lower than the target 7,800PPM. Therefore, the process parameters can be used in production. Then, these process parameters are applied in practice and 30 samples are collected. The results from practical applications show that the leakage rate is 7,111PPM, which also reaches to the project target. Meanwhile, the process capability is 2.451, as shown in Figure 4, which is also improved compared with 2.147 before the improvement.

[Insert Figure 4 here]

5.5 Control

In the control phase of DMAIC, the key factors found from the former phases are controlled and monitored with the control plans to sustain the effectiveness achieved through the project. Several actions adopted are shown in Table X to prevent any quality deterioration.

[Insert Table X here]

After implementing the control plans, the leakage rates in 30 consecutive days are collected from March to April 2019, and then a p control chart has been plotted in Figure 5. This shows that the process is in-control and the leakage rate is 6,270PPM. Two-sample test is applied for the sampled leakage rates before and after improvement. As shown in Table XI, the two-sample test results indicate that the means of leakage rates before and after improvement are significantly different. Thus, the proficiency, casual work, Ag-W thickness, Ag-W installation status and furnace entry interval have all been effectively controlled, and the leakage of the magnetron tube core is greatly improved.

[Insert Figure 5 here]

[Insert Table XI here]

5.6 Benefits of the project

After this Six Sigma project has been implemented, the quality of the magnetron tube core was indeed improved, and the economic benefits was obtained as well. The tube core leakage is reduced to about 7,100PPM from 15,380PPM. The annual output is 12,800,000 pieces, and the price of magnetron is 49.5 RMB per piece. All the loss due to the leakage of the tube core has been reduced by 5,246,000 RMB each year. Moreover, the application cost during this project is about 200,000RMB. Then, the economic benefit is 5,046,000RMB per year.

From the improved results, the project achieved the expected goals and effectively improved the quality of products and the company's market competitiveness. Moreover, these project activities have made the magnetron operation methods better and improved the process level. Furthermore, the team members accumulated much experience and enhanced their skills and capabilities of statistical analysis. Additionally, the success of this project assists in creating and strengthening the quality awareness of the basic level employees, and then brought good changes to the corporate culture of Company T. All these achievements will further promote the effective continuous improvement in Company T.

6. Discussion

This paper provides a Six Sigma case study from the magnetron manufacturing process. Specifically, the improvement of the magnetron tube core quality is selected as a Six Sigma project, where the magnetron tube core cannot be rework once it is leaked. Quality improvements in this area have not been widely studied, as well as the application of Six Sigma methodology, in previous literature (Altuntas *et al.*, 2020; Sánchez-Rebull *et al*., 2020; Srinivasan *et al.*, 2016). In this case study, the magnetron quality is improved indeed by reducing the tube core leakage rate about 54% in a short term, which also leads to a considerable financial income annually. This illustrates that the Six Sigma methodology, along with the DMAIC scheme, may be implemented and will be effective in a wider range of company as expected (Tsarouhas and Sidiropoulou, 2024; Uluskan and Oda, 2020; Yadav *et al.*, 2019).

Nowadays, an increase in data availability and complexity requires upgrading the Six Sigma toolkit with some advanced statistical tools, such as machine learning models (decision trees, logistic regression, k-nearest neighbors, and random forest) and more sophisticated multivariate statistical techniques (Zwetsloot *et al.*, 2018; Ferrer, 2021; González-Cebrián *et al.*, 2022). In Improve phase of the case study, a logistic exchange is adopted to convert the leakage rate, a discrete variable, into a continuous variable. This has not been widely considered and effectively processed in previous application of Six Sigma methodology. However, it may be common that the response variable is discrete in some cases. This logistic exchange method provides a competitive idea to deal with these issues in DOE. Other methods such as logistic regression could be attempted in DOE analysis to further improve the analysis results.

Furthermore, the top leader support and the cross-departmental collaboration have promoted the deployment of Six Sigma project in this case study. In the quick improvement, for example, the standard operating qualification assessment, the reward and punishment measures, and other improvement measures are proposed. However, to ensure these measures implemented as expected relies on the management involvement and commitment, organizational infrastructure, and linking Six Sigma to employees. These can be thought to be the critical success factors for the effective implementation of Six Sigma projects (Ng and Hempel, 2017; Stankalla *et al.,* 2018). In Company T, the Six Sigma Promotion Organization and a Six Sigma promotion and evaluation system has been established while carrying out the Six Sigma, and Six Sigma promotion activities have been managed as an important annual strategy. All these are the basis of the successful implementation of Six Sigma projects.

7. Managerial implications and lessons learned

The Six Sigma project of magnetron quality improvement outlined above has enabled Company T to secure competitive advantages in the market. Management involvement and commitment during both the introduction and expansion stages of the Six Sigma project are crucial for its success, as highlighted in Coronado and Antony (2002), Gijo et al. (2011), and Zhang et al. (2015). Additionally, success factors such as training, on-site quality management systems, and fostering quality awareness are essential during the project's implementation. This case study offers significant implications and lessons:

- Extending the line of thought presented in this case study and employing the DMAIC framework with Six Sigma tools can enhance product or process quality in similar manufacturing systems.
- Top leadership support is paramount for the successful implementation of Six Sigma projects. Strategic backing from company leaders facilitates the execution of cross-departmental activities on the frontline and ensures timely feedback on improvement efforts.
- Comprehensive Six Sigma training, particularly in basic statistics and the practical use of data analysis tools, is essential for employees. This equips team members with the ability to identify CTQs from various process indicators and apply diverse analytical techniques to the collected data.
- The establishment of an on-site quality management system is imperative to ensure the thorough implementation and efficient control of improvement measures within the production site. Company T has implemented such a system, which not only maintains the standard quality level of the magnetron but also facilitates Six Sigma quality enhancements, serving as a robust mechanism for implementing improvement initiatives.
- Enhancing and cultivating quality awareness among employees is essential as it profoundly influences their motivation and behavior. Quality awareness stands out as a pivotal factor contributing to the development of a quality culture (Davison and Al-Shaghana, 2007). As underscored in the research of Davison and Al-Shaghana (2007), organizational culture significantly impacts organizational performance and long-term efficacy. Thus, fostering quality awareness holds paramount importance in enhancing product quality and competitiveness.

8. Conclusions

The Six Sigma method through DMAIC attracted much attentions nowadays. This paper presents a case study of Six Sigma project on quality improvement of the magnetron in Company T. The implementation of this project in the case study followed a step-by-step DMAIC method, while adopting some tools such as the C&E matrix, FMEA, and DOE. Through the case study, the leakage rate of magnetron tube core has been reduced about 54%, which further improves the production quality and reduces the loss. The annual financial income resulted from this project was about 5.046 million RMB. This indeed gave a great encouragement for the team members and instilled confidence in the senior management of Company T. Also, the employees improved their capabilities in statistical analysis and problem-solving.

Motivated and encouraged by the successful and effective deployment of Six Sigma project, the company decided to increasingly promote the implementation of Six Sigma among the magnetron factory. Specifically, the company will comprehensively popularize Six Sigma quality management knowledge, improve the professional and technical level of quality management personnel, strengthen technical training, and establish a more professional Six Sigma improvement team and guidance team.

8.1 Limitations of this study

The main limitation of this study is it was carried out on a small number of production processes. The improvements in other aspects such as after-sales quality and supplier quality are still needed.

8.2 Future research

Several Six Sigma tools were used in the case study, which have been well applied in the existing literatures. However, in improve phase, the logistic exchange of response variable was introduced in DOE to obtain a continuous description of leakage rate. This has not been discussed in most existing works. An advanced DOE method dealing with the discrete response variable is further needed to be developed in future.

Moreover, Six Sigma is suggested to be integrated with other management methods such as Lean Production, TPM, ISO90001, and performance excellence model to gain more effective continuous improvement results (Raisinghani *et al*., 2005; Zhang *et al*., 2015; Uluskan *et al*., 2017).

References

Alcaide-Muñoz, C. and Gutierrez-Gutierrez, L. J. (2017), "Six Sigma and organisational ambidexterity: a systematic review and conceptual framework", *International Journal of Lean Six Sigma*, Vol. 8 No. 4, pp. 436-456.

Altuntas, S., Dereli, T. and Kaya, İ. (2020), "Monitoring patient dissatisfaction: a methodology based on SERVQUAL scale and statistical process control charts", *Total Quality Management and Business Excellence*, Vol. 31 No. 9-10, pp. 978-1008.

Antony, J. and Desai, D. A. (2009), "Assessing the status of six sigma implementation in the Indian industry: results from an exploratory empirical study", *Management Research News*, Vol. 32 No. 5, pp. 413-423.

Antony, J., Antony, F. J. and Kumar, M. (2007), "Six sigma in service organizations: Benefits, challenges and difficulties, common myths, empirical observations and success factors", *International Journal of Quality and Reliability Management*, Vol. 24 No. 3, pp. 294–311.

Büyüközkan, G. and Öztürkcan, D. (2010), "An integrated analytic approach for Six Sigma project selection", *Expert Systems with Applications*, Vol. 37, pp. 5835-5847.

C.R., A. and Thakkar, J.J. (2019), "Application of Six Sigma DMAIC methodology to reduce the defects in a telecommunication cabinet door manufacturing process: A case study", *International Journal of Quality and Reliability Management*, Vol. 36 No. 9, pp. 1540-1555.

Chen, H.-T. and Chen, K.-S. (2016), "A paired-test method to verify service speed improvement in the Six Sigma approach: a restaurant's case study", *Total Quality Management and Business Excellence*, Vol. 27 No.11-12, pp. 1277-1297.

Coronado, R. B. and Antony, J. (2002), "Critical success factors for the successful implementation of six sigma projects in organisations", *The TQM Magazine*, Vol. 14 No. 2, pp. 92-99.

Costa, J. P., Lopes, I. S. and Brito, J. P. (2019), "Six Sigma application for quality improvement of the pin insertion process", *Procedia Manufacturing*, Vol 38, pp. 1592-1599.

Davison, L. and Al-Shaghana, K. (2007), "The link between Six Sigma and quality culture - An empirical study", *Total Quality Management and Business Excellence*, Vol. 18 No. 3, pp. 249-265.

Desai, D. and Prajapati, B.N. (2017), "Competitive advantage through Six Sigma at plastic injection molded parts manufacturing unit: A case study", *International Journal of Lean Six Sigma*, Vol. 8 No. 4, pp. 411-435.

Ferrer, A. (2021), "Multivariate six sigma: A key improvement strategy in industry 4.0", *Quality Engineering*, Vol. 33 No. 4, pp. 758-763.

Foster Jr., S. T. (2007), "Does Six Sigma Improve Performance?", *Quality Management Journal*, Vol. 14 No. 4, pp. 7-20.

George, M., Rowlands, D., Price, M. and Maxey, J. (2005), *The lean six sigma pocket toolbook*, The McGraw-Hill.

Gijo, E. V. and Rao, T. S. (2005), "Six sigma implementation - Hurdles and more hurdles". *Total Quality Management*, Vol. 16 No. 6, pp. 721-725.

Gijo, E. V., Scaria, J. and Antony, J. (2011), "Application of Six Sigma methodology to reduce defects of a grinding process", *Quality and Reliability Engineering International*, Vol. 27, pp. 1221-1234.

González-Cebrián, A., Hermenegildo, M., Climente, M. and Ferrer, A. (2022), "Multivariate Six Sigma: A case study in an outpatient pharmaceutical care unit", *Quality Engineering*, Vol. 34 No. 2, pp. 277-289.

He, Z., Deng, Y., Zhang, M., Zu, X. and Antony, J. (2017), "An empirical investigation of the relationship between Six Sigma practices and organisational innovation", *Total Quality Management and Business Excellence*, Vol. 28 No. 5-6, pp. 459-480.

Jirasukprasert, P., Garza-Reyes, J. A., Kumar, V., and Lim, M. K. (2014), "A Six Sigma and DMAIC application for the reduction of defects in a rubber gloves manufacturing process", *International Journal of Lean Six Sigma*, Vol. 5 No. 1, pp. 2-21.

Lee, T. W. (1999), *Using Qualitative Methods in Organizational Research*. Thousand Oaks, CA: Sage.

Linderman, K., Schroeder, R. G., Zaheer, S. and Choo, A. S. (2003), "Six Sigma: a goal-theoretic perspective", *Journal of Operations Management*, Vol. 21, pp. 193-203.

Ng, I. C. and Hempel, P. S. (2017), "Organisational culture and the implementation of Six Sigma in Southern China", *Total Quality Management & Business Excellence*, Vol. 31 No. 1-2, pp. 82-98.

Ninerola, A., Sánchez-Rebull, M. and Hernández-Lara, A. (2020), "Quality improvement in healthcare: six sigma systematic review", *Health Policy*, Vol. 124 No. 4, pp. 438-445.

Oprime, P. C., Pimenta, M. L., Jugend, D. and Andersson, R. (2021), "Financial impacts of innovation in Six Sigma projects", *Total Quality Management and Business Excellence*, Vol. 32 No. 7-8, pp. 829-851.

Padmarajan, N. and Selvaraj, S. K. (2021), "Six sigma implementation (DMAIC) of friction welding of tube to tube plate by external tool optimization", *Materials Today: Proceedings*, Vol. 46, pp. 7344-7350.

Pakdil, F., Toktaş, P. and Can, G.F. (2021), "Six sigma project prioritization and selection: a multi-criteria decision making approach in healthcare industry", *International Journal of Lean Six Sigma*, Vol. 12 No. 3, pp. 553-578.

Pande, P. S., Holpp, L. and Pande, P. (2002), *What is Six Sigma?*, McGraw-Hill, New York, NY.

Park, S. H. (2002), "Six Sigma for productivity improvement: Korean business corporations", *Productivity Journal*, Vol. 43, pp. 173-183.

Raisinghani, M. S., Ette, H., Pierce, R., Cannon, G. and Daripaly, P. (2005), "Six Sigma: concepts, tools, and applications", *Industrial management and Data systems*, Vol. 105 No. 4, pp. 491-505.

Sánchez-Rebull, M. V., Ferrer-Rullan, R., Hernández-Lara, A. B. and Nierola, A. (2020), "Six sigma for improving cash flow deficit: a case study in the food can manufacturing industry", *International Journal of Lean Six Sigma*, Vol. 11 No. 6, pp. 1105-1125.

Sharma, P., Malik, S.C., Gupta, A. and Jha, P.C. (2018), "A DMAIC Six Sigma approach to quality improvement in the anodising stage of the amplifier production process", *International Journal of Quality and Reliability Management*, Vol. 35 No. 9, pp. 1868-1880.

Soundararajan K. and Janardhan R. K. (2019), "Cost-reduction and quality improvement using DMAIC in the SMEs", *International Journal of Productivity and Performance Management*, Vol. 68 No. 8, pp. 1528-1540.

Srinivas, S. and Sreedharan, V. (2018), “Failure analysis of automobile spares in a manufacturing supply chain distribution centre using six sigma DMAIC framework”, *International Journal of Services and Operations Management*, Vol. 29 No. 3, pp. 359-372.

Srinivasan, K., Muthu, S., Devadasan, S. R. and Sugumaran, C. (2016), "Six Sigma through DMAIC phases: a literature review", *International Journal of Productivity and Quality Management*, Vol. 17 No. 2, pp. 236-257.

Stankalla, R., Koval, O. and Chromjakova. F. (2018), “A review of critical success factors for the successful implementation of Lean Six Sigma and Six Sigma in manufacturing small and medium sized enterprises”, *Quality Engineering*, Vol. 30 No. 3, pp. 453-468.

Sunder M, V. and Antony, J. (2015), “Six-sigma for improving Top-Box customer satisfaction score for a banking call centre”, *Production Planning & Control*, Vol. 26 No. 16, pp. 1291-1305.

Sunder M, V. and Kunnath. N. R. (2020), “Six Sigma to reduce claims processing errors in a healthcare payer firm”, *Production Planning & Control*, Vol. 31 No. 6, pp. 496-511.

Tague, N. R. (1995), *The Quality Toolbox*, ASQ Quality Press, Milwaukee, WI.

Tsarouhas, P. (2021), "Reliability, availability and maintainability analysis of a bag production industry based on the six sigma DMAIC approach", *International Journal of Lean Six Sigma*, Vol. 12 No. 2, pp. 237-263.

Tsarouhas, P. and Sidiropoulou, N. (2024), "Application of Six Sigma methodology using DMAIC approach for a packaging olives production system: a case study", *International Journal of Lean Six Sigma*, Vol. 15 No. 2, pp. 247-273.

Uluskan, M. (2016), "A comprehensive insight into the Six Sigma DMAIC toolbox", *International Journal of Lean Six Sigma*, Vol. 7 No. 4, pp. 406-429.

Uluskan, M. and Oda, E.P. (2020), "A thorough Six Sigma DMAIC application for household appliance manufacturing systems: Oven door-panel alignment case", *The TQM Journal*, Vol. 32 No. 6, pp. 1683-1714.

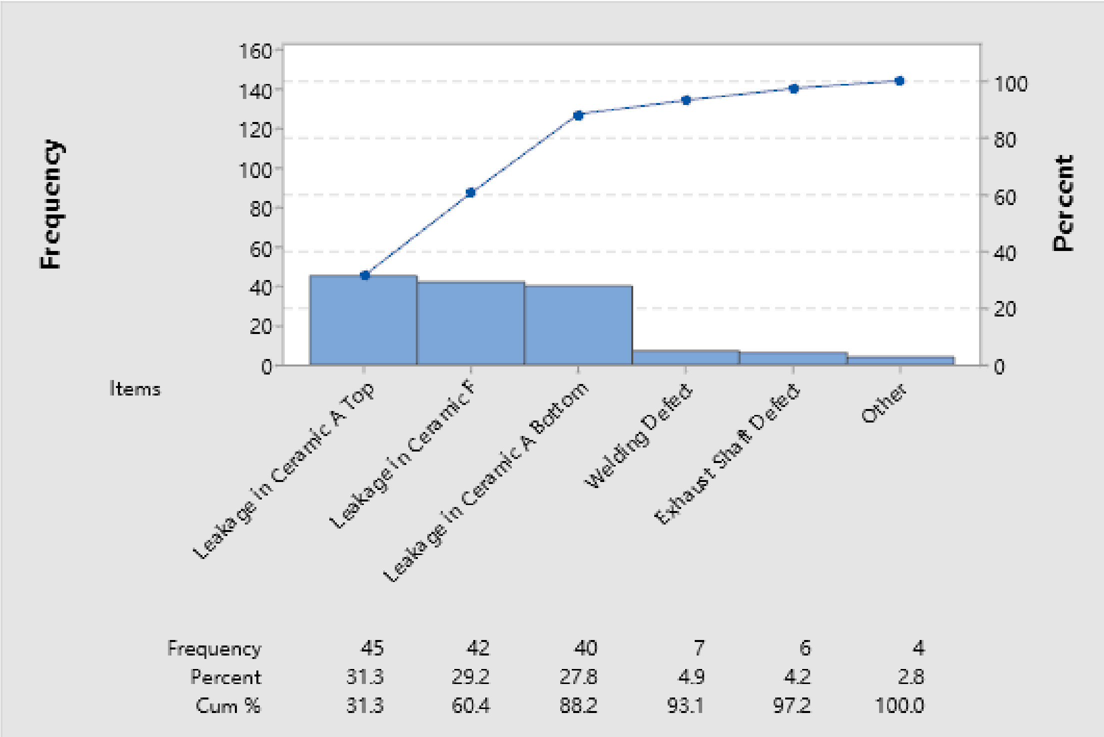
Uluskan, M., Godfrey, A. B. and Joines, J. A. (2017), "Integration of Six Sigma to traditional quality management theory: an empirical study on organisational performance", *Total Quality Management and Business Excellence*, Vol. 28 No. 13-14, pp. 1526-1543.

Wei C.-C. and Cheng Y.-L. (2020), "Six Sigma project selection using fuzzy multiple attribute decision-making method", *Total Quality Management and Business Excellence*, Vol. 31 No. 11-12, pp. 1266-1289.

Yadav, N., Mathiyazhagan, K. and Kumar, K. (2019), "Application of Six Sigma to minimize the defects in glass manufacturing industry: A case study", *Journal of Advances in Management Research*, Vol. 16 No. 4, pp. 594-624.

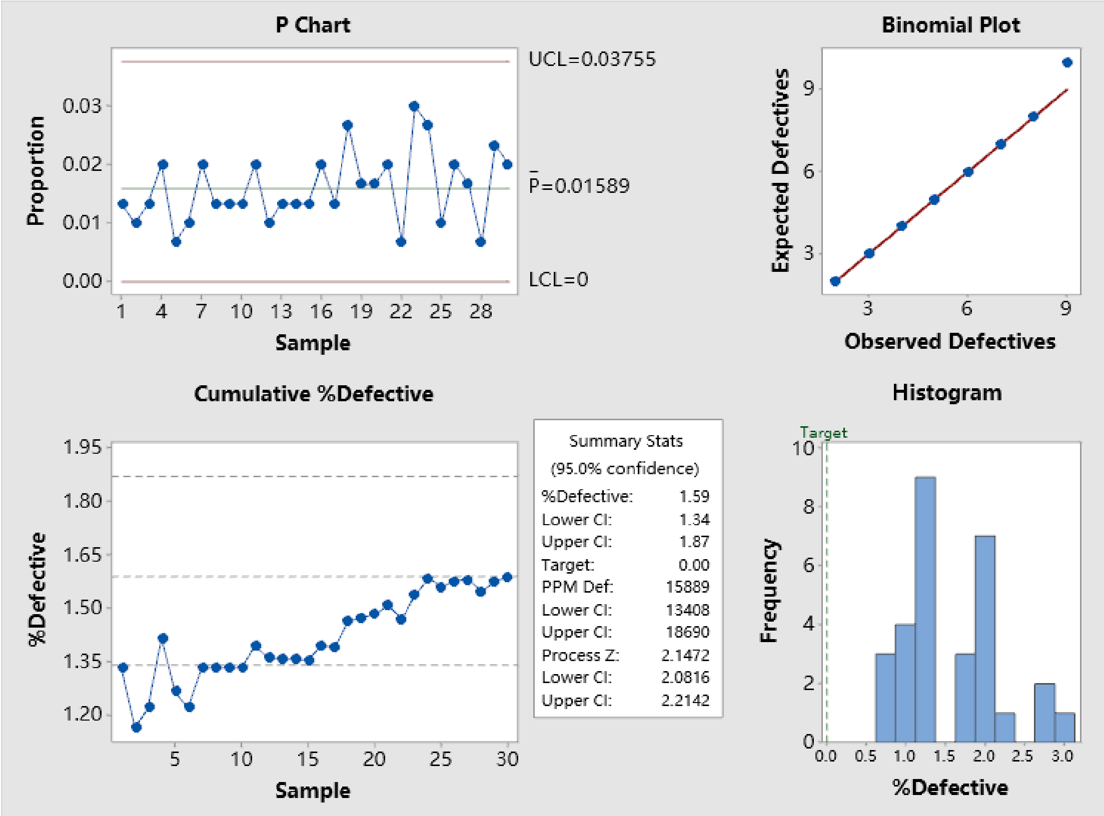
Zhang, M., Wang, W., Goh, T. N. and He, Z. (2015), "Comprehensive Six Sigma application: a case study", *Production Planning & Control*, Vol. 26 No. 3, pp. 219-234.

Zwetsloot, I. M., Kuiper, A., Akkerhuis, T. S., and de Koning, H. (2018), “Lean Six Sigma meets data science: Integrating two approaches based on three case studies”, *Quality Engineering*, Vol. 30 No. 3, pp. 419-431.



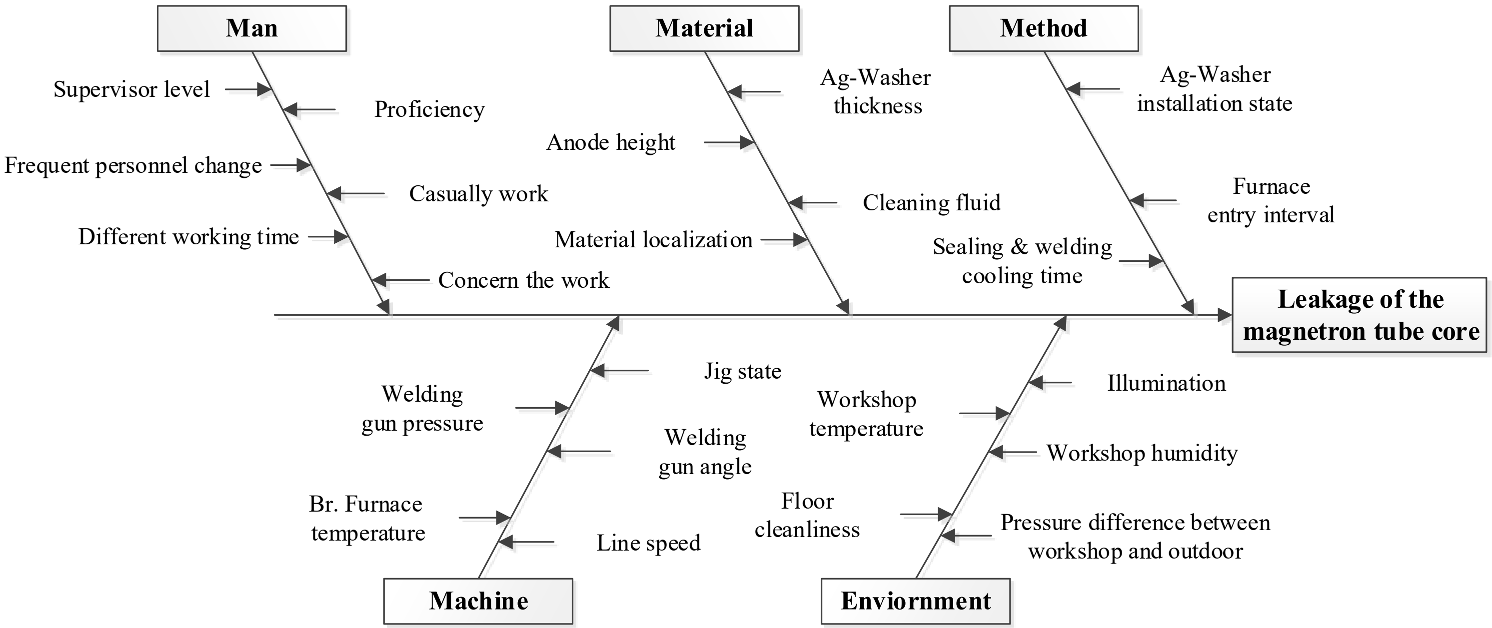
Source: Authors' own work

Figure 1 Pareto analysis for tube core leakage defect



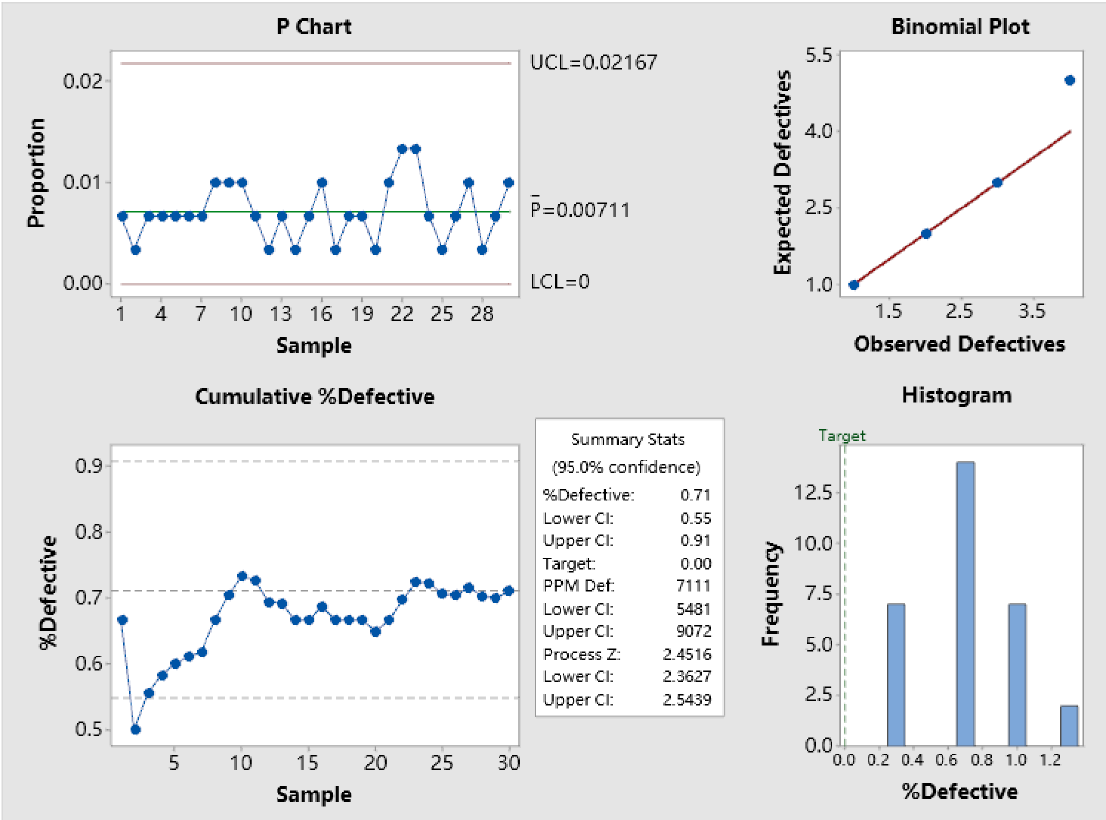
Source: Authors' own work

Figure 2 Process capability analysis before improvement



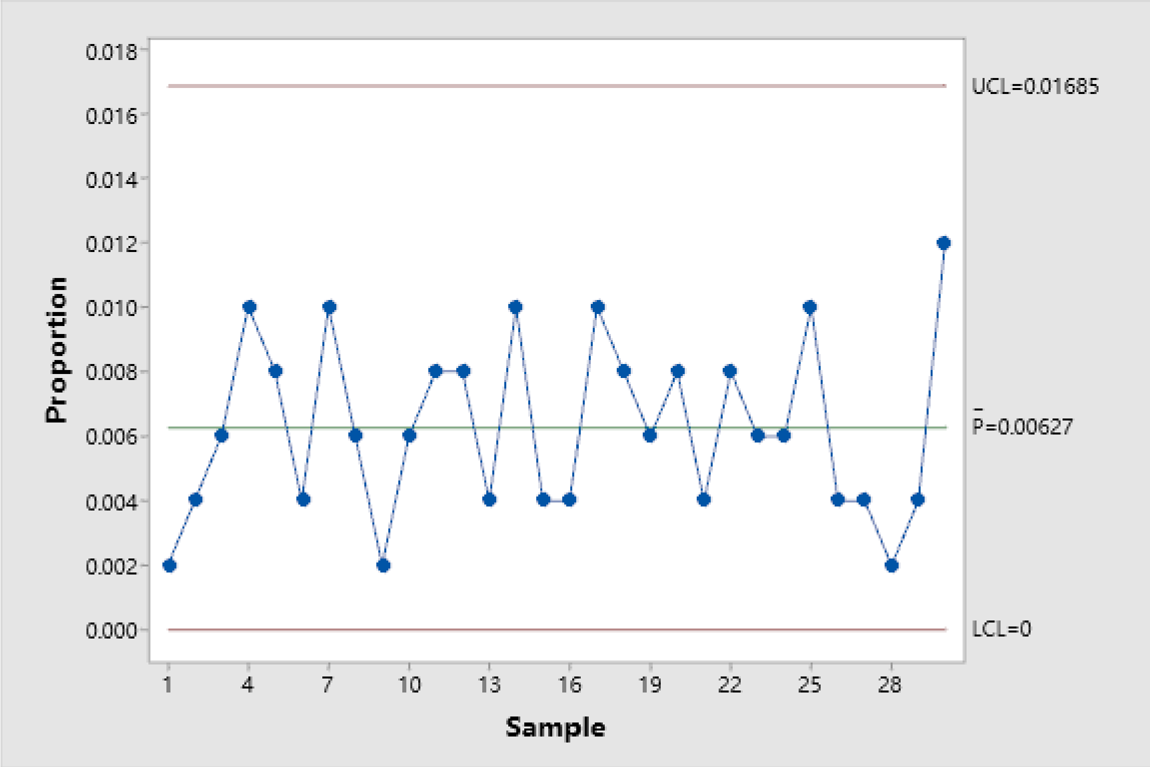
Source: Authors' own work

Figure 3 The cause and effect diagram of the leakage of the magnetron tube core



Source: Authors' own work

Figure 4 Process capability analysis after improvement



Source: Authors' own work

Figure 5 The *p* control chart for the tube core leakage rate after implementing control plans

Table I Process map analysis using SIPOC model

SUPPLIER (S)	INPUT (I)	PROCESS (P)	OUTPUT (O)	CUSTOMER (C)	
Material supplier Electric power plant Equipment supplier	Raw materials (magnets, ceramics, etc.) Equipment (exhaust furnace, bending machine, etc.) Personnels (production employees, inspectors) Operation methods (instruction book, craft, etc.)	① Parts cleaning → ② Tube core assembly → ③ Exhaust → ④ Exterior assembly → ⑤ Aging → ⑥ Characteristic inspection	Magnetron	Internal customers	Quality Department Sales Department
				External customers	Consumers

Source: Authors' own work

Table II Attribute agreement analysis for MSA

Within appraisers assessment agreement

Appraiser	# Inspected	# Matched	Percent	95% CI
Operator A	20	20	100.00	(86.09, 100.00)
Operator B	20	20	100.00	(86.09, 100.00)

 # Matched: Appraiser agrees with him/herself across trials.

Each appraiser vs standard assessment agreement

Appraiser	# Inspected	# Matched	Percent	95% CI
Operator A	20	20	100.00	(86.09, 100.00)
Operator B	20	20	100.00	(86.09, 100.00)

 # Matched: Appraiser's assessment across trials agrees with the known standard.

Between appraisers assessment agreement

# Inspected	# Matched	Percent	95% CI
20	20	100.00	(86.09, 100.00)

 # Matched: All appraisers' assessments agree with each other.

All appraisers vs standard assessment agreement

# Inspected	# Matched	Percent	95% CI
20	20	100.00	(86.09, 100.00)

 # Matched: All appraisers' assessments agree with the known standard.

Source: Authors' own work

Table III C&E matrix of the leakage of the magnetron tube core

No.	Rating of importance (1-10)	10	10	10	Total
	Process Input \ Key requirements	Ceramic A Top	Ceramic F	Ceramic A Bottom	
1	**Supervisor level**	3	3	3	90
2	**Proficiency**	9	9	9	270
3	**Different working time**	3	3	3	90
4	**Casual work**	9	9	9	270
5	Frequent personnel change	1	1	1	30
6	Concern the work	1	1	1	30
7	**Jig state**	9	9	9	270
8	Welding gun angle	0	0	0	0
9	Line speed	1	1	1	30
10	Welding gun pressure	0	0	0	0
11	**Br. furnace temperature**	9	9	9	270
12	**Ag-W thickness**	9	9	9	270
13	Cleaning fluid	0	0	0	0
14	Material localization	1	3	1	50
15	Anode height	3	1	3	70
16	**Ag-W installation state**	9	9	9	270
17	**Furnace entry interval**	9	9	9	270
18	Sealing & welding cooling time	0	0	0	0
19	Workshop temperature	1	1	1	30
20	Workshop humidity	1	1	1	30
21	Floor cleanliness	0	0	0	0
22	**Pressure difference between workshop and outdoor**	3	3	3	90
23	Illumination	0	0	0	0

Source: Authors' own work

Table IV FMEA of the magnetron tube core leakage

Items	Potential failure mode	Potential effects of failure	S (Severity rating)	Potential causes	O (Occurrence rating)	Current controls	D (Detection rating)	RPN
Supervisor level	Incorrectly guide production	Low efficiency and bad quality performance	5	Insufficient management level	3	Skill training	3	45
Proficiency	**Abnormal work**	**Bad quality performance**	**7**	**Insufficient skills**	**6**	**Job training for new hires**	**5**	**210**
Different working time	Non-standard work	Bad quality performance	7	Insufficient night shift management	7	Supervisor Management	3	147
Casual work	**Non-standard work**	**Leakage of tube core**	**7**	**Insufficient management**	**7**	**Teaching the standard work**	**5**	**245**
Jig state	**Clamping damage**	**Inaccurate installation position**	**8**	**Jig aging & bumped**	**6**	**Visually inspection**	**7**	**336**
Br. furnace temperature	Temperature cannot be maintained	Incomplete welding	9	Insufficient melting of Ag	8	Automatic alarm	1	72
Ag-W thickness	**Insufficient amount of Ag**	**Leakage of tube core**	**9**	**Insufficient Ag-W thickness**	**7**	**Sampling inspection**	**7**	**441**
Ag-W installation state	**Large variance**	**Uneven welding**	**9**	**Lacking Ag**	**6**	**Education and training**	**8**	**432**
Furnace entry interval	**Different temperature**	**Leakage of tube core**	**9**	**Insufficient melting of Ag**	**8**	**N**	**4**	**288**
Pressure difference between workshop and outdoor	No pressure difference	Tube core contamination	3	Foreign matter in the air	5	Fan control	2	30

Source: Authors' own work

Table V The improved FMEA of the magnetron tube core leakage

Items	Controls before improvement	Prior RPN	Measures taken	S	O	D	RPN
Proficiency	**Job training for new hires**	210	Standard operating qualification assessment is added. At least 1 year of working experience is needed.	7	1	4	28
Casual work	**Teaching the standard work**	245	Defective product traceability system is adapted. Reward and punishment measures is implemented.	7	1	5	35

Source: Authors' own work

Table VI Two-proportion tests for Jig state, Ag-W thickness, Ag-W installation state and furnace entry interval

Items	Sample	N	Event	Sample P	Difference	95% CI for Difference	*Z*-Value	*p*-Value
Jig state	Sample 1	3000	39	0.01300	-0.00100	(-0.00820, 0.00620)	-0.27	0.785
	Sample 2	1500	21	0.01400				
Ag-W thickness	Sample 1	1200	7	0.00583	-0.00950	(-0.01707, -0.00193)	-2.46	0.014
	Sample 2	1500	23	0.01533				
Ag-W installation state	Sample 1	2000	9	0.00450	-0.00630	(-0.01130, -0.00130)	-2.47	0.014
	Sample 2	2500	27	0.01080				
Furnace entry interval	Sample 1	1500	3	0.00200	-0.00506	(-0.00964, -0.00048)	-2.17	0.030
	Sample 2	1700	12	0.00706				

Source: Authors' own work

Table VII Full factorial design and experiment data

Std Order	Run Order	Center Points	Blocks	Ag-W Thickness	Ag-W Installation State	Furnace Entry Interval	Sample Sizes	Leakage Numbers	y
7	1	1	1	0.0400	-1	5.0	230	2	-4.4950
4	2	1	1	0.0550	-1	0.0	340	2	-4.8900
3	3	1	1	0.0400	-1	0.0	400	6	-4.1003
11	4	0	1	0.0475	-2	2.5	470	5	-4.4304
1	5	1	1	0.0400	-3	0.0	400	6	-4.1021
6	6	1	1	0.0550	-3	5.0	510	4	-4.7155
2	7	1	1	0.0550	-3	0.0	390	5	-4.2525
9	8	0	1	0.0475	-2	2.5	420	4	-4.5224
8	9	1	1	0.0550	-1	5.0	540	3	-5.0095
5	10	1	1	0.0400	-3	5.0	520	5	-4.5387
10	11	0	1	0.0475	-2	2.5	550	5	-4.5900

Source: Authors' own work

Table VIII Full factorial design analysis (full model)

Factorial Fit: Magnetron tube core leakage versus Ag-W thickness, Ag-W installation state, Furnace entry interval

Estimated effects and coefficients for the magnetron tube core leakage (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		-4.513	0.02345	-192.46	0.000
Ag-W thickness	-0.408	-0.204	0.0275	-7.42	0.002
Ag-W installation state	-0.222	-0.111	0.0275	-4.03	0.016
Furnace entry interval	-0.353	-0.177	0.0275	-6.43	0.003
Ag-W thickness*Ag-W installation state	-0.244	-0.122	0.0275	-4.44	0.011
Ag-W thickness * Furnace entry interval	0.062	0.031	0.0275	1.13	0.321
Ag-W installation state *Furnace entry interval	0.096	0.048	0.0275	1.75	0.155

Model Summary

S = 0.0917464 R-Sq = 97.15% R-Sq(adj) = 90.10%

Analysis of Variance for the magnetron tube core leakage

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.680672	0.680672	0.226891	37.51	0.002
2-Way Interactions	3	0.145628	0.145628	0.048543	8.02	0.036
Residual Error	4	0.024198	0.024198	0.006049		
Curvature	1	0.000004	0.000004	0.000004	0.00	0.984
Lack of fit	1	0.011364	0.011364	0.011364	1.77	0.315
Pure Error	2	0.012831	0.012831	0.006415		
Total	10	0.850498				

Source: Authors' own work

Table IX Factorial design analysis after optimization (reduced model)

Factorial Fit: Magnetron tube core leakage versus Ag-W thickness, Ag-W installation state, Furnace entry interval

Estimated effects and coefficients for the magnetron tube core leakage (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		-4.513	0.02766	-163.16	0.000
Ag-W thickness	-0.408	-0.204	0.03244	-6.29	0.001
Ag-W installation state	-0.222	-0.111	0.03244	-3.41	0.014
Furnace entry interval	-0.353	-0.177	0.03244	-5.45	0.002
Ag-W thickness*Ag-W installation state	-0.244	-0.122	0.03244	-3.77	0.009

Model Summary

S = 0.0777783 R-Sq = 94.06% R-Sq(adj) = 92.89%

Analysis of Variance for the magnetron tube core leakage

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.680672	0.680672	0.226891	26.95	0.001
2-Way Interactions	1	0.119321	0.119321	0.119321	14.18	0.009
Residual Error	6	0.050504	0.050504	0.008417		
Curvature	1	0.000004	0.000004	0.000004	0.00	0.985
Lack of fit	3	0.03767	0.03767	0.012557	1.96	0.356
Pure Error	2	0.012831	0.012831	0.006415		
Total	10	0.850498				

Source: Authors' own work

Table X The control plan of key factors

No.	Key factors	Specifications / Requirements	Measuring methods	Measuring tools	Control style	Relative department
1	Proficiency	Standard operation	Assessment	Standard Procedure/ Stopwatch	Procedure control/ Operating instructions	Production
2	Casual work	Quality consciousness	Assessment	Statistics	Adapting defective product traceability system and implementing reward and punishment measures.	Production
3	Ag-W thickness	0.055mm±0.001	Measuring instrument	Three-coordinates measuring machine	Design change/ Inspection instructions	Design/ Quality
4	Ag-W installation state	offset by 1mm±0.1 from the outer edge	Measuring instrument	Vernier caliper	Statistical control (10 pcs/ 2 hours)/ Operating instructions	Production
5	Furnace entry interval	5cm±0.5	Measuring instrument	Box ruler	Statistical control (10 pcs/ 2 hours)/ Operating instructions	Production

Source: Authors' own work

Table XI Two sample test for the leakage rates before and after improvement

Items	Sample	**N**	**Mean**	**StDev**	Difference	95% CI for Difference	*t*-Value	*p*-Value
Leakage Rates	Before	30	0.01589	0.00604	0.00962	(0.00717, 0.01208)	7.93	0.000
	After	30	0.00627	0.00277				

Source: Authors' own work