

RESEARCH ARTICLE

A case study of paste sachet production defect analysis using the Six Sigma DMAIC Approach

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Abstract - Upholding operational process stability is vital to control the quality of produced goods. Six Sigma has emerged as a prominent continuous improvement technique that supports the operational excellence of the food manufacturing sector. This case study explores the potential of tackling the leak issues in the filling-sealing operation of hot-filled paste sachet products using the Vertical Form-Fill-Seal (VFFS) machine. The DMAIC (Define, Measure, Analyse, Improve, Control) methodology was employed with other quality tools to achieve the recommended corrective measures. The results demonstrate that operational guidelines and parameters remain the crucial components to determine sealing integrity. Sigma level increases from 3.3 to 4.3 with a DPMO reduction of 27,328, significantly improving the production of good sachets. Six Sigma adoption also resulted in a declining trend of defects for the subsequent production.

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1. Introduction

Food manufacturers operating in the Volatile, Uncertain, Complex, Ambiguous (VUCA) environment strive to minimise defects while maximising the pass product percentage. Variability in the food industry is mostly associated with perishability and seasonality, and statistical process control (SPC) has been effective in reducing variability to yield a predictable process (Rique Junior et al., 2020; Lim & Antony, 2019). This subsequently underscores problem-solving capabilities as a crucial domain to solve problems in a structured manner. As one of the continuous improvement initiatives, Six Sigma emphasises operational improvement and cost reduction (Şişman, 2023) to promote the right manufacturing solutions via problem identification, data collection, potential causes identification, and remedial action development (Mittal et al., 2023). As the food manufacturing sector aims towards operational streamlining by reducing cycle time and eliminating defects, Six Sigma has emerged as a prominent data-driven strategy to identify and mitigate the root causes that lead to process variability (Abbess et al., 2022). Such an approach has been proven effective in achieving operational efficiency improvement and fulfilling both internal and external customer requirements. Nevertheless, the implementation of continuous improvement (CI) methodologies in the food processing sector remains limited due to its conservative nature (Lim & Antony, 2019).

Table 1

List of abbreviations and definitions

Abbreviation	Description	Abbreviation	Description
BOPP	Bi-axially oriented polypropylene	OEM	Original equipment manufacturer
CI	Continuous improvement	OPL	One point lesson
COF	Coefficient of friction	OD	Orientation degree
CTQ	Critical-to-quality	OW	Operating window
DPI	Dye penetrant testing	PET	Polyethylene terephthalate
DPMO	Defect per million opportunities	PP	Polypropylene
DMAIC	Define, Measure, Analyse, Improve, Control	SIPOC	Supplier, Input, Process, Output, Customer
FMCG	Fast moving consumer goods	SPC	Statistical process control
FTR	First time right	VFFS	Vertical form, fill, and seal
MD	Machine direction	VUCA	Volatile, Uncertain, Complex, Ambiguous

The present investigation focuses on the implementation of quality control and defect detection in the company and the factors causing defects in hot-filled paste sachet production using the vertical form, fill, and seal (VFFS) machine. It analyses the paste sachet leak issue using the Define, Measure, Analyse, Improve, and Control (DMAIC) approach and other quality tools across the stages. The sachet-leaking issue contributes to direct economic losses with a defect percentage of 3% based on total sachets produced. Even with the rework of the leaking sachets, losses from scrap packaging materials are still incurred by the manufacturer. In-process losses and wastes directly contribute to packaging defects. Subsequently, replacement with sustainable packaging material aligns with the global carbon footprint initiative,

while performance optimisation for VFFS with flexible packaging application promotes “first time right” (FTR) during filling and sealing operations. Clark et al. (2002) compiled a summary of VFFS development and advocated its positive effect on film structure in terms of stiffness, seal strength, coefficient of friction (COF), machinability, and packaging performance. In actual production, VFFS operates at high speed and dwell time should be adjusted to match the temperature and pressure settings without affecting the production line speed and production output volume (Najarzadeh & Aiji, 2014). This case study explores the sealing integrity of hot-filled paste sachet packaging to eliminate leaking issues. It used the DMAIC methodology to resolve paste sachet leaks at the ABC food manufacturing plant and continuously improve the quality of filling and sealing operations for paste sachet products. Performance improvement is crucial for companies to sustain and remain competitive in the OEM industry because it contributes to zero-defect management and sustainability initiatives. Table 1 lists the abbreviations and definitions of keywords used in the study.

2. Literature Review

The Six Sigma DMAIC methodology is significant in the food industry to deal with defects and promote productivity improvement. Heightened customer requirements and demands alongside reduced costs often challenge the internal food manufacturing operation. Customer satisfaction is commonly reflected through product and service quality, necessitating organisations to focus on operational improvement to boost product quality (Hakimi et al., 2018). The concept of Six Sigma is closely associated with continuous improvement initiatives and lean manufacturing approaches; it leverages statistical methods to identify defects and the probable causes, thereby supporting quality tools to quicken project completion. Lim et al. (2014) outlined that food products’ inherent properties and production variability may challenge production, and Six Sigma tools can assist in understanding the process variability and capability. Past research has reported that tools such as cause-and-effect diagrams, Pareto charts, and control charts are adequate to resolve 95% of manufacturers’ problems (Antony et al., 2021). Although the correct selection of quality tools is associated with “right first time”, many quality practitioners are unaware of such a notion, leading to wrong tool adoption (Antony, 2014).

The application of Six Sigma is widespread in various production processes and food sectors. Several studies have adapted the concept to investigate filling defects in food production. For instance, Kartika et al. (2018) resolved herbal sachet filling issues by reducing the defect to below 2% and increasing the sigma level to 4.3 via DMAIC. Desai et al. (2015) found that Indian milk manufacturers reduced the weight variance of milk powder and achieved a 50% cut-off of line rejection. The study by Henny et al. (2019) employed DMAIC and successfully minimised waste in sambal and shrimp paste production, which was mainly associated with transportation and processing. Such an approach was also proven effective in reducing packaging defects, resulting in a 5% reduction of overfilling gingerbread and rework (Dora & Gellynck, 2015) and eliminating inappropriate sealing and cutting parameters as well as reverse packaging labelling that could cause a high rejection ratio in soy sauce packaging (Sukwadi et al., 2021). Furthermore, VFFS operation is extensively used for packing liquid products (Matthews et al., 2011). Rique Junior et al. (2020) proposed an SPC method to assess the quality control of the VFFS packaging process of fruit pulp sachets. Packaging process capability was reported at the 2-sigma level after elimination of special-cause variation, followed by online monitoring to assure process stability (Rique Junior et al., 2020). Merabtene et al. (2022) evaluated the heat-sealing parameters and runnability issues of flexible paper and thermoplastic film in VFFS machines under two different sealing jaw designs. In terms of sealing window, thermoplastic film had a smaller sealing window compared to paper-based packaging. While the heat-sealing factor is driven by sealing temperature, pressure, and dwell time (Yuan et al., 2007), adjustments and controls are necessary to attain desirable seal strength, tightness, and material bonding (Troughton, 2009). The final condition of the film after sealing is also dependent on the packaging material characteristics, including material type, thickness, density, additives, and adhesive used (Aithani et al., 2006).

Flexible packaging is considered one of the emerging trends in fast-moving consumer goods (FMCG) for food and pharmaceutical product applications (Merabtene et al., 2022). Laminates are frequently used in food packaging, with polyethylene terephthalate (PET), aluminium (Al), polypropylene (PP), and nylon being common base materials for flexible packaging. To enhance the sustainability of laminates, PET and aluminium layers can be replaced with renewable and recyclable materials such as polyolefins. Bi-axially oriented polypropylene (BOPP) and metallised BOPP (metBOPP) are the common replacement materials due to their versatility and moisture barrier properties (Kumar et al., 2022). Each material layer exhibits unique features with varying sealing behaviours and conditions (Merabtene et al., 2022).

Table 2

DMAIC methodology

Define	Measure	Analyse	Improve	Control
Identify the issues and define the customer specification and target	Use existing data to evaluate the problem	Define key process parameters and set the improvement goal	Outline the idea to improve the system based on the previous analysis outcome	Generate a plan to sustain the initiative
Critical-to-quality (CTQ)	Defect per million opportunities (DPMO)	Cause-and-effect diagram 5 Why analysis		

3. Methodology

The improvement activities followed the DMAIC methodology to address leakage in hot-filled sachets. High sachet rejection due to leakage is intolerable as it directly correlates with food safety issues and may cause financial losses to the company. The Six Sigma project design was based on Rawendra and Puspita (2020), which focused on reducing packaging defects in milk sachets. Critical-to-quality (CTQ) reflects customers' satisfaction level while key customer complaints provide information on the pitfalls of defective products (Mittal et al., 2023). Antony et al. (2021) outlined Ishikawa's seven basic quality tools for managing most manufacturing issues. For DPMO selection, the number of defects is a crucial indicator for assessing the current state, since this study aimed to eliminate the sachet leaking issue. This is because DPMO identifies total defects in a production run against defect opportunities.

3.1 Case Company and Study Settings

The case company (i.e., ABC) was founded in 1997 and is located in Semenyih, Selangor. The business initially focused on the trading of fresh vegetables before transitioning into manufacturing, specifically on paste and sauce production, in 2000. The company is certified in FSSC 22000 (Food Safety System Certification), HACCP (Hazard Analysis and Critical Control Point), and Halal. Due to the expansion and surge of production orders, the case company began to adopt Six Sigma methodologies to reduce costs and enhance its market competitiveness. The Manufacturing Excellence team was responsible for the facilitation of the 6-month Six Sigma improvement project from September 2024 to February 2025. The Production team was the largest stakeholder of the project, specifically the machine operators in charge of the VFFS operation. The performance of Machines 1 and 2 performance on October 2024 was collected since both machines ran similar products and the data collected over this period reflected the current state. Improvements were conducted on Machine 2 since it had better reliability than Machine 1. Data collection entailed the production log, defect records, and interviews with the machine operators. Different types and percentages of defects were collected for 2 days of operation. After the improvement, the 2-day operation data from the similar machine were compared to assess the effectiveness of the solution.

4. Results and Discussion

4.1 Define

The DMAIC methodology began with the Define phase, which was crucial for problem statement definition. A clear and concise problem statement would steer the right direction for actions to execute in the later steps. This study utilised a project charter, including a problem statement and CTQ descriptions. Overall, the strategic objective of the project hinged on the reduction of the paste sachet product leaking issue, and the final outcome entailed the packaging material characteristics and machine operating conditions. The problem statement was fixed to reduce the leaked paste sachets. This definition of the problem statement steers the investigation to recognise the key quality parameters of the product. In this case, the CTQ of paste sachet products involves the sealing integrity of the filled sachet products. One of the issues faced by ABC is packaging leaks on ready-to-cook paste sachets. Leakage refers to fluid movement through a leak regardless of the hole size. Fluid leakage is dependent on differential pressure, induced temperature, and the nature of the leaking fluid (Moghimy & Park, 2017). Leakage is possible in all sealing regions of the sachet that compromise the sealing integrity. The sealing process is initiated via heat application on the sealing bar or rotary jog (Moghimy et al., 2018). The packaging leaks and descriptions are classified in Table 3.

Figure 1

Positioning of three-side seal sachet

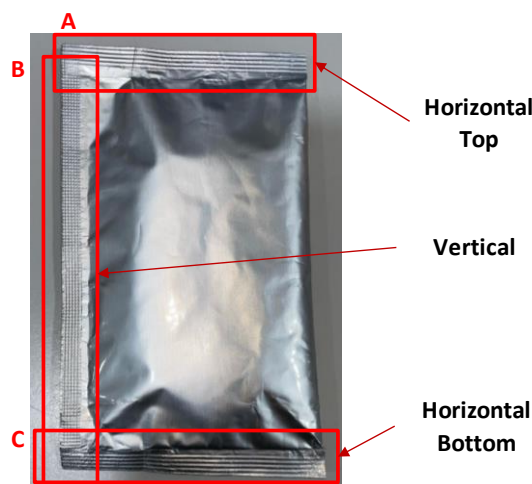


Table 3*Categories of packaging leaks with description*

Types of packaging leak	Description
Horizontal leak	The leakage occurs at the horizontal side of the packaging.
Vertical leak	The leakage occurs at the vertical side of the packaging.
Overlapping	The leakage may occur on both sides of the packaging due to one side having excess than the other.
Torn	The leakage occurs due to a tear on the body of the packaging.
Delaminated	The lamination of the packaging peels off.

The packaging leaking issue of paste sachets is reflected by complaints received by ABC in September 2024. These complaints mainly involved leaking defective products that were produced in the previous months. ABC had two units of VFFS machines for sachet production. The VFFS machine comparison in Table 4 shows that both machines run a similar number of products per month. Machine 2 had more convincing machine uptime and sachet defect percentage; therefore, it was chosen as the research object for further monitoring and analysis to minimise sachet leak issues. Packaging leakage might occur at any time during the production process of paste filling. In this scenario, the machine was not running 24 hours consecutively, with adequate time for changeover operation.

Table 4*VFFS machine comparison*

Indicators	Machine 1	Machine 2
Number of products run per month	6 products	4 products
Machine uptime (%)	70%	85%
% Defective Sachets (Average)	12.56%	8.62%
Overall Equipment Effectiveness (OEE)	62%	70%

Filling and sealing operations are crucial determinants for packaging integrity, where any failures and discrepancies will lead to packaging leakage. Operator competency directly influences the performance and end result of the packaging sealing integrity. In this case, a single-line VFFS was employed to perform the filling and sealing operation. The machine was run for three-side seal aluminium foil packaging in the form of a roll that moves around the film roll feed. The film tension amount and positioning were controlled by the dancer arms and laser sensor, respectively (Matthews et al., 2011). Later, the packaging was conveyed through the former, where the sealing jogs gripped and pulled the film towards the vertical seal (Ilhan et al., 2021). The three sealing rollers were implemented in sequence, namely the vertical seal, hot tack, and horizontal seal. Hot-tack played a role in withstanding the filled product weight and avoiding seal separation, thereby promoting better yield (Tuominen et al., 2011). The packaging was sealed horizontally and hot-filled with paste through a nozzle stored in the hopper, which served as the reservoir for hot-filled paste pumping from the agitated holding tank. The levelling sensor controlled the discharge of paste from the holding tank to the hopper (Dudbridge, 2016). The hopper was equipped with an agitator to avoid the separation of fat from the paste (Zuzarte et al., 2020). After the filling process and horizontal sealing, the last rotary jog provided the linear horizontal pattern to the sealing region. Next, the filled sachet moved to the checkweigher and underwent the chlorinated cooling water tunnel to lower its temperature. After cooling, the sachet proceeded to end-line sorting and assembly. For quality inspection, a compression test was performed to assess the integrity of seal regions on the sachet.

4.2 Measure

Samples were randomly collected and assessed for the positioning of leaks to measure the defect quantity. All sachets were produced by one similar machine. Thus, the primary factor focused on the timeline of the sachet production. Table 4 displays the classification scheme for the sachet leak defect, where the evaluation of the leak defect was dependent on the positioning of the leak (major). Meanwhile, the minor issues outlined in Table 5 focus on the superficial feature of the sachet condition since they contribute to CTQ attributes.

Table 5*Categories of packaging leak with description*

Major						Minor	Others
T	B	V	C	E	I	TN	Film
Top	Bottom	Vertical	Center	Eyemark	Inkjet condition	Cracked structure	Delamination

Table 6 outlines the defect summary for Day 1 sachet production. The top sachet position had the highest leakage percentage (28.95%), followed by the bottom position (9.97%), vertical position (4.13%), and central position (0.24%). Cracked structures were observed at 12.20%, which could be attributed to a high probability of sachet leakage. Figure 2 shows the defect distribution timeline for Day 1 production. The 15:00 and 12:00 timestamps had the highest and second-

highest defect frequencies; therefore, sachets from these timestamps were segregated for further evaluation. The defect scatter diagram in Figure 3 exhibits the breakdown of major and minor defects during Day 1 production. Major defects outnumbered minor defects, and this trend persisted throughout the production day. Although minor defects did not cause direct leak issues, sealing integrity might degrade over time due to environmental noise such as storage and handling conditions.

Table 6

Defect summary for Day 1 production

Time Phase	Total Defect Items	%	Total Defects								Others	Total
			Major				Minor					
			T	B	V	C	E	I	TN	Film		
9:00	3	0.13	1	2	0	0	0	0	0	0	3	6
10:00	2	0.09	1	1	0	0	0	0	0	0	2	2
11:00	131	5.80	48	6	3	0	0	1	47	0	48	153
12:00	381	16.87	143	30	8	0	0	9	79	2	177	448
13:00	213	9.43	104	20	14	1	3	11	34	0	95	282
14:00	161	7.13	67	35	12	0	0	11	26	1	73	225
15:00	506	22.41	160	25	24	0	3	9	105	2	268	596
16:00	175	7.75	67	33	12	2	2	9	20	0	86	231
17:00	228	10.10	89	33	18	1	2	9	17	0	116	285
18:00	249	11.03	73	45	18	2	4	16	8	0	159	325
19:00	128	5.67	36	20	8	1	0	3	5	1	79	153
20:00	70	3.10	34	34	1	0	1	11	4	1	54	140
21:00	1	0.04	1	0	0	0	0	0	0	0	0	1
22:00	10	0.44	4	1	0	0	0	0	4	0	4	13
Total	2258	100.00	828	285	118	7	15	89	349	7	1164	2860
% of frequency of defect types occurring within the date			28.95	9.97	4.13	0.24	0.52	3.11	12.20	0.24	40.70	

Table 7

Defects before improvement

Timeline	Order	Batch	Number of Defects	Total Sachet Production	Defect Rate
Sept 2024	1	25	5,148	172,112	2.99 %

Notes:

DPMO value before improvement = $5,148 / 172,112 \times 1,000,000 = 29,911$

DPMO after improvement was 29,911 and fell between sigma 3.3 and 3.4 in the sigma table conversion value, with 96% yield.

Figure 2

Defect distribution timeline for day 1 production

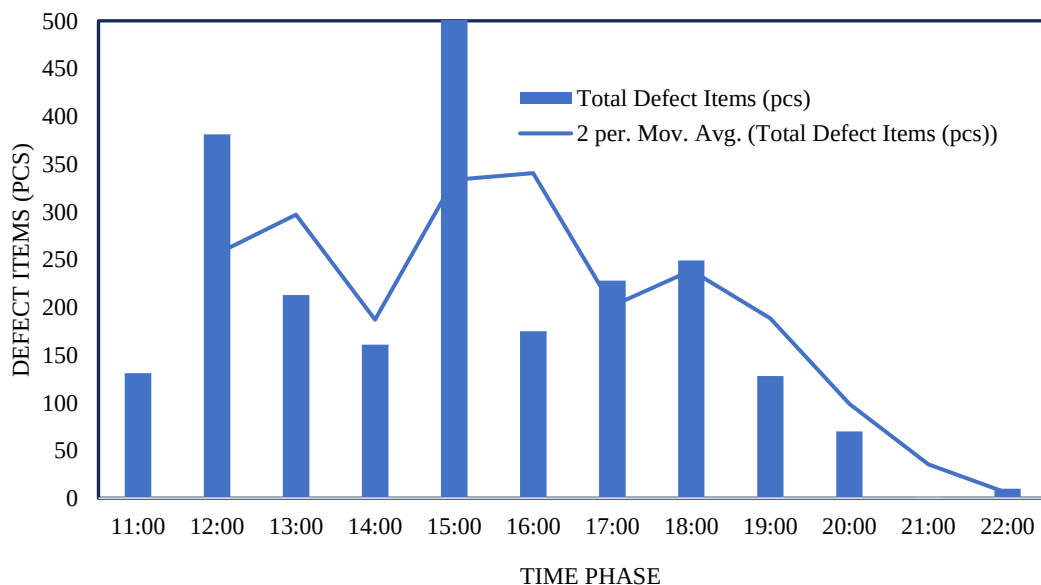
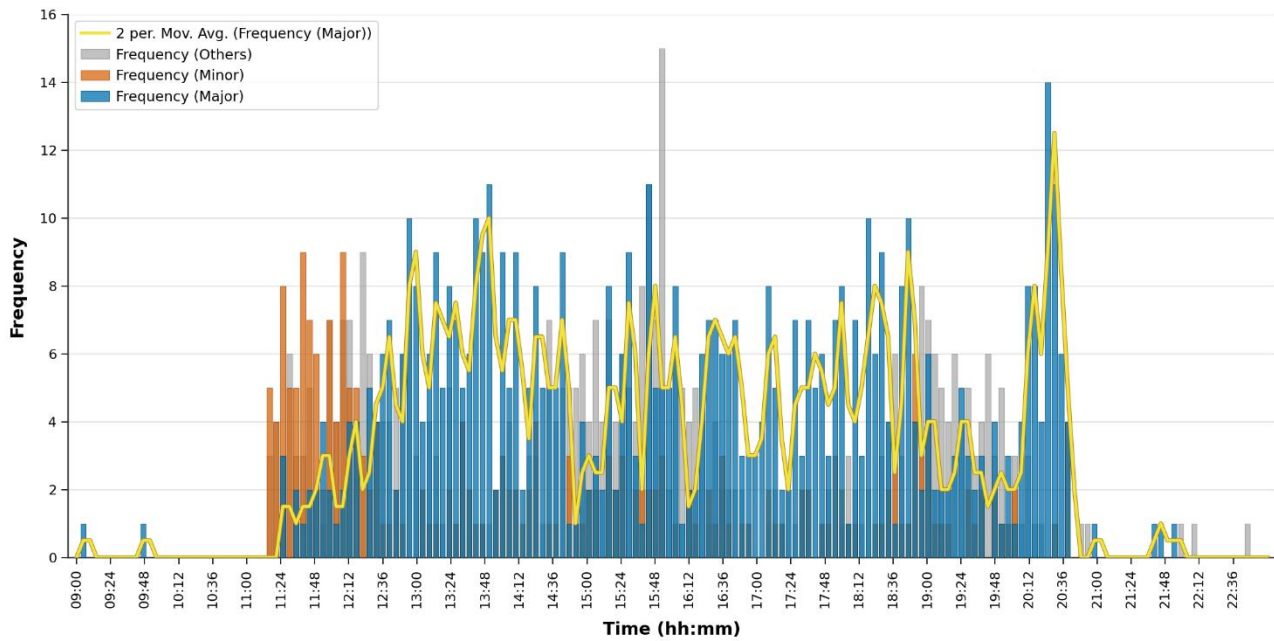


Figure 3*Defect scatter diagram for day 1 production***Table 8***Defect summary for Day 2 production*

Time Phase	Total defect items	%	Total Defects								Others	Total
			Major					Minor				
			T	B	V	C	E	I	TN	Film		
8:00	28	82.35	21	25	0	0	0	0	0	0	23	69
9:00	6	17.65	5	6	0	0	0	0	0	0	4	15
10:00	0	0	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0	0	0	0	0	0
12:00	0	0	0	0	0	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
Total	34	100.00	26	31	0	0	0	0	0	0	27	84
% of frequency of defect types occurring within the date			30.95	36.90	0.00	0.00	0.00	0.00	0.00	0.00	32.14	

Table 8 outlines the defect summary of Day 2 sachet production. The number of defects was significantly lower than that of Day 1 production, with the majority of major defects being on the upper side compared to minor defects. The y-axis of the defect scatter diagram displays the number of leakages, while the x-axis denotes the timeline of the sachet production. Similar trends were observed on Day 2 production, where the intended defect occurrence persisted for a designated period until the sachet condition reverted to normal. Top and bottom position leaks were also prevalent in Day 2 production. Based on the Pareto principle (i.e., 80/20 rule), the majority of the sachet leak issues occurred at top and bottom sections of the sachet.

4.3 Analyse

The fishbone diagram in Figure 5 was utilised to identify the potential causes of sachet leakage against 5M (Man, Machine, Material, Method, Measurement) and 1E (Environment). As shown in Figure 6, the potential causes of leaked

sachets were prompted by the lack of a failure detection system, on-line inspection reliability, and insufficient training and feedback from machine operators. Subsequently, the 5 Why analysis was performed to analyse the four most probable causes of packaging leak issues. It involved asking the question "Why?" for five times to uncover the hidden factors causing the problem. The first factor was a non-standardised process parameter caused by unclear operational guidelines and work instructions and the lack of operators' experience in performing adjustments during production. Loopholes in the detection and segregation process of adjusted process also contributed to the high quantity of leak sachets at peak operational hours. Additionally, improper residue cleaning procedure and nozzle adjustment caused sealing uncertainties during operation. The use of the fishbone diagram as an open root cause analysis tool and the 5 Why analysis as a closed root cause analysis served as a comprehensive overview (Desai et al., 2015). Ilhan et al.'s (2021) study on the factors causing poor seal integrity pinpointed material properties, process parameters, contaminants, and further processing. The information further solidifies the potential causes derived in this study.

Figure 4

Defect scatter diagram for day 2 production

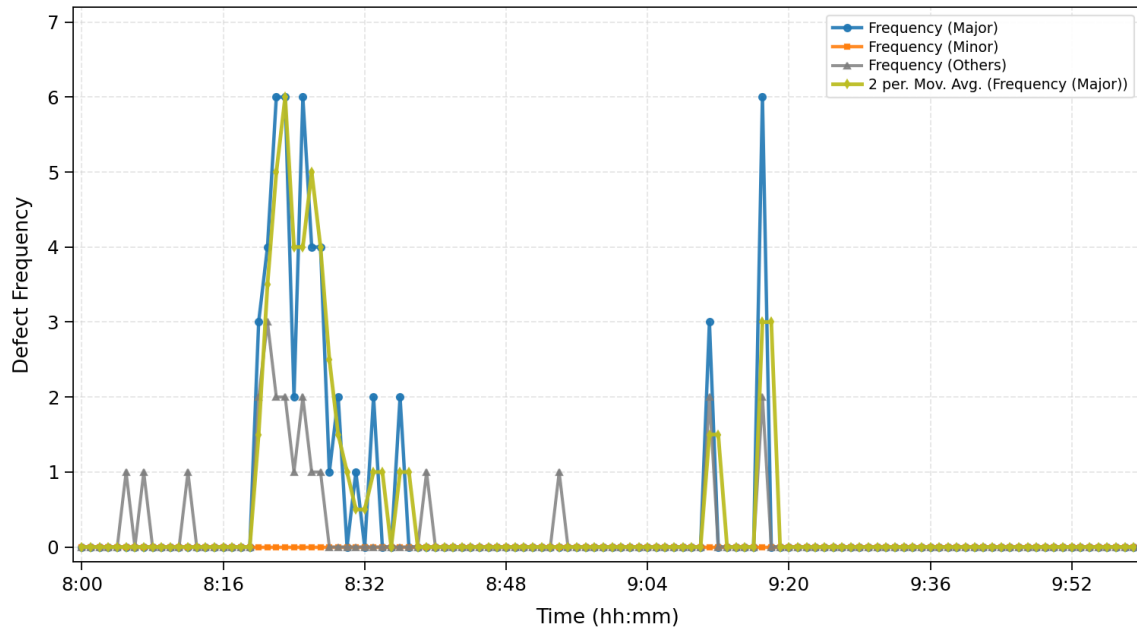


Figure 5

Fishbone diagram

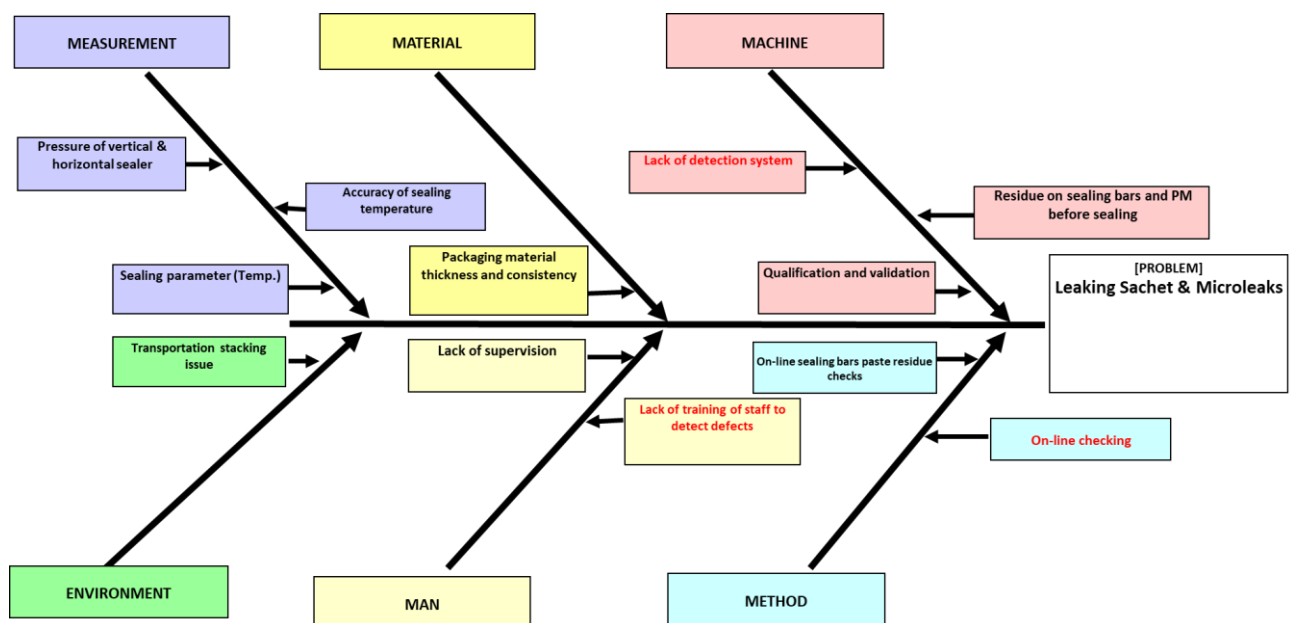


Figure 6*5 Why analysis*

5 WHY ANALYSIS					
FACTOR	WHY 1	WHY 2	WHY 3	WHY 4	WHY 5
Non-standardized process parameter	Inadequate monitoring on the process parameter during product run	Unclear work instruction for machine parameter	Operational parameter dependent on operator experience	Absence of qualification and validation protocol to define the optimal working ranges	
Leaked sachets detected at certain peak hours	Film alignment and adjustment issue during product run	Inadequate SOP for machine parameter adjustment	Inadequate detection and segregation system on the sachet from adjusted process		
Material thickness	Insufficient incoming material assessment	Limitation of testing the material thickness (only the front part of the roll was being assessed)			
Abnormal sealing performance	Residue buildup on the sealing bar	Inadequate monitoring and cleaning of the buildup residue	Absence of SOP for the conducted work		

Table 9*Calibration of temperature sensor for VFFS machine*

	A	B	C	$D=(C-A)/A*100$
Location	Set Value	Present Value	Measured alue	Deviation
Vertical (Front)	160.0	162.4	161.9	-1.19%
Vertical (Rear)	160.0	161.8	161.5	-0.94%
Horizontal (Front)	160.0	162.4	162.1	-1.31%
Horizontal (Rear)	160.0	160.8	161.1	-0.69%
Vertical (Front)	170.0	170.4	170.2	-0.12%
Vertical (Rear)	170.0	171.2	171.4	-0.82%
Horizontal (Front)	170.0	170.2	170.5	-0.29%
Horizontal (Rear)	170.0	171.3	171.2	-0.71%
Vertical (Front)	180.0	181.2	180.7	-0.39%
Vertical (Rear)	180.0	180.4	181.1	-0.61%
Horizontal (Front)	180.0	180.8	181.0	-0.56%
Horizontal (Rear)	180.0	182.4	182.1	-1.17%
Vertical (Front)	190.0	191.2	191.4	-0.74%
Vertical (Rear)	190.0	190.8	191.0	-0.53%
Horizontal (Front)	190.0	191.4	192.0	-1.05%
Horizontal (Rear)	190.0	190.7	192.4	-1.26%

4.4 Improve

The Improve phase outlined the plan to improve the operational parameters of the machine and its maintenance. Initiatives to eliminate the leak issues included replacing the nozzle, adjusting the sealing jog temperature and pressure, and assessing the sealing strength. These actions were then converted into a one-point-lesson (OPL) to assist shopfloor operators' understanding of the visual representation of the information. Dye penetrant testing (DPI) was conducted as a visual test to assess the sealing integrity of the filled sachet. Such testing has been widely applied to examine sealing integrity and the location of leaks in sachets. According to ASTM F1929 (2015), DPI begins by cleaning any residue on the sealing area before spraying Taseto red penetrant on the sealing zone and wiping off excess liquid penetrant. The time taken for the penetrant to diffuse through the sealing area determines the sealing integrity, where a prominent sealing will not allow the penetrant to diffuse. This approach was initially used to check the integrity of iron welding (Vera et al., 2024). Furthermore, calibration of the temperature sensor and display was also performed for the VFFS machine. The outcomes showed that the deviations were less than 1% (see Table 9). The set temperature and measured value fell within the acceptable range. The results provide information for the operational window assessment test to acquire the optimal

operating parameters. Yuan and Hassan (2007) established a sealing operation window for bar-type sealing and the failure modes are derived from ASTM F88 (2015).

A carbon test was also conducted as a verification protocol for sealer performance under the defined machine parameters. Figure 13 outlines the pressure measurement outcomes using two different film sheets. Usual thermal paper only displays the pattern once in contact with sealer but could not withstand high pressure and temperature settings. Therefore, this study used the Fujifilm Prescale pressure measurement film to assess the uniformity of the pressure distribution that corresponded to the colour density (Orr & Shelton, 1997). Pairing with Fujifilm Thermoscale for heat distribution measurement allowed access to both temperature and pressure settings, which used similar working principles based on colour density and hue that were exclusive for heat distribution application. Figure 9 displays the temperature measurement using Fujifilm Thermoscale, where colour density and hue were dependent on the sealing timing and temperature settings of the machine. The results in Figure 9 show that the displayed temperature value is reliable and confident. Operations window (OW) assessment is one of the approaches to determine the optimal working range of the sachet filling and sealing operation. OW serves as a robustness checking metric to ensure the operation is feasible under minimal noise factors (Clausing, 2004). Table 11 delineates the sealing operation window assessment by adjusting two crucial parameters: temperature and pressure settings. During the assessment, the pressures for both horizontal and vertical sealers were set at -0.2 and -0.4, respectively. Pressure fixation enables better contact between film layers; the setting is closely associated with temperature (Leminen et al., 2017). Poor combination decreases the polymer viscosity and enhances the negative pressure effect (Farris et al., 2009). For temperature settings, both horizontal and vertical sealers were increased/decreased by 5 °C. A total of 49 combinations were tested and five sachets were sampled for each run. Direct observations of sealing condition were conducted on both sides of sachets. Low temperature and operating outside the OW lead to incomplete sealant melting that hinders the overall seal integrity (Matthews et al., 2013). Operating beyond the OW exponentially increases the squeeze-out amount while reducing sealant viscosity (Morris & Scherer, 2016).

Tensile strength assessment for the sealed regions was also performed to further validate the sealing integrity of the sachet. Figure 11 shows the sealing strength of three sides of the sachet sealing area, where peak sealing strength was observed for horizontal top and bottom sides at 170 °C and 175 °C for the vertical side. Each sealing strength assessment was repeated twice to obtain an average sealing strength reading. For heat-sealed food packaging, heat sealing mechanism, form-fill-seal systems and sealing type are associated with leak formation (Ilhan et al., 2021). Seal strength increases at optimal temperature setting and dwell time enhancement that proliferate the formation of entanglements (Matthews et al., 2013). Table 12 outlines the sealing strength assessment for different sets of temperature parameters. In terms of material properties, the packaging material composition for suppliers A and B is shown in Table 10. Based on the product specification, both suppliers had similar results for heat seal strength and hot tack, while the bonding strength within the layer varied. The variation in sealant, printing, and adhesive layers might cause the food components to absorb through the polymer layers, thus weakening the bond strength within layer and eventually leading to delamination. For multilayer film, Planes et al. (2011) suggest improving the mechanical properties if they contain a stiff layer.

Table 10

Specification of packaging material

Supplier	Raw material	Polyester (PET)	Polyethylene (PE)	Aluminium (ALU)	Low Linear Density Polyethylene (LLDPE)	Total Thickness
A	Composition	12 μ $\pm$ 1 μ	15 μ $\pm$ 5%	7 μ + 1 μ	60 μ	94 μ $\pm$ 9 μ
B		12 μ	15 μ	7 μ	60 μ	94 μ $\pm$ 10%

Another factor influencing heat sealing performance is film orientation. Orientation degree (OD) and machine direction (MD) determine the maximum sealing strength, with more molecular orientation across the seal length being preferable to the rigid and brittle formation (Hashimoto et al., 2006). Relaxation and thickness change are crucial elements for heat sealing efficiency. Replacement of a shorter nozzle was performed on the VFFS machine to mitigate contamination at the seal area. The nozzle was also improvised by reducing its length by 10 mm (see Figure 7) to reduce the pressure of the liquid filling operation during hot tack. This is because extremely high pressure of liquid pumping from the hopper will interrupt the hot tack integrity and hinder overall sealing performance.

Replacement of cleaning tool for sealers was suggested after Gemba walk. It entails replacing the existing long thread wire brush with those of shorter thread (Rawendra & Puspita, 2020). A shorter-thread wire brush can slot inside the sealing jog gap for better contaminant cleaning within difficult-to-reach areas. However, the wire brush's durability is not a concern since high usage of wire brush is unavoidable during machine operation. Liquid food contaminant or residue buildup on the sealing interface causes a heat sink effect and decreases heating efficiency, resulting in the build-up of solid residue from melted sealant during filling and sealing operation. Moreover, slanting degree adjustment of the feeder before entering the conveyor to checkweigher reduces tearing at the edge and central positions of the sachet. The filled sachet underwent a press test and tensile operation to check the sealing integrity. All data collected from the inspection test were further analysed to ensure the efficacy of the measures.

Figure 7

Nozzle length reduction

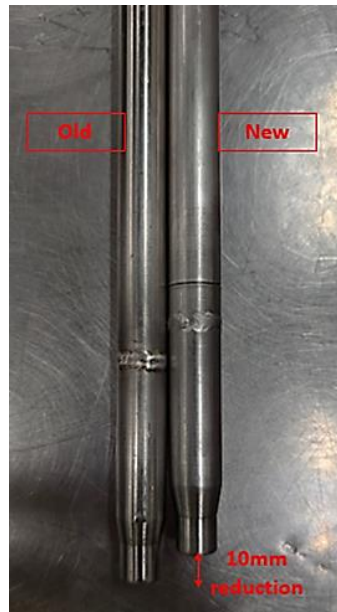


Figure 8

Carbon and temperature tests using film measurement (Thermal paper – Top; Fujifilm Prescale – Bottom)



Figure 9

Temperature measurement using Fujifilm Thermoscale

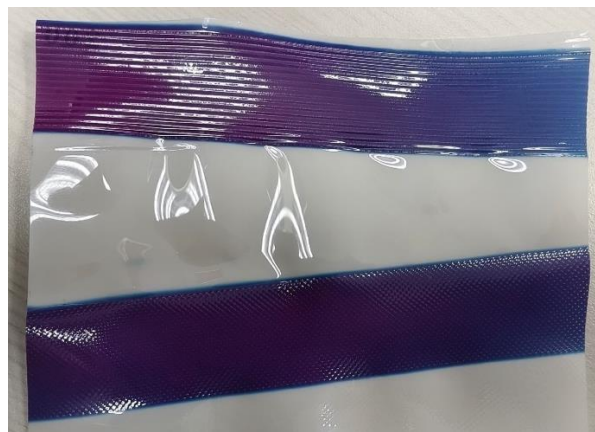


Table 11*Sealing operation window assessment*

No.	Temperature Settings				Sampling Qty (Empty)	Sealing Condition		Description
	Vertical		Horizontal			Vertical	Horizontal	
	Front	Rear	Front	Rear				
A1	160	160	150	150	5	✗	✗	Failed Vertical & Horizontal Sealing
A2	165	165	150	150	5	✗	✗	Failed Vertical & Horizontal Sealing
A3	170	170	150	150	5	✓	✗	Failed Horizontal Sealing
A4	175	175	150	150	5	✓	✗	Failed Horizontal Sealing
A5	180	180	150	150	5	✓	✗	Failed Horizontal Sealing
A6	185	185	150	150	5	✓	✗	Failed Horizontal Sealing
A7	190	190	150	150	5	✓	✗	Failed Horizontal Sealing
B1	160	160	155	155	5	✗	✗	Failed Vertical & Horizontal Sealing
B2	165	165	155	155	5	✗	✗	Failed Vertical & Horizontal Sealing
B3	170	170	155	155	5	✓	✗	Failed Horizontal Sealing
B4	175	175	155	155	5	✓	✗	Failed Horizontal Sealing
B5	180	180	155	155	5	✓	✗	Failed Horizontal Sealing
B6	185	185	155	155	5	✓	✗	Failed Horizontal Sealing
B7	190	190	155	155	5	✓	✗	Failed Horizontal Sealing
C1	160	160	160	160	5	✗	✗	Failed Vertical & Horizontal Sealing
C2	165	165	160	160	5	✗	✗	Failed Vertical & Horizontal Sealing
C3	170	170	160	160	5	✓	△	Ruptured inner horizontal sealing lining
C4	175	175	160	160	5	✓	✓	
C5	180	180	160	160	5	✓	✓	
C6	185	185	160	160	5	✓	✓	
C7	190	190	160	160	5	✓	✓	
D1	160	160	165	165	5	✗	✗	Failed Vertical & Horizontal Sealing
D2	165	165	165	165	5	✗	△	Failed Vertical Sealing Ruptured inner horizontal sealing lining
D3	170	170	165	165	5	✓	△	Ruptured inner horizontal sealing lining
D4	175	175	165	165	5	✓	△	Ruptured inner horizontal sealing lining
D5	180	180	165	165	5	✓	✓	
D6	185	185	165	165	5	✓	✓	
D7	190	190	165	165	5	✓	✓	
E1	160	160	170	170	5	✗	✓	Failed Vertical Sealing
E2	165	165	170	170	5	✗	✓	Failed Vertical Sealing
E3	170	170	170	170	5	✓	✓	
E4	175	175	170	170	5	✓	✓	
E5	180	180	170	170	5	✓	✓	
E6	185	185	170	170	5	✓	✓	
E7	190	190	170	170	5	✓	✓	
F1	160	160	175	175	5	✗	✓	Failed Vertical Sealing
F2	165	165	175	175	5	✗	✓	Failed Vertical Sealing
F3	170	170	175	175	5	✓	✓	
F4	175	175	175	175	5	✓	✓	
F5	180	180	175	175	5	✓	✓	
F6	185	185	175	175	5	✓	✓	
F7	190	190	175	175	5	✓	△	Overlapping at horizontal seal
G1	160	160	180	180	5	✗	✓	Failed Vertical Sealing
G2	165	165	180	180	5	✗	✓	Failed Vertical Sealing
G3	170	170	180	180	5	✓	✓	
G4	175	175	180	180	5	✓	✓	
G5	180	180	180	180	5	✓	✓	
G6	185	185	180	180	5	✓	✓	
G7	190	190	180	180	5	✓	△	Overlapping at horizontal seal

Table 11. continued

Fixed Parameter (Pressure)				Legend	
Vertical		Horizontal		✓	Pass
Front	Rear	Front	Rear	△	Conditionally-Pass
-0.4	-0.4	-0.2	-0.2	✗	Failed

Table 12

Sealing strength assessment for different operational parameters

Set	Horizontal/Vertical	Sealing Strength (gf/15mm)		
	H/V (°C)	Point 1 (Top)	Point 2 (Side)	Point 3 (Bottom)
1	155/160	1,919	164	559
2	165/165	4,160	75	3,965
3	170/170	0	3,047	4,784
4	170/175	4,555	3,916	4,674
5	175/170	4,335	3,599	4,719
6	175/175	4,197	3,555	4,051
7	175/180	3,660	3,554	3,255
8	178/178	3,476	3,841	3,999
9	178/178	3,619	2,913	2,738
10	180/180	3,729	3,667	4,023
11	180/185	2,780	2,603	2,751
12	182/182	3,979	3,662	3,442

Legends

Peak (For Vertical Side) Peak (For Horizontal)

Suggested Settings based on Tensile Strength:

Horizontal: 170 °C Vertical: 175 °C

4.5 Control

Table 13 outlines the number of defects post improvements. Three consecutive orders of similar product yielded 453,750 sachets, with 1,172 sachets being defective. The defect rate was 0.25%, which was less than the target defect of 2%. The outcome of the sachet production fulfils the expected target. DPMO after improvement was 2,583 and fell between sigma 4.2 and 4.3, with 99.7% yield. Corrective action successfully increased the sigma level to 4. In an actual production environment, the value reflects the process reliability and consistency. Table 14 shows the sigma level increment to 4.3 after improvement, with a DPMO difference of 27,328. These results suggest that the corrective and control measures were effective.

Table 13

Defects after improvement

Timeline	Order	Batch	Number of defects	Total Sachet Production	Defect Rate
Nov 2024	1	25	425	171,875	0.25%
Dec 2024	2	26	392	178,750	0.22%
March 2025	3	15	355	103,125	0.34%
Total			1,172	453,750	

DPMO value after improvement = $1,172 / 453,750 \times 1,000,000 = 2,583$

Table 14

DPMO comparison before and after improvement

	Before improvement	After improvement
DPMO	29,911	2,583
Sigma	3.3	4.3

5. Conclusions

The results of this study indicate that the highest leakage categories in hot-filled paste sachets produced by the VFFS machine in ABC are horizontal top and bottom position leaks and vertical leaks. Six Sigma DMAIC was effective in rectifying the primary issues of sachet leakage, with the lack of operational parameters and procedures emerging as the

major culprits. Subsequent corrective actions were deployed, including the calibration of the temperature sensor, operating window assessment, sealing strength assessment, dye penetrant and film measurement approaches, filling nozzle improvisation, changing to a shorter thread wire brush, and establishing OPL for quick operational setup. Furthermore, Sigma level shifted from 3.3 to 4.3, followed by a leap of 1 sigma level with 27,328 DPMO reduction before and after improvement. The overall defect rate of less than 2% not only addressed major sachet defects but also denoted a downward trend of minor sachet defects.

These findings are useful for food industry managers and practitioners to resolve the sealing issue of sachet products. Paste and sauce manufacturers can adopt DMAIC to pinpoint the problem and its extent. Full comprehension of the root causes can guide stakeholders in devising improvement actions to minimise or eliminate the issue. In most cases, food manufacturers have inadequate control and monitoring over the critical processes. Therefore, structured and systematic CI approaches are necessary for quality improvement purposes. The food industry is also keen to maintain a low defect rate of 2%, which can be achieved through the DMAIC methodology. However, the single case study and industry-specific nature of the current study may limit the generalisability of its findings. Future research can examine the applicability of DMAIC across other functions in the food industry and in mediating the performance measurement of VFFS machines in food operations.

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Declaration of Competing Interests

The authors declare no conflicts of interest.

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Tay Guo Xuan: Conceptualisation; Formal analysis; Visualisation; Supervision; Writing - original; Resources

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Availability of Data and Materials

The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human or animal participants, nor did it require ethical approval.

Generative Artificial Intelligence Declarations

The authors claim that artificially intelligent-assisted technologies in the form of generative AI were not used to generate content, ideas, or theories. AI was only used to enhance readability and refine the language. This was done with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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