STATISTICAL CONTROL AND DESIGN OPTIMIZATION IN SLITTING PROCESS

by

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ABSTRACT

The incorrect slitting is the defect waste in slitting process which does not meet the single pack width and crease-to-edge width requirements. It is the highest contributor to the overall defect waste in slitting process at Company X Jurong (CXJ). To address this problem, the key input and output variables were identified. The inputs are the tension settings and knives' positioning, and the output is crease-to-edge width. The objectives are to optimize the tension settings and to achieve a centered process by a proper calibration of knives' positioning. The Design of Experiments (DoE) was conducted to study the significance of tension towards crease-to-edge width variance. For 200 mL pack size, it was found that the variance is constant within the allowable setting range. For 250 mL pack size, it was found that the overall average variance best represents the variance of the data within the allowable range. However, the process is currently off-centered. Therefore, a proper training for detecting any mean shift happening in the process to the operators utilizing the digital camera measurement system is recommended.

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CHAPTER 1

INTRODUCTION

This thesis is based on group project collaboration between three team members during an 8-month internship in 2010 in a food packaging company, namely Company X, to help statistically-control the production process and improve the quality of process outputs. Company X operates in a serial-flow production process to manufacture beverage cartons. Three main production processes are printing, laminating and slitting, in a sequential order. The quality issue being addressed in this thesis is at the slitting process. The objective is to eliminate non-conformance in a systematic manner and find the optimum operating point for quantifiable machine parameters at slitting process.

1.1 Company Background

Company X is a multinational food processing and packaging company of Swedish origin. Currently, it has become one of the world's largest suppliers of packaging systems for milk, fruit juices and drinks, and many other products. It also provides the integrated processing, packaging, distribution line and plant solutions for food manufacturing.

Company X regionalizes its production in four regions: Europe, Central Asia (Middle East) & Africa, Asia Pacific and America. Each of these regions has regional headquarters to serve the regional needs. The manufacturing plant in the South East Asia cluster is located in Jurong area, Singapore. This plant, namely Company X Jurong (CXJ), serves customers from more than 17 countries. Compared to plants from other clusters, CXJ operates on small and more customized orders. Hence, frequent setups are

needed, close monitoring and careful scheduling are required to ensure continuous improvements are maintained, and the lead time for delivery to customers is minimized.

A World Class Manufacturing (WCM) methodology was used in order to ensure operational improvement, downtime minimization and to boost the performance of CXJ. WCM is designed to ensure flexibility with maximum performance possible. The production is in small batches to satisfy the variations and the volatility in the demands. The inventories are organized on a "just-in-time" basis. The attention is focused on rapid machine changeover; simpler and more flexible machinery is often used. Quality is ensured at each production process in order not to allow, as much as possible, any defects to pass through the plant. Achieving the standard of World Class Manufacturing is an essential step to firm restructuring. There are three levels in WCM philosophy; i.e. Level I -Ground-Breaking WCM, Level II – Innovative WCM and Level III – Creative WCM. Currently, CXJ is in the transition from Level II to Level III WCM. In order to attain this level of prestigious achievement which demands the highest level of manufacturing standards, CXJ is required to meet a set of critical factors in the development process of the factory. One of them is the *quality* factor, in which the use of more advanced and sophisticated statistical quality tools is indispensable. These tools will eliminate non-conformances in a systematic manner. The aim is to deliver the highest quality possible through defect-free manufacturing. One of the most commonly used tools for quality improvement which meets the WCM standards would be Statistical Process Control (SPC) and Process Optimization. According to Wikipedia, SPC is the application of statistical methods to the monitoring and control of a process to ensure that it operates at its full potential to produce conforming product [1]. In common industry practices, Design of Experiments (DoE) is frequently used in Process Optimization method. This milestone achievement, if it is attained, will serve as an intangible asset to the company, CXJ in particular, to increase its value of brand recognition to worldwide customers. As a result, the positive effects on bottom line profits could be seen, as the brand strength drives global sales year after year.

1.2 The Products

Company X focuses on carton production. Each individual carton pack consists of 6 layers of material. Paper as the base material provides the structure and support to the package. The paper is coated with a layer of aluminum foil to ensure that it is aseptically packaged and to guarantee preservation of flavor. The rest of the four layers are made of poly ethylene (PE), and they are as follows: the decorative layer on the outermost layer for protection; an adhesive layer between the paper and the Aluminum foil; and two internal coating layers (IC layers) to seal in the liquid. The comprehensive picture of all the layers is illustrated in the following figure (Figure 1.1) below.

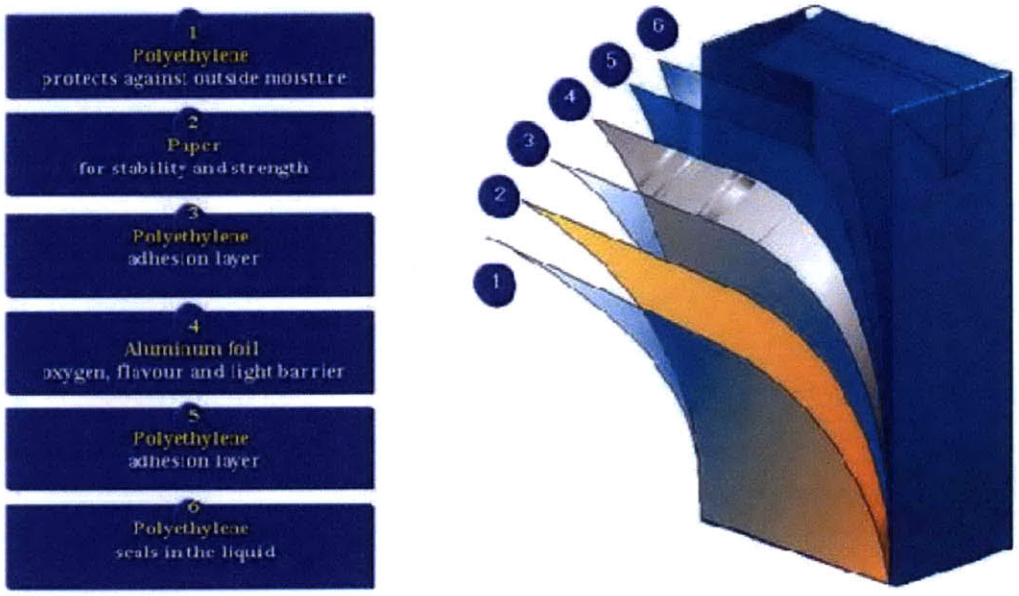


Figure 1.1 The Layer Structure of Packages [2]

1.3 The Manufacturing Processes

The general production flow in the Company X consists of three main processes: printing, laminating and slitting. The flow is illustrated in the figure below (Figure 1.2).

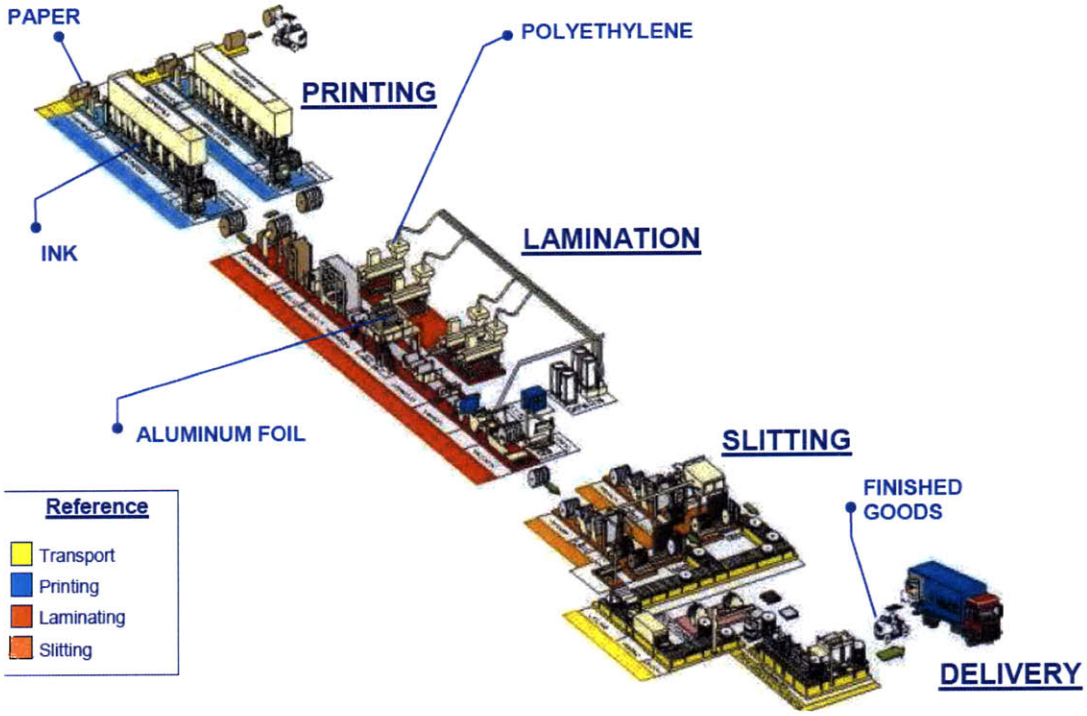


Figure 1.2 Production Layout [2]

1.3.1 Printing

In the printing stage, the design patterns on the cliché (i.e. printing plate cast) are reproduced onto the paper using water-based ink. Before going through the re-winder section, the printed paper goes through the creasing station in order to form the fold creases as well as to punch the holes for the straws. Currently, Company X has two different types of printers: flexography (two printers) and offset (one printer). The offset printing is aimed at higher resolution design, which serves more on the high-end type of products. The detailed scheme for the printing machine (flexography type) is shown in Figure 1.3 below.

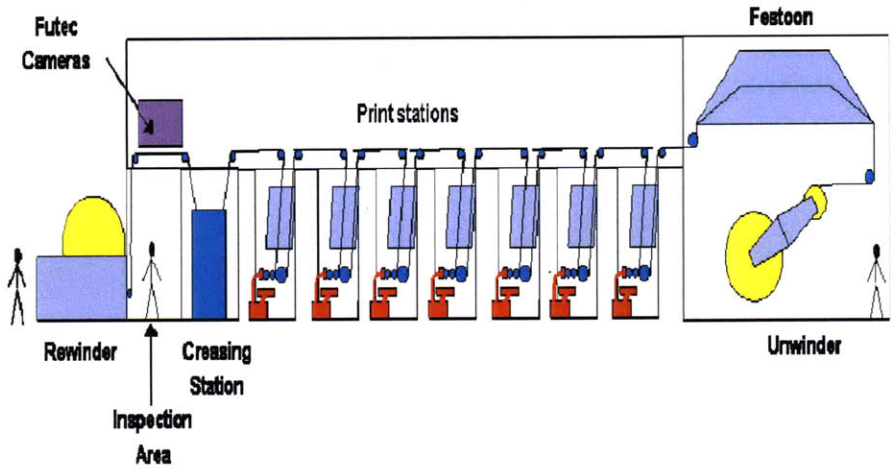


Figure 1.3 Schematic Diagram of Flexography Printer [2]

1.3.2 Laminating

In the laminating process, there are total of 3 sub-stations which form a total of 6 different layers to complete the lamination. The first sub-station provides the adhesive layer of PE between the paper and the Aluminum (Al) foil. The second sub-station provides the internal coating (IC) layers which consist of 2 different layers of PE for prevention of contamination and leakage. The last sub-station adds the decorative layer of PE for protection on the outer surface of the base material (paper). Currently, Company X has two laminators, i.e. laminator 21 and 22. The schematic layout of all of 3 sub-stations in laminating process is shown below (Figure 1.4).

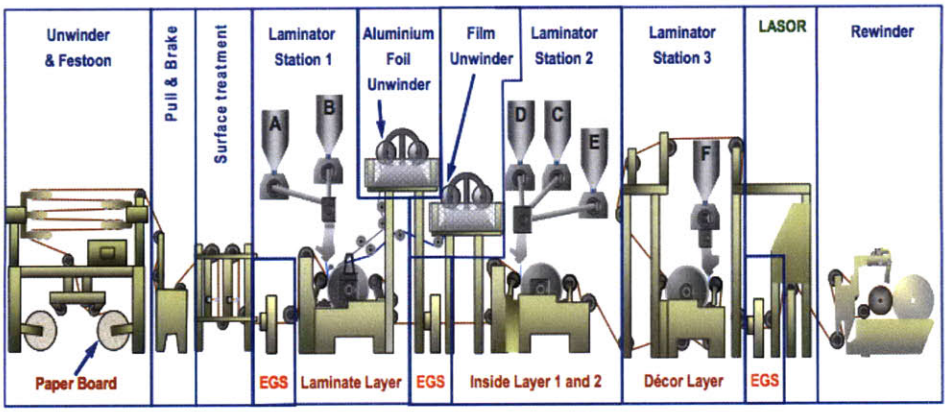


Figure 1.4 Schematic Diagram of Lamination Station [2]

1.3.3 Slitting

Each paper roll across the width consists of several webs, i.e. packs, as it can be seen from Figure 1.5. In the slitting stage, the entire roll is being cut into reels of single pack width so they can be directly fed into the filing machines at customers' locations. The process flow starts from the unwinder section where the roll is being unwound, then proceeds to the slitting section in which subsequently the slitted rolls is being rewound back into reels of single packs. The whole process is illustrated in Figure 1.5 below.

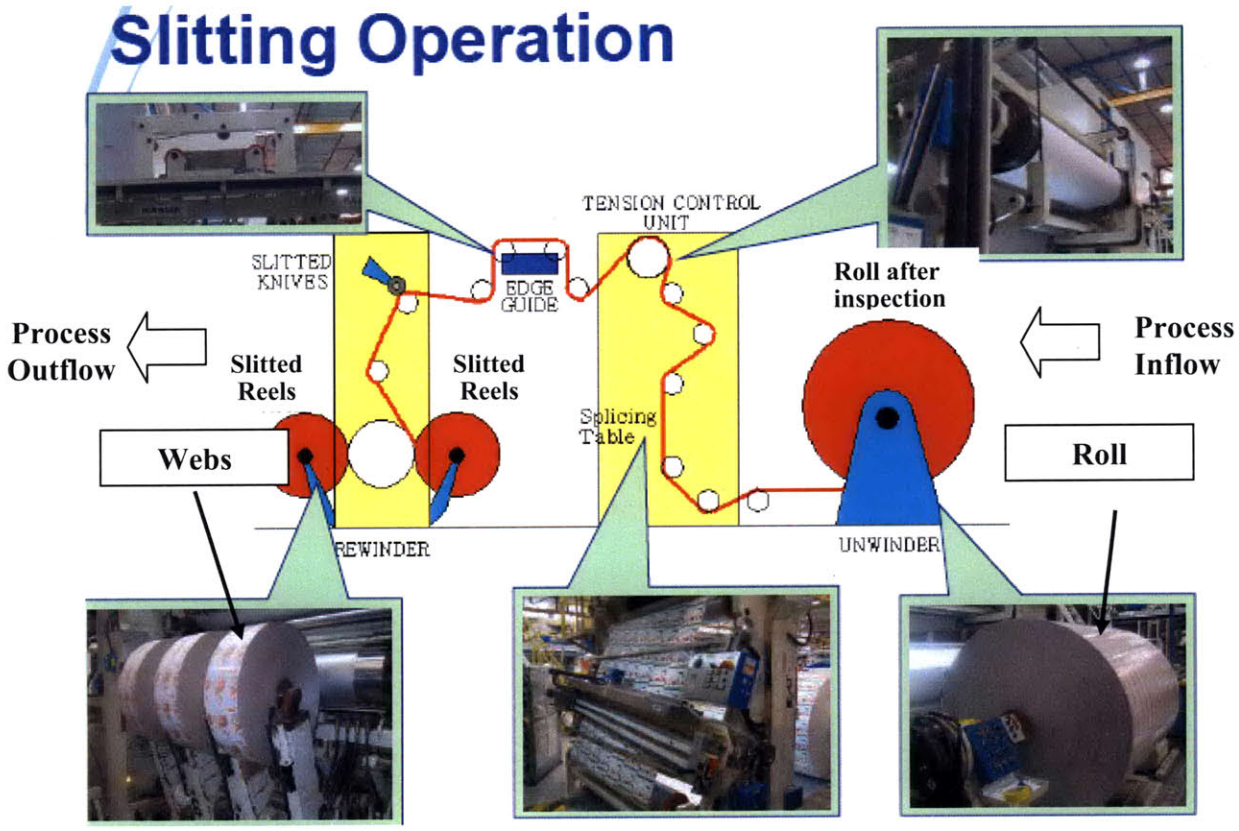


Figure 1.5 Schematic Diagram of Slitting Process [2]

1.4 Organization of Thesis

This thesis is divided into seven chapters. The general background of the company, the brief descriptions about its products and the major manufacturing processes involved were elaborated in first chapter. The problems are defined in Chapter 2, together with the objectives as well as the scope of the project. Chapter 3 presents the previous work that has been done to minimize the effects from current problems as well as a literature review on the fundamentals of physics from the process to give a better understanding of the process and to identify the critical parameters affecting the process; and on the various methods generally used in process control. Chapter 4 goes into details the methods being used to identify and analyze the problems systematically. Results obtained and the discussions of the study are presented in Chapter 5. Chapter 6 concludes the thesis with the findings and some recommendations. Future work that can be done to further improve the current work is discussed in the final chapter.

CHAPTER 2

PROBLEM STATEMENT

2.1 Problem Description

Since 2001, CXJ has been undergoing three typical World Class Manufacturing (WCM) development levels [2]. Level I, i.e. Ground-Breaking level, was initiated in 2001. It consists of three phases; pilot phase, expansion phase and stabilization phase. During these phases, the main target was to eliminate non-conformance since the waste rate was relatively high (e.g. in 2003, total waste around 8.5%). Waste in general consists of two types, i.e. defect waste and process waste.

By introducing the basic quality control tools like *5 Whys*, *root cause analysis*, as well as other basic quality control toolkits; the waste rate was reduced considerably and the plant expanded significantly. The second level of development, which is Innovative WCM, was attained in 2005. In this level, the waste rates had been reduced notably to 6.9% (defect waste – 1.29% and process waste – 5.54%) and it was kept stable by standardizing the process and other high level quality control tools (i.e. *sporadic* type of losses had been eradicated).

Since 2007, CXJ has reached the third level of development, i.e. Creative WCM. At this level, the defect waste rate was further reduced to 1.37%. The total waste rate and its breakdown from 2003 to 2010 are presented in Table 2.1 below. However, hundreds of infrequent and random defects remained. Thus, more advanced statistical quality control tools such as daily quality maintenance and Statistical Process Control (SPC) should be introduced to achieve the goal of zero defects.

Table 2.1 Total Waste and Its Breakdown from 2003 to 2010

Year	Defect Waste	Process Waste	Total Waste
2003	1.47%	6.96%	8.43%
2004	1.34%	5.39%	6.73%
2005	1.29%	5.54%	6.83%
2006	1.15%	5.98%	7.13%
2007	1.37%	5.66%	7.03%
2008	1.50%	5.02%	6.52%
2009	1.37%	4.53%	5.90%
2010	1.22%	4.57%	5.79%

The problem focus of this project is on the defect waste caused by incorrect slitting (as it can be seen from Figure 2.1, indicated by a white line formed) at Jurong manufacturing plant in Singapore, which is the highest contributor to the defect waste rate for the slitting process thus far. There are several major types of defects that contribute to slitting defect waste, which is shown in Figure 2.2. In this type of defect waste itself, i.e. incorrect slitting, it is further broken down into two sub-types, i.e. F501-01 – incorrect slitting across the webs and F501-02 – incorrect slitting at single web. The phenomenon of this type of defect waste remained fluctuating in the past three months from April to June 2010, as it can be seen from Figure 2.3 to Figure 2.5 below. In April 2010, the average count for F501-01 is 16.70 counts and for F501-02 is 0.27. In May 2010, the average count for F501-01 is 17.13 and for F501-02 is 1.39. In June 2010, the average count for F501-01 is 17.25 and for F501-02 is 0.57.

Figure 2.1 The Example of Incorrect Slitting

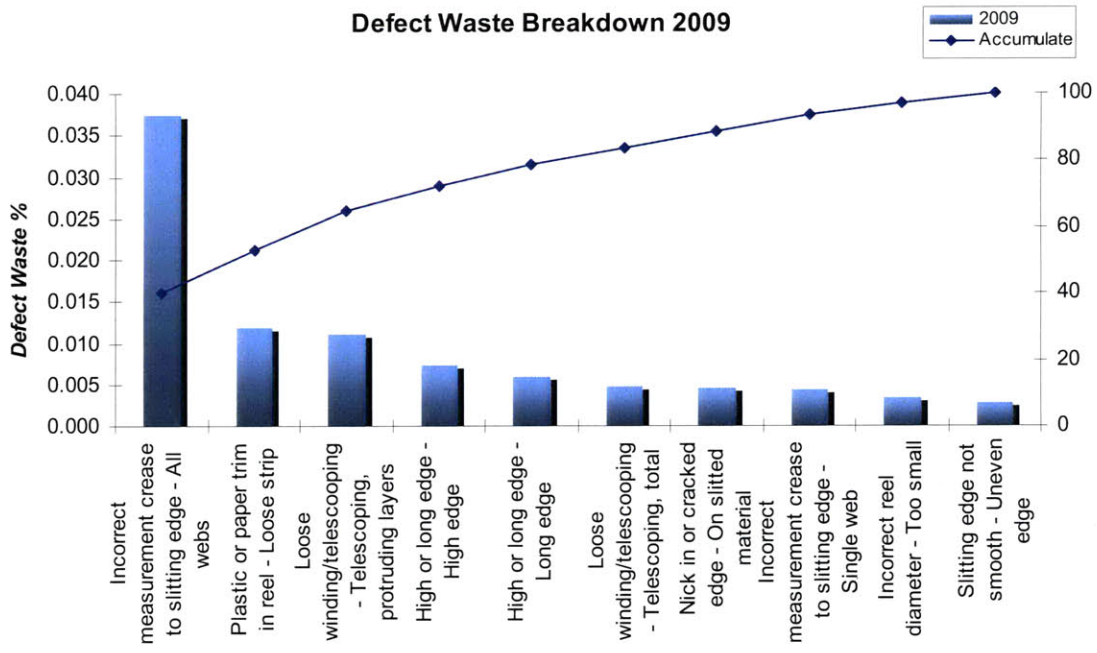


Figure 2.2 Major Slitting Defect Waste in 2009 [2]

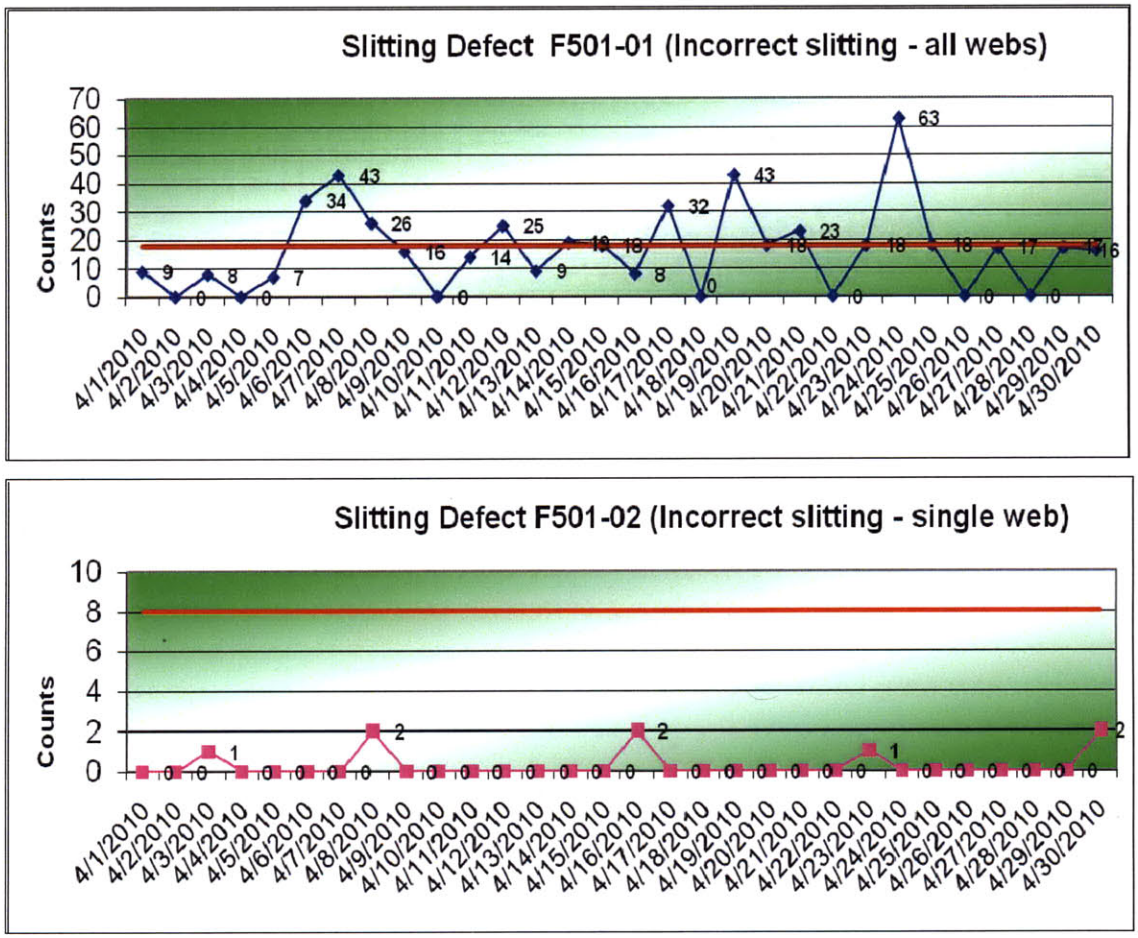


Figure 2.3 Incorrect Slitting Defect Waste in April 2010

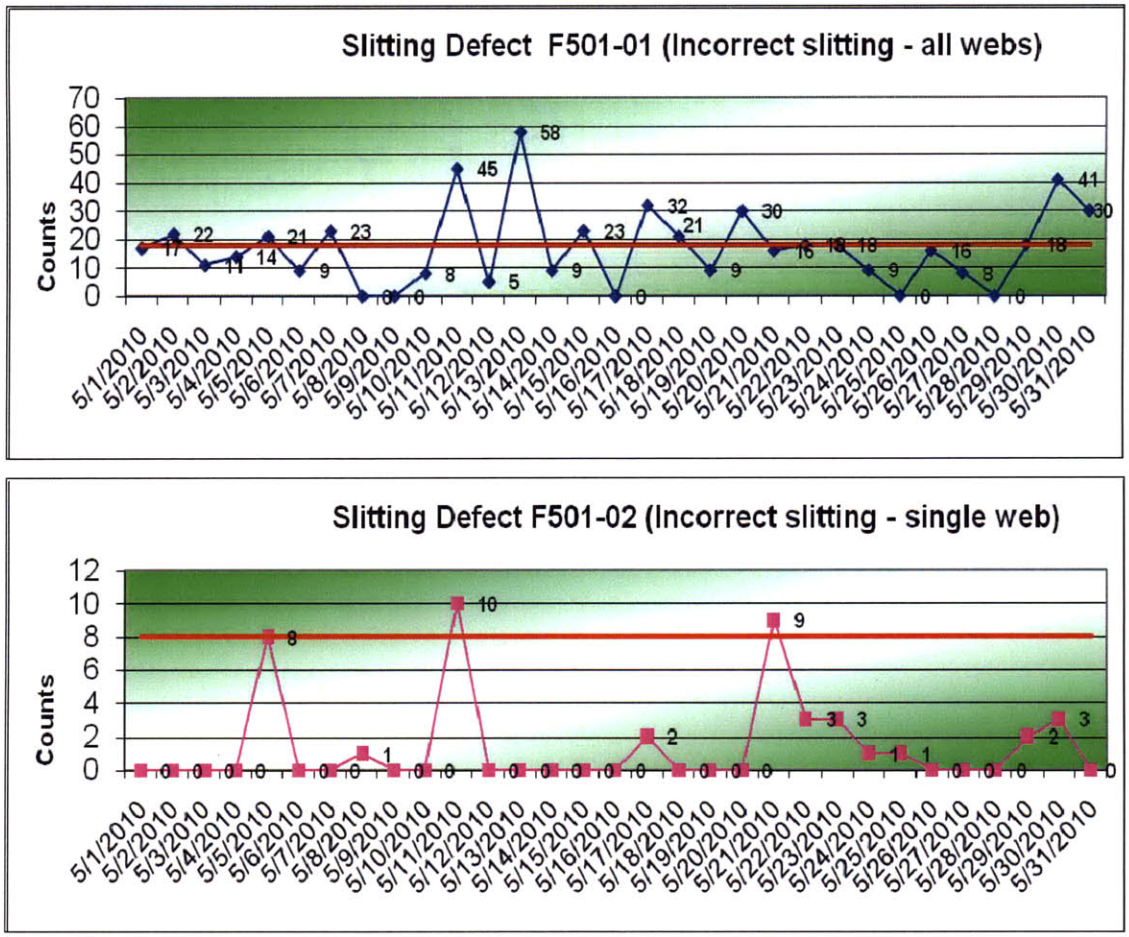


Figure 2.4 Incorrect Slitting Defect Waste in May 2010

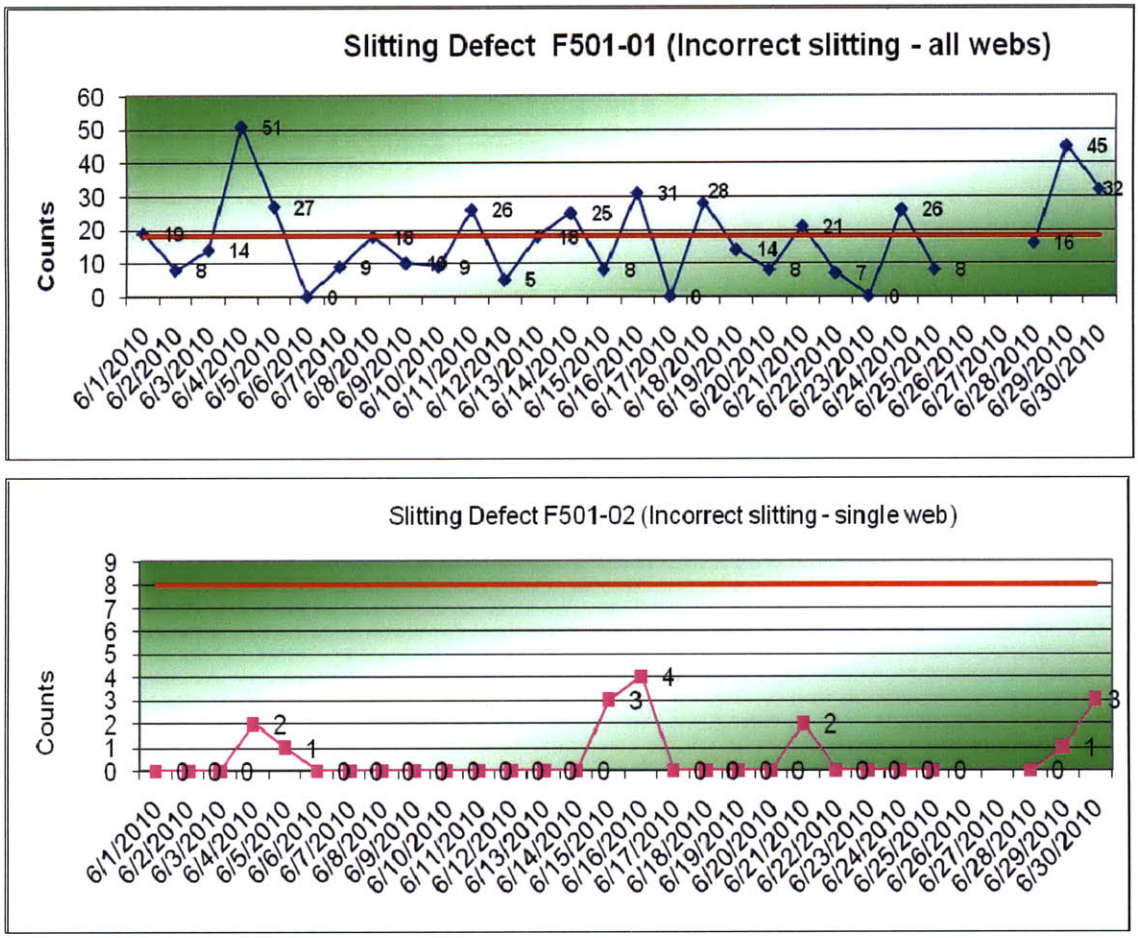


Figure 2.5 Incorrect Slitting Defect Waste in June 2010

Currently, there are four slitter machines installed in place, namely slitter 52, 53, 54 and 55. The breakdown across of all four machines in terms of defect waste meter per month in 2009 can be seen from Figure 2.6 below. Slitter 55 contributed the highest amount of defect waste (3,670 meters). Nevertheless, due to the limitation of the output measurement system at the slitter machines, in which currently they are using manual measurement system (i.e. measuring tapes), the concentration of the project has been shifted to slitter 54. This particular machine is equipped with a real-time camera output measurement system in order to meet the adequate measurement standards.

The detailed methodology steps being used will be further elaborated in chapter 4. There are six machine parameters observed to be significant contributors to the variation in crease-to-edge width, traced from the beginning of the line up to point of cut, i.e. roll centering, splicing table, guiding line camera system, tension, knife setup and positioning and the line speed. The quantifiable machine parameters being analyzed are tension, line speed and knife setup and positioning. The literature review as part of the preliminary work will be further discussed in details in chapter 3.

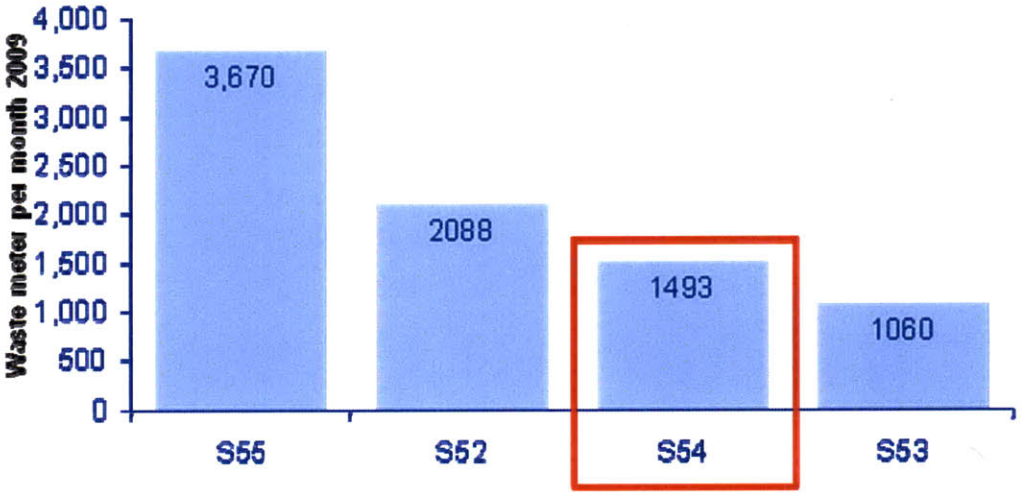


Figure 2.6 Incorrect Slitting Waste Meters across 4 Slitters [2]

2.2 The Objectives

The primary objective of this project is to identify and reduce the external disturbances at the slitting process and to fine-tune the quantifiable machine parameters to obtain the least variance operating point. The optimal operating point is to be established to yield the best conforming output measurement. Hence, waste rate could be reduced and if possible, eliminated, thus making the process more robust. An Out-of-Control Action Plan will also be constructed to maintain the process-in-control condition in the future.

CHAPTER 3

LITERATURE REVIEW

This chapter helps to give a more detailed overview of process control methodology, the physics of the process to identify the critical factors affecting the slitting process and also the previous research or work that has been done thus far. It consists of three main sections: process control overview, the fundamentals of physics about web stability and previous work section. The first two sections are important since they provide a better understanding of the physics of the process and how to approach the problem systematically. The previous work section serves as the guidelines and also the fundamentals in which this project would be based upon.

3.1 Process Control Overview

This section relies mainly on Hardt's work as described in his paper about manufacturing processes and process control [3]. In this section, general process overview, the hierarchy of process methodology and process classification of control is elaborated.

3.1.1 General Process Overview

A manufacturing process can be defined as an interaction of equipment with material to transform it into part conforming to specifications. The interaction takes place in form of energy exchange, which could be mechanical, electrical, thermal or/and mechanical. Since the transformation is always driven by and governed by equipment, the only control inputs over the process, other than changing the material itself, is through the equipment. The output of the produced part can be classified into two categories: geometry and properties. Geometry defines macroscopic shape of the product, like

length and height. Properties characterize those constitutive and intrinsic attributes of the material, like stiffness and strength. Figure 3.1 illustrates the schematic diagram of this model.

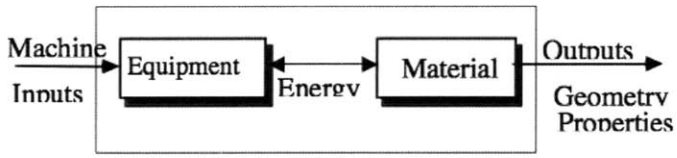


Figure 3.1 Schematic Diagram of the Process Model [3]

As noted, the manufacturing is about two elements: equipment and material. Both define the internal variables called process parameters. The process parameters include equipment state and properties as well as material state and properties. State refers to those energy pairs such as pressure-flow, temperature-entropy and voltage-current. Properties are those well-known intrinsic quantities like melting point, viscosity, and Young's modulus. They could be either of the equipment or of the material. The disturbances are present in those process parameters.

To help understand the relationship between process parameters (equipment state and properties as well as material state and properties), disturbances, controllable inputs and outputs (geometry and properties), the following mathematical model to characterize the causality is presented. And, the schematic diagram of this model is given is Figure 3.2. It is noted that the controllable inputs are the subset of the process parameters that are accessible and controllable in a reasonable time frame relative to the process execution time.

$$\underline{Y} = \phi(\underline{\alpha} + \Delta\underline{\alpha}, \underline{u})$$

where:

$\underline{Y}$ = outputs (geometry and properties)

ϕ = process transformation function

$\underline{\alpha}$ = process parameters

$\Delta\underline{\alpha}$ = disturbance to process parameters

$\underline{u}$ = controllable inputs

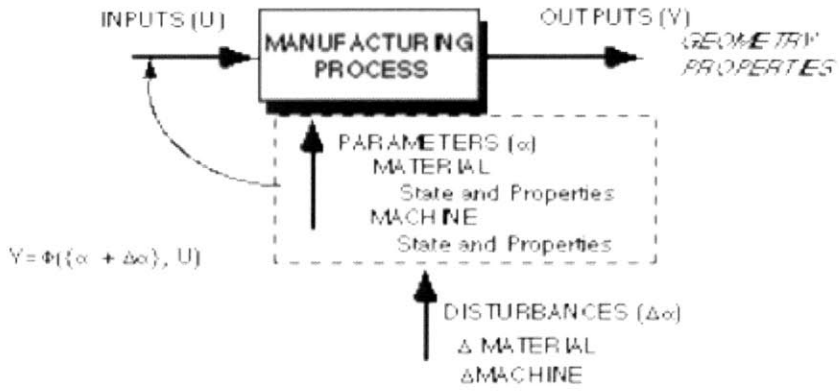


Figure 3.2 Schematic Diagram of Process Causality Model [3]

3.1.2 Hierarchy of Process Control Methodology

Based on the process model given in the previous equation, we further take the partial differentiation and then derive the first-order variation equation:

$$\Delta\underline{Y} = \frac{\partial Y}{\partial \alpha}\Delta\underline{\alpha} + \frac{\partial Y}{\partial u}\Delta\underline{u}$$

where:

$\Delta\underline{Y}$ = variation of the output

$\frac{\partial Y}{\partial \alpha}$ = disturbance sensitivity of the process

$\Delta\underline{\alpha}$ = parameter disturbances

$\frac{\partial Y}{\partial u}$ = input-output sensitivity or "gain"

$\Delta\underline{u}$ = controllable input changes

To minimize $\Delta \underline{Y}$, we could address the challenges from three aspects with each of its distinctive methods:

1. Reduction in Sensitivity — Process Optimization

This method is to minimize the term $\frac{\partial Y}{\partial \alpha}$ such that the variation in outputs is minimized. It would be helpful if the quantitative form of this partial differentiation characterizing the process could be derived analytically. However, in most cases, the physics of the process are too complicated to obtain insights at this level. Therefore, the use of design of experiments could be used, instead of calculating the variation at different operating points and select the one with the minimum variation as the most robust operating point. This optimal operating point corresponds to a set of optimized process parameters that lead to minimal change in outputs. The schematic diagram of this method is shown in Figure 3.3.

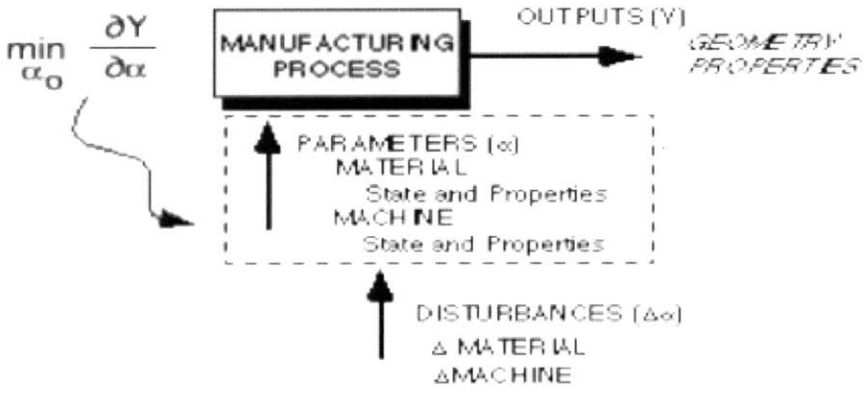


Figure 3.3 Schematic Diagram for Design Optimization [3]

2. Reduction in Disturbances – Statistical Process Control

This method is to reduce the disturbances' term of $\Delta \underline{\alpha}$ such that the variation in the outputs is minimized. Its schematic diagram is shown in Figure 3.4 below. Statistical process control is a monitoring tool in nature. Once an out-of-control point is detected on the control charts, it provides no prescription for action, but implies that the disturbance exists and should be eradicated immediately before it leads to large changes

in outputs like defects. Therefore, in addition to establishing the mechanism of data acquisition and plotting the control charts, another important practice is to construct the Out-of-Control Action Plan (OCAP). It is the OCAP that offers detailed and practical corrective actions to actually eliminate the disturbances.

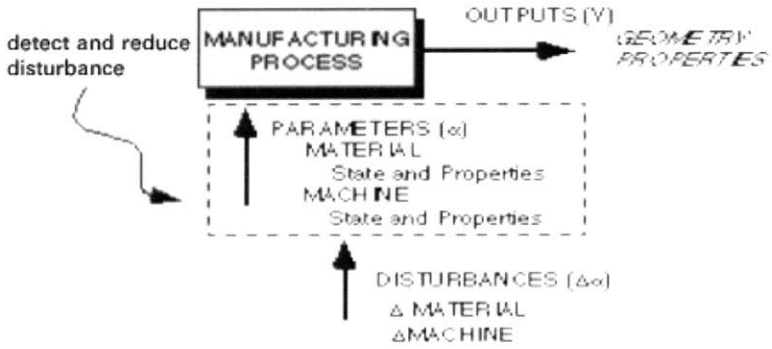


Figure 3.4 Schematic Diagram of Statistical Process Control [3]

3. Measurement of Output and Manipulation of Inputs – Feedback Control

Like the previous method, this method is also to reduce the disturbance term of $\Delta\alpha$ such that the variation in outputs is minimized. Nevertheless, the difference is that the feedback control loop is employed in this method to ensure that the process states conform to what they are supposed to exactly be. Usually, these process states are machine temperature, pressure, and velocity, which are directly measured by instruments in a real-time manner. It is noted that the outputs are excluded from the control loop, as shown in Figure 3.5.

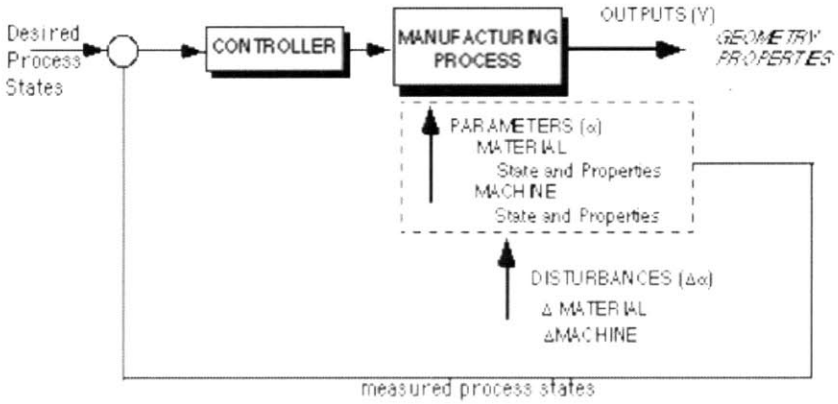


Figure 3.5 Schematic Diagram of Feedback Control of Process State [3]

3.2 Web Stability

Slitting is one of the web handling processes. Tension is one of the factors that make the web stable during the slitting process. In this project, the effect of web tension both at main pull-unit and at rewinder section will be investigated on slitting performance. Through a set of designed experiments carried out, the importance of web tension towards the web in motion will be observed. Hawkins has analyzed this tension factor using the fundamental of physics about web stability and come to three relevant important conclusions, which will be elaborated further below [4].

First, the web must be in tension when running through slitting process since the web, which can be visualized as a matrix of closely spaced threads or strings, is strong in tension but weak in compression. In slitting process, the pulling effect generally comes from tracking friction with the machine rollers.

Second, due to web stiffness, the paper will exert some compressive forces in the transverse direction while being pulled in the axial direction. The direct effect is either to cause wrinkling problems on the web when the tension is sufficiently large or to cause the whole web to shift laterally when the tension is not substantially enough to hold the web stable and stay on its original position. Both effects will lead to the defect waste caused by incorrect slitting. This phenomenon is commonly known as Poisson effect.

Third, the larger the tension applied to the web, the narrower the center of the web span. Both the length of the web span and also the tension do contribute to the web-narrowing process. When the tension applied on the left side is not exactly equal to the right side of the span, the web is said to be skewed. As a result, the skewed web will have uneven tension profile across the width when the tension is applied and paper shrinkage will likely to occur. Shrinkage effect has a direct impact towards the incorrect slitting process. There will be no permanent width reduction (shrinkage) when the tension applied does not exceed the yield point of the material, i.e. within the elastic region. Therefore, careful setting of tension point during the slitting process would be necessary in order to prevent incorrect slitting defect waste from re-occurring.

3.3 Previous Work

This section elaborates on the previous work that has been done by Company X to help to reduce the defect waste as well as the claims (internal and external) [2]. There were a few projects that had been completed, and they are as follows:

3.3.1. Corrective Action Report 1

The defect found was incorrect measurement from the crease to the slitting edge. The type and size of the product under the defect are brick aseptic slim and 200 mL in volume. The defect is illustrated in Figure 3.6 below.

Figure 3.6 Incorrect Slitting with Waste Strip [2]

Incorrect slitting was found after producing 4600 packs (797 m) from the beginning of the reel. After further investigation, it was found that the technician did not check the crease-to-edge width again during unloading after slitting. He was inexperienced with the machine and did not follow the Quality Inspection Procedure (QIP).

The preventive measures taken were to counsel the technician involved to inspect thoroughly according to the QIP and a briefing was conducted to create awareness and to serve as a reminder to the standard QIP.

3.3.2. Corrective Action Report 2

Incorrect slitting width from crease to edge was also found from the customer claims in the database, which is illustrated in Figure 3.7 below. The type and size of the product under this particular defect are brick aseptic medium and 200 mL in volume. This incorrect slitting process affected the whole web reels (i.e. across the rolls width).

Figure 3.7 Incorrect Slitting with White Line [2]

The investigation found that there was an incorrect slitting on the reel after producing 7000 packs (1,120 m) from the beginning of the reel. After the analysis, the root cause was determined to be from poor guiding of the line guider (i.e. the line guider is not stable with light color of guiding line such as yellow), in which material set up must be carried out when there is a change in line width or color of the line.

One Point Lesson (OPL) was established [2], which has the objective of standardizing the procedure of material set up for the Charge-Coupled Device (CCD) line guider. Appendix A gives the detailed Standard Operating Procedure (SOP) for this particular lesson.

3.3.3. Corrective Action Report 3

Another incorrect slitting defect was found in a few particular webs out of the whole roll, in which the crease to edge width measurement did not meet the specifications. The white line was present but was unable to be detected during the slitting process. Figure 3.8 below shows the sample of defect found under this particular claim.

Figure 3.8 The Defect Waste of Incorrect Slitting with White Line [2]

From the analysis, the suspected root cause were found to be the new process technician in-charge did not realize the movement of the turret unwinder loading of the new roll, which caused the production roll to shift, resulted in incorrect slitting. The technician

was suspected not to be properly briefed and trained on the movement of the turret unwinder loading of the new roll.

The corrective actions measures undertaken were to brief that particular technician in-charge under the claim and to conduct an On Job Training (OJT) on the respective slitting machines before releasing them into the production floor. The regular guidance and inspections from the shift managers are also necessary to ensure the prevention of the problem re-occurring in the future.

In this previous work section, the examples of three corrective action reports have been elaborated. These three corrective actions as well as the other standard operating procedures that have been established by the company are necessary to keep the process stationary. This is one of the required conditions in order to do a proper and accurate design of experiments which would be part of the methodology steps used in this project. The chronological steps of methodology used would be further elaborated in the next chapter.

CHAPTER 4

METHODOLOGY

DMAIC (*Define*, *Measure, Analyze, Improve* and *Control*) is a structured five-step problem solving procedure that can be used to successfully complete projects by proceeding through and implementing solutions that are designed to solve the root causes of quality and process problems, and to establish best practices to ensure that the solutions are permanent and can be replicated in other relevant business operations [5]. In this project, DMAIC problem solving process is used. Its process flow is illustrated in Figure 4.1 below. Each step will be further elaborated in each of the subsequent five sections.

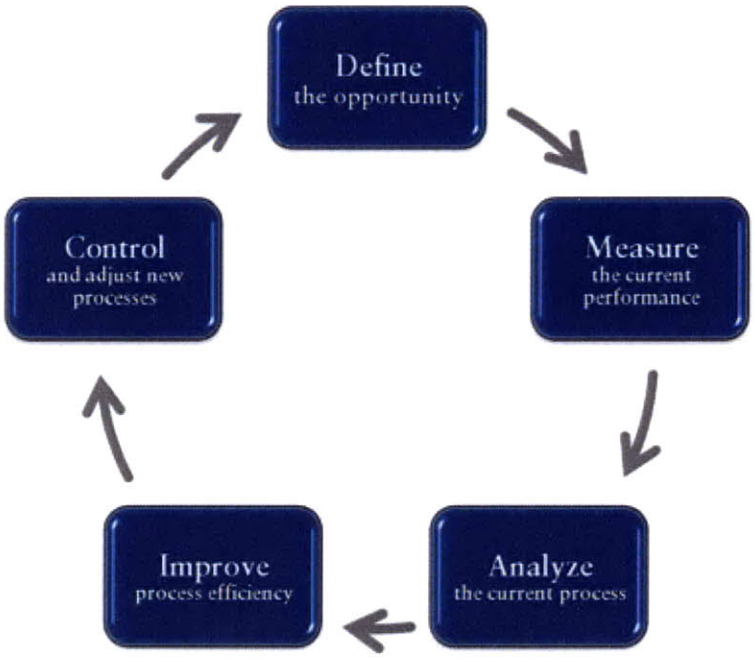


Figure 4.1 DMAIC Problem Solving Process [6]

4.1. The Define Step

The underlying objective for this step is to identify the opportunity and also to verify or validate the breakthrough potential resulted from the project undertaken. The project must be important to the customers and also important to the business. All of the stakeholders involved have to agree on the potential benefits and the usefulness of the project.

In this step, a project charter will be established (as shown in Figure 4.2 below). This charter contains a short and brief description of the project and its scope, the potential benefits to the organization and the milestones to be accomplished during the project. The high-level map of the slitting process will also be provided, such as SIPOC (Suppliers, Input, Process, Output and Customers) diagram. This diagram gives a simple overview of the process and is useful for understanding and visualizing basic process elements, which is illustrated in Figure 4.3 below.

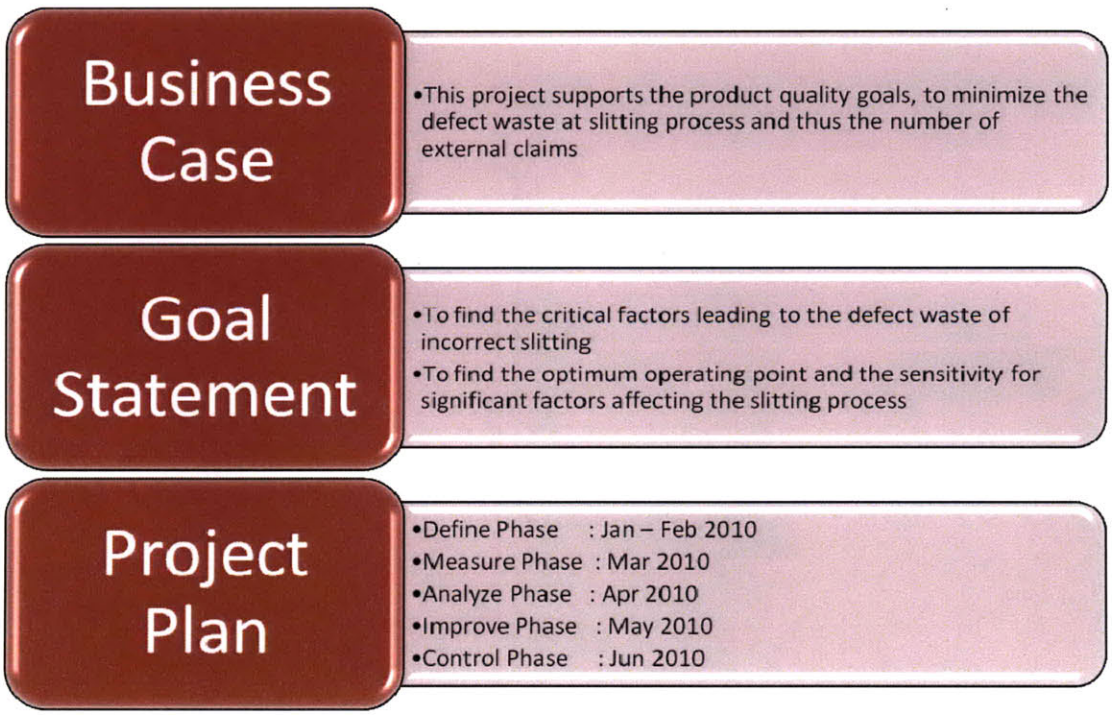


Figure 4.2 Project Charter

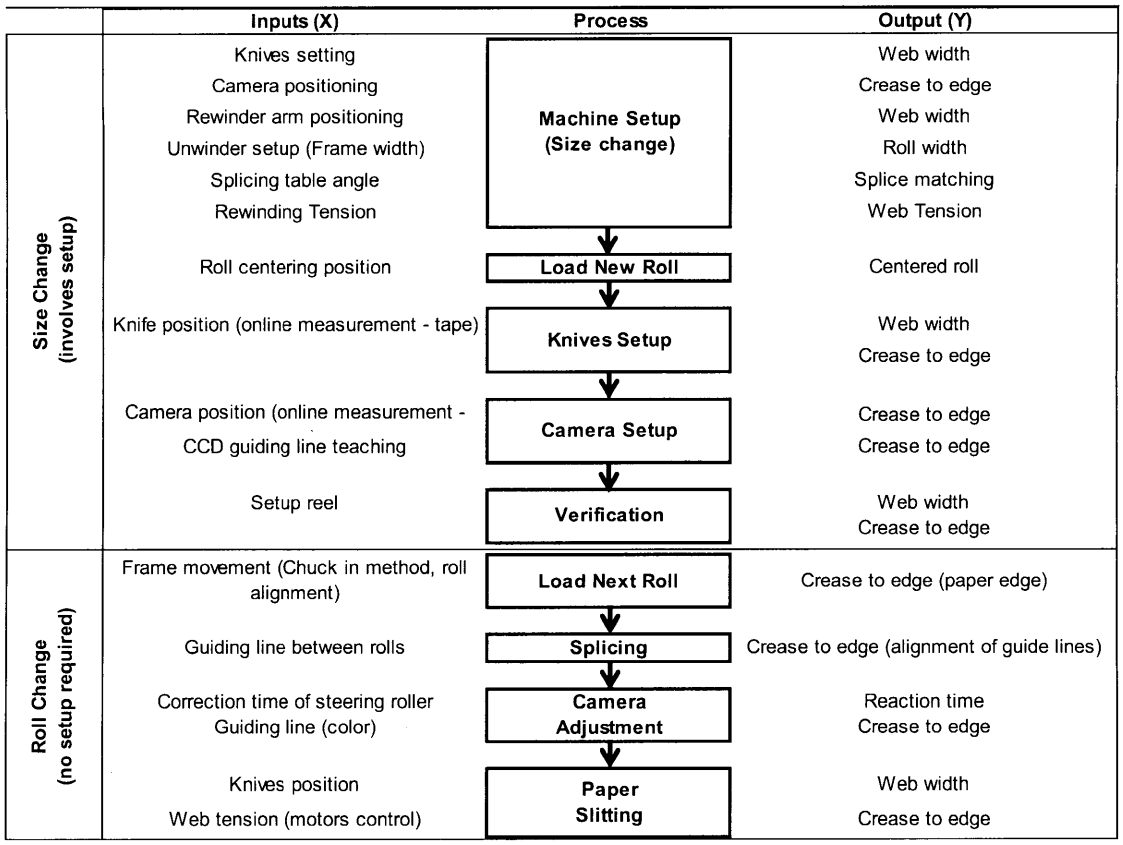


Figure 4.3 SIPOC Diagram

This diagram provides the detailed step sequence together with the identified inputs and outputs for different set of conditions. Two basic conditions during slitting process are change of roll and change of size. During the change of roll, it does not require any setup or restoration to basic conditions, since it is running at the same pack sizes. On the other hand, during the change of size, setup is necessary to restore the basic conditions since the roll size being slit is no longer the same as the previous one.

4.2 The Measure Step

The objective of this step is to evaluate and understand the current state of the process. This involves collecting data on measures of quality on the output from the process, i.e. slitting process. Using one of the basic tools of quality control, i.e. *Ishikawa Fishbone* Diagram, the KPIV (Key Process Input Variables) and KPOV (Key Output Process Variables) will be identified. Figure 4.4 below illustrates the fishbone diagram that has

been developed. In general, there are 6 main areas that contribute to the output quality, i.e. 6Ms (Man, Method, Machine, Materials, Milieu and Management). In the manufacturing process in particular, the first four factors are considered to be more significant contributors to the quality being measured, i.e. *man*, *method, machine* and *materials*.

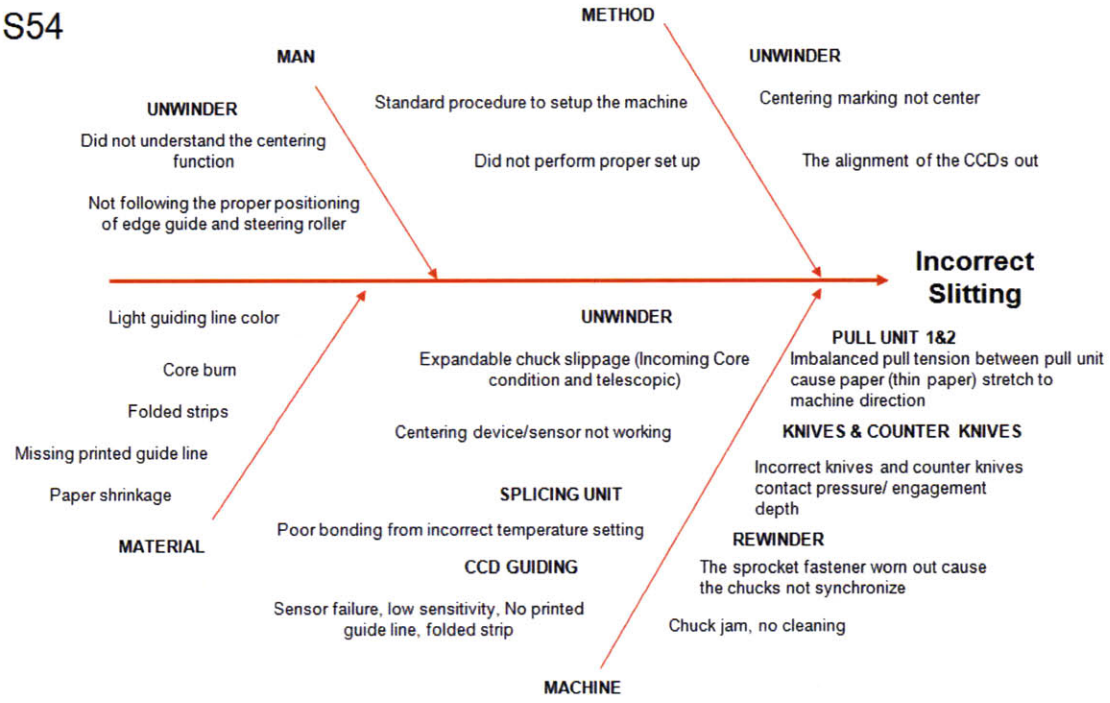


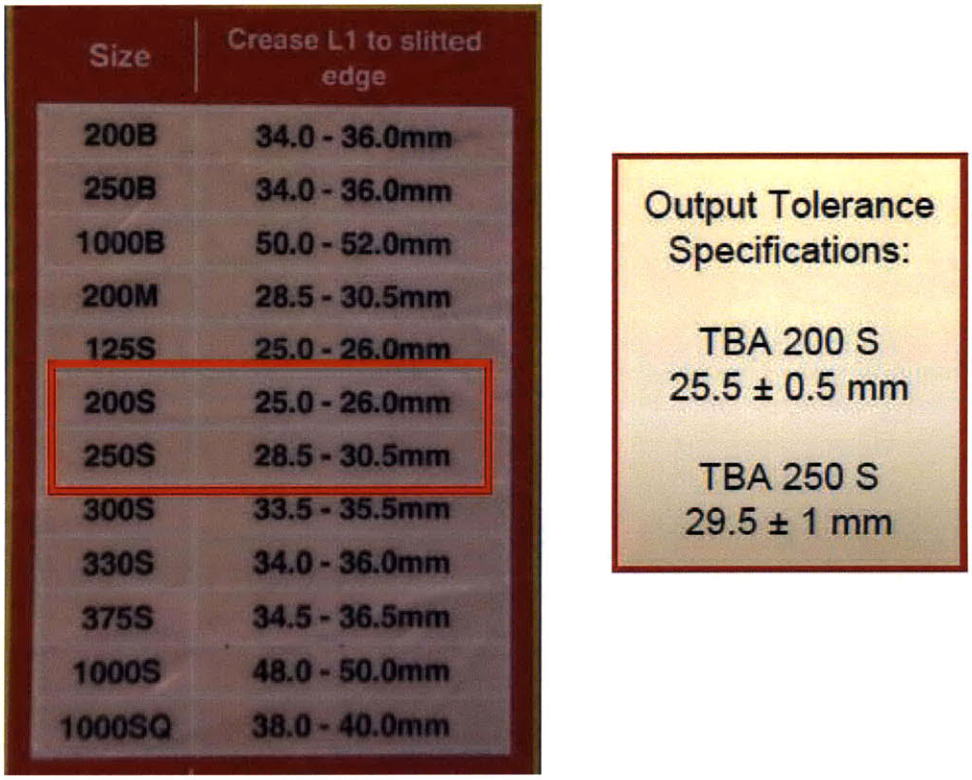
Figure 4.4 Ishikawa Diagram

Proper trainings were conducted at various sections on the slitting process to ensure consistency at the *man* factor. Standard operating procedures were also established to ensure the *method* reliability. Tighter tolerance specifications on the incoming *materials* (i.e. paper, aluminum foil and ink) were implemented in order to minimize variations to be brought downstream. The focus of this project is to fine-tune the *machine* parameters that are quantifiable in order to obtain the least variance at the optimum operating point. The KPOV of this project is crease-to-edge width (mm), which is illustrated in Figure 4.5 below. There are six machine parameters observed to be significant contributors to the variation in crease-to-edge width, traced from the beginning of the line up to point of cut, i.e. roll centering, splicing table, guiding line camera system, tension, knife setup

and positioning and the line speed. Roll centering requires a standard and fixed reference point to achieve consistency in the procedure. Alignment at splicing table during the splice currently is using the operator's rough estimation by sight which might only be accurate up to certain accuracy (~ 1 mm). Guiding line camera system is auto-feedback control system that helps to re-align shifted paper back to its original position. During the realignment, the steering roller will make transient-state adjustments to bring the paper back to its preset position. All of these above-mentioned factors will contribute to the overall variation in the process. The KPIV of this project are the quantifiable machine parameters, namely tension, line speed and knife setup and positioning.

Figure 4.5 Crease-to-Edge Width

Since there are various sizes being run in the factory, the attention will be focused into two most frequently produced sizes at slitter 54, i.e. TBA (Tetra Brik Aseptic) 200 mL slim and 250 mL slim. The tolerance range specifications are 25-26 mm for 200 mL slim and 28.5-30.5 mm for 250mL slim as it can be seen from Figure 4.6 below.



Size	Crease L1 to slitted edge
200B	34.0 - 36.0mm
250B	34.0 - 36.0mm
1000B	50.0 - 52.0mm
200M	28.5 - 30.5mm
125S	25.0 - 26.0mm
200S	25.0 - 26.0mm
250S	28.5 - 30.5mm
300S	33.5 - 35.5mm
330S	34.0 - 36.0mm
375S	34.5 - 36.5mm
1000S	48.0 - 50.0mm
1000SQ	38.0 - 40.0mm

Figure 4.6 Crease-to-Edge Width Tolerance Specifications

After the key process input and output variables have been defined and measured, the process capability of the slitting process at slitter 54 will then be calculated to have a better understanding of the current status of the process. The key process variable to characterize the process capability of slitting process is the crease-to-edge width.

Two kinds of indices are utilized in this project to calculate the process capability, i.e. C_p and C_{pk}. They are defined as follows:

$$C_p = \frac{USL - LSL}{6\sigma}$$

$$C_{pk} = \min\left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right]$$

Where: USL = Upper Specification Limit

LSL = Lower Specification Limit

μ = process mean

σ = process standard deviation

The difference between C_p and C_{pk} is that C_p will not be able to detect the mean shift; it only estimates the overall capability of the process to manufacture. C_{pk} overestimates the process capability if the process target is not centered at the nominal value of the tolerance specifications. The process output is assumed to be approximately normal distributed. Table 4.1 below shows the relationship between process standard deviation (σ), process yield and process fallout in terms of parts per million (ppm). This process capability measured serves as the baseline performance of the process.

Table 4.1 Process Capability Level

Cpk	Sigma Level (σ)	Process Yield (%)	Process Fallout (ppm)
0.33	1	68.27%	317311
0.67	2	95.45%	45500
1.00	3	99.73%	2700
1.33	4	99.99%	63
1.67	5	99.9999%	1
2.00	6	99.9999998%	0.002

4.3 The Analyze Step

The purpose of this step is to use the data from the *measure* step to begin to determine the cause-and-effect relationships in the process and to understand the different sources of variability. The sources of variability can be categorized into two main types; i.e. common causes and assignable causes. Common causes are sources of variability that are embedded in the system or process itself; while assignable causes usually arise from an external source. Removal of a common cause of variability means changing the process while removing an assignable cause usually involves eliminating that specific problem. Tools that are used for this project are control charts, which is useful in separating common cause from assignable cause of variability; statistical hypothesis testing; confidence interval estimation; regression analysis and residual plots. The regression analysis and residual plots will be extensively used for analysis during the *improve* step.

4.3.1 Shewhart Control Charts

Shewhart control charts are also one of the basic statistical quality tools to determine whether or not a manufacturing process is in the state of statistical process control. This condition of statistically in control process is an essential part of the Design of Experiments (DoE) that will be implemented in the *analyze* step. They were used to check whether a process should undergo a formal examination in order to find out assignable causes. The ultimate goal is to minimize variability in the process.

4.3.2 Hypothesis Testing

Hypothesis testing is a statement about the values of the parameters of a probability distribution [5]. In a formal manner, there are two statements being prescribed in the *hypothesis testing*: the *null hypothesis* (H_0) and the *alternative hypothesis* (H_1) or commonly known as *two-sided alternative hypothesis*. There is a close connection between *shewhart control charts* and *hypothesis testing*. In every points being plotted in the control chart, we are testing the *null hypothesis* of μ_1 (expected mean) = μ_0 (process mean). Thus, points plotted within the control limits are equivalent to failing to reject the hypothesis of statistically in-control process and points plotted outside the control limits are equivalent to rejecting this hypothesis.

4.3.3 Confidence Interval Estimation

Confidence Interval is an interval estimate of a parameter between two statistics with some probability. This tool provides the indication of the reliability of an estimate. Two metrics commonly used for this tool: confidence level (i.e. how likely the interval will contain the parameter) and confidence limits (i.e. the end points of the confidence intervals). This tool holds the assumption of normally distributed population from which the samples were being taken from, and they must be independent of each other.

4.3.4 Linear Regression Model

Linear Regression Model is a mathematical model to linearly-correlate between two or more variables to find out the relationships for prediction, process optimization or process control. There are two basic parts in the model, i.e. the *dependent variable* (*response*), often uses y as the variable; and the *independent variables* (*predictors* or *regressors*), commonly expressed as $x_1, x_2, x_3 \ldots, x_k$. The true functional relationship is unknown, and the regression model is used to fit to a set of sample data. The general expression is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon$$

where: y = response (dependent variable)

β = regression coefficients

x = repressor (independent variables)

ε = the error term

4.3.5 Residual Plots

Residual Plot is a graph that shows the residuals on the vertical axis and the independent variables on the horizontal axis. If the points in the residual plot are randomly distributed around the horizontal axis, the linear regression model is a good approximation for the data; otherwise a non-linear model is more appropriate. One example of the residual plot that shows a random pattern is shown in Figure 4.7 below.

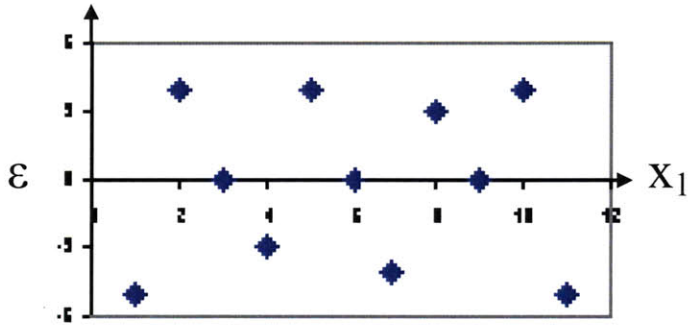


Figure 4.7 Random Patterns in a Residual Plot

4.4 The Improve Step

At this stage, creative thinking about the specific changes that can be made in the process is essential, in order to achieve the optimized process performance. Design of Experiments (DoE) and Response Surface Model (RSM) are the tools to be used at this stage.

4.4.1 Design of Experiments (DoE)

DoE is most probably the most important statistical tool in the *improve* step. It will be applied to an actual physical process to determine which factors influence the outcome of a process, the sensitivity of each factor and the optimal combination of factor settings. Two factors being analyzed through DoE are main pull-unit web tension (N) and re-winder tension (%). A full 2^2 factorial design of experiments plus a center point was chosen so that both factors could take on maximum and minimum values, and the center point was designed for curvature. Using this design, the process will be run at five different design points (2^2 + center point). This five design points will be applied to two most frequently produced pack sizes, i.e. 200 mL slim and 250 mL slim. The material used for this experiment is *klabin* paper, with stiffness of 80 mN for 200 mL slim and 115 mN for 250 mL slim. The same type of material was used in order to achieve consistency and better reliability in the analysis and also to minimize variations that come from the *material* factor. The allowable range for the pull-unit web tension is from 1650 N to 1800 N and for re-winder tension is from 65% to 80% from the maximum tension. Furthermore, three replicates are run at each design point so that the variance at each design point could be calculated. The table of two sets of design points for this particular DoE is shown in Table 4.2 below.

Table 4.2 Design of Experiments Table

Experiment	Size	Pull Unit Tension (N)	Rewinder Tension (%)	No of Runs
1	200S	1650	85%	3
2	200S	1650	65%	3
3	200S	1800	85%	3
4	200S	1800	65%	3
5	200S	1725	75%	3
6	250S	1650	75%	3
7	250S	1650	55%	3
8	250S	1800	75%	3
9	250S	1800	55%	3
10	250S	1725	65%	3

4.4.2 Response Surface Model

Response Surface Model (RSM) is a model that explores the relationships between the independent variables and the response (dependent variable). This model uses a sequence of *designed experiments* to obtain an optimal response through optimum operating points for each factor being analyzed. This model is only an approximation, but nevertheless is still useful and widely used for an optimized performance, since it is easy to estimate and apply, even when little is known about the process. The example of *response surface model* is illustrated in Figure 4.8 below.

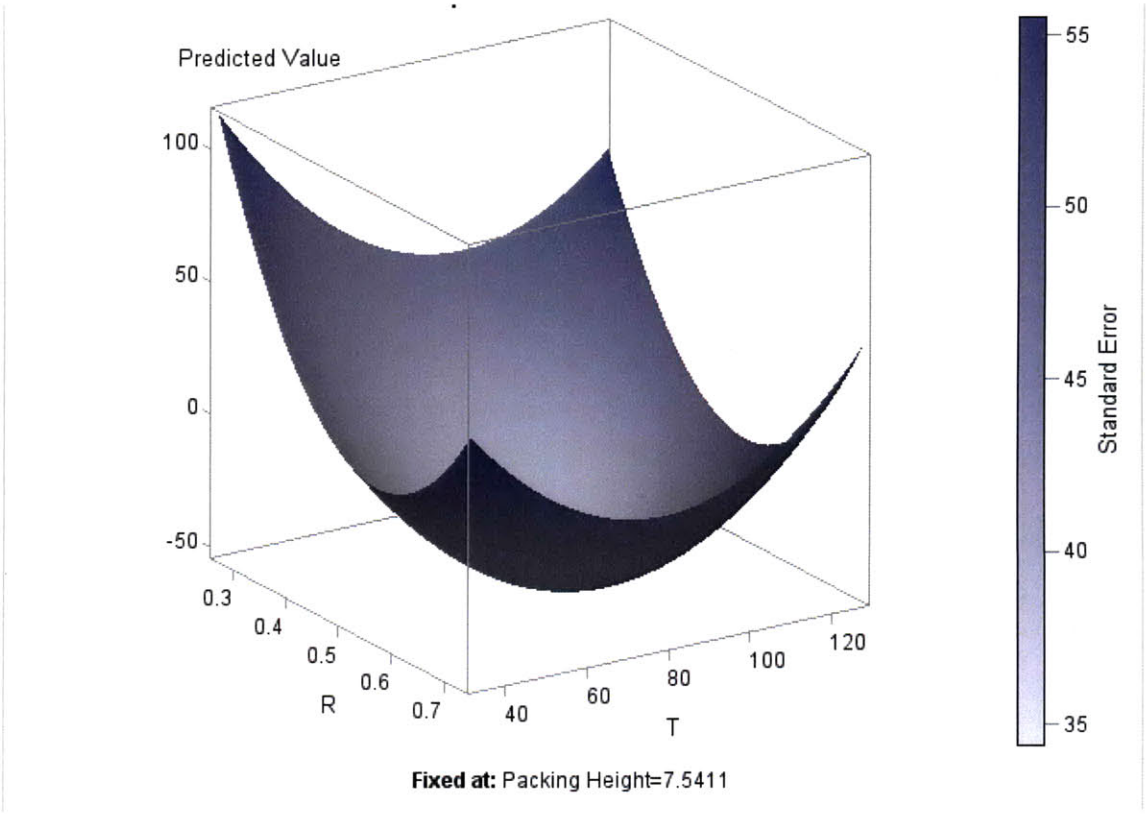


Figure 4.8 Example of Response Surface Model [7]

4.5 The Control Step

The objectives of this last step in DMAIC problem solving process are to complete all of the remaining work on the project and to hand off the improved process back to the process owner along with a process control plan and other necessary procedures to ensure that the gains from the project will be implemented. Two statistical tools are used for this stage: *Shewhart control charts* and *Out-of-Control Plan* (OCAP).

4.5.1 Shewhart Control Charts

After eliminating the assignable causes that had been identified in the *analyze* step and optimizing the process performance, the new samples will be collected for verification.

Phase two process screening and monitoring through the control charts will be implemented. The observed results will then be verified with the analysis done in the previous step. In addition, the review of process performance will be done periodically in the future as a measure of effectiveness and sustainability.

4.5.2 Out-of-Control Action Plan (OCAP)

A *Out-of-Control Action Plan* (OCAP) will be drafted to provide detailed instructions on step-by-step actions that should be taken if there is an out-of-control point was detected or an indication of out-of-control trend being observed. This plan serves as a set of corrective actions that could effectively help the operators or production people to remove the unnecessary disturbances and assignable causes in the system. The objective is to sustain a stationary and stable process throughout. The ability to respond rapidly to unanticipated failures will also be factored into the plan.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the results and analysis from the data collected through Design of Experiments (DoE) in the production floor. It presents the current level of system performance, the cause-and-effect relationships with different sources of variability in the slitting process. The specific changes that could be made to achieve optimized process performance will be presented in the next chapter under recommendations section.

The experimental objective is to measure the effect of tension (both at the main pull-unit and the rewinder section) on the crease-to-edge width (the output variable). The experiments are conducted through a few steps. The first step is to restore the machine to basic conditions. This can be done during the change of size at slitting process (setup period). In these experiments, there were two restorations of basic conditions, i.e. 200 mL slim and 250 mL slim. During setup, the knives' positioning have to be reset, the guiding line camera system has to be re-positioned, rewinder arms are adjusted to fit into the current size and the unwinder section (frame width) is also adjusted to match with the incoming roll size. The splicing table angle is also fine-tuned to align it with the current pack size. The knives' positioning in the current situation is done through a manual measurement using a measuring tape to decide whether or not the slitting point for each pack is in the correct position.

After all these steps are done, the incoming roll will be run into the machine. The products are called slitted reels or webs. This indicates the start of production process. One roll of paper could produce up to two and a half set of reels. The quantity of webs per reel differs, depending on the size. For 200 mL slim size, one set of slitted reels consists of 9 webs. For 250 mL slim size, one set consists of 8 webs. The data (i.e. the

crease-to-edge width of the reels or webs – left or right side, as it can be seen from Figure 4.5) starts to be collected once the restoration to basic condition is done. The data are collected through the real-time camera measurement system (newly installed system which is fully operating during the improve phase of this project), which can only measure one slitted reel or web at one time. The camera is able to move laterally to capture different measurements at different positions across the roll width as shown in Figure 5.1 below. The measurements taken are based on meter count, which means that one data point is taken for each meter of material. Figure 5.2 shows the close-up view of the camera system installed at slitter 54.

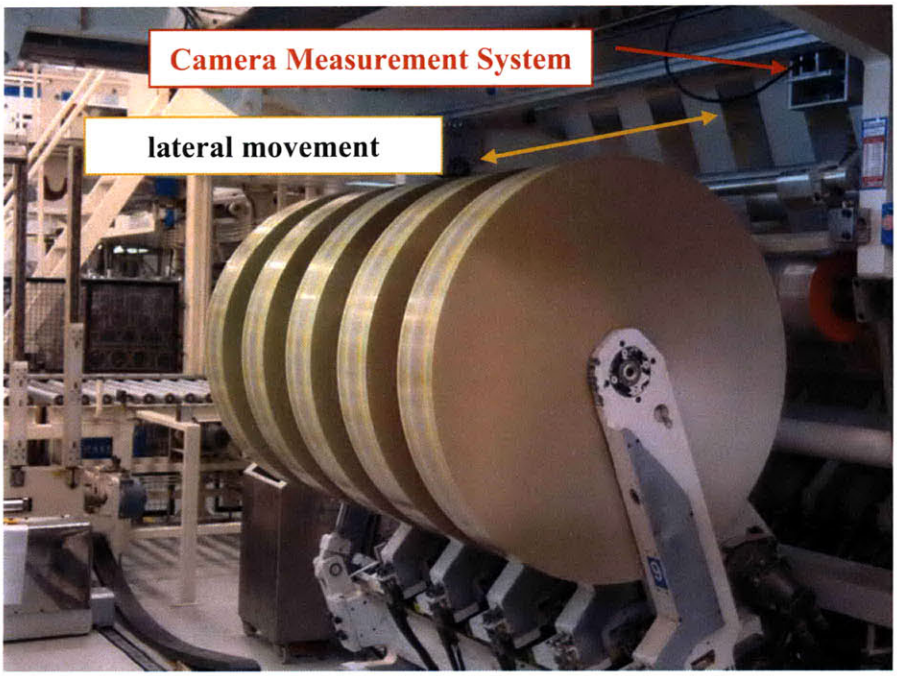


Figure 5.1 Real-Time Camera Measurement System

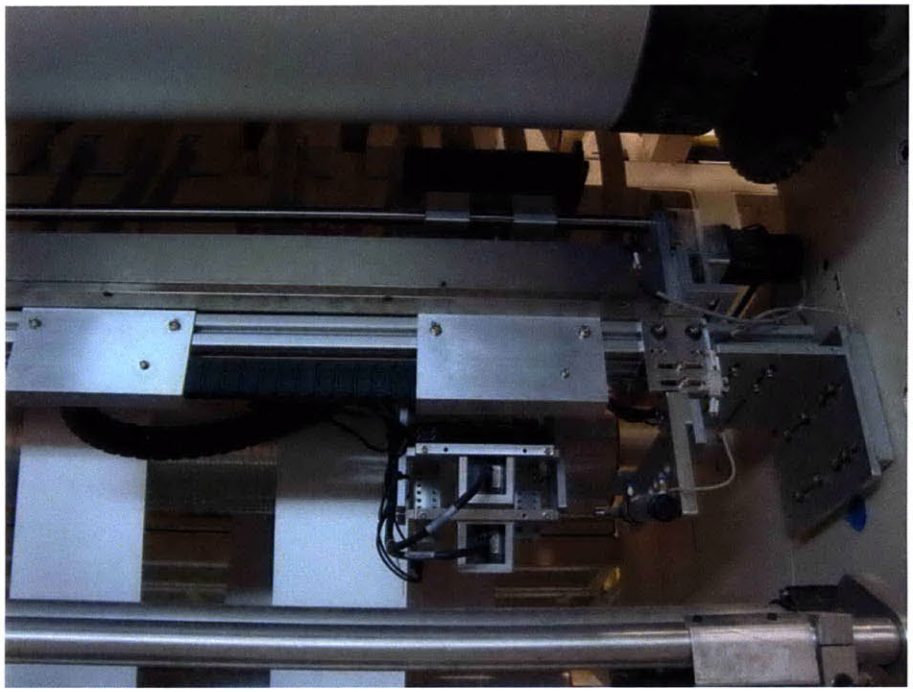


Figure 5.2 Close-Up View of Camera Measurement System

This camera works through the encoder which is synchronized with the main pull-unit roller to capture the meter run of material. The encoder will trigger the camera to capture an image at a maximum speed of 1000 m/min, i.e. almost 17 captured images per second, for every meter run of material. These images are then processed to measure the crease-to-edge width of that particular reel where the camera is initially positioned. The data is captured in a text file and also being plotted in the real-time run chart displayed on the computer screen near to the operator working space. Before it is fully operating, proper calibration of the camera system has to be done, such as the lighting intensity and the pixel conversion and scaling to actual meter width of the material.

From the ANOVA results, it is found that for 200 mL slim pack size, the variance could be assumed constant within the allowable operating range with different tension setting combinations. And for 250 mL slim pack size, the response variance is uniform across all points in the allowable setting range.

5.1 Process Capability Analysis

The current process capability at slitter 54 is calculated based on two of the most frequently produced pack sizes, i.e. 250 mL slim and 200 mL slim. The type of the paper being analyzed for these two pack sizes is *Klabin*, which is the major type of paper (around 70% of total production) at CXJ. Data collected were based on the steady-state speed of 800 m/min. The transient-state data (i.e. ramp up and slow down stage) were removed since the accuracy and validity of the data are critical to the reliability of the analysis. The preset states for the current performance are as follows:

Table 5.1 Preset State for 200 mL Slim and 250 mL Slim

Recipe	Pull Unit Web Tension (N)	Rewinder Tension (%)
200 slim	1650	70%
250 slim	1800	65%

Ensuring a state of statistical control is also essential to the correct interpretation of any process capability analysis. If the process is not in control, its parameters become unstable and the future value for these parameters in the future would be uncertain. Thus, it would be inaccurate to predict the process capability of current performance if the process is not stable. One of the indicators of an out-of-control process is out-of-control points, i.e. below or above the control limits. However, it is a common practice to compute process capability from a sample of historical data without any consideration as to whether the process is in the state of statistical process control [5]. Figure 5.3 and 5.4 below illustrate the XBar control chart from the data collected for 250 mL slim and 200 mL slim respectively. Figure 5.5 and 5.6 further explain the state of current system performance in terms of moving range (i.e. the difference between two successive data points) from each meter run for 250 mL and 200 mL respectively.

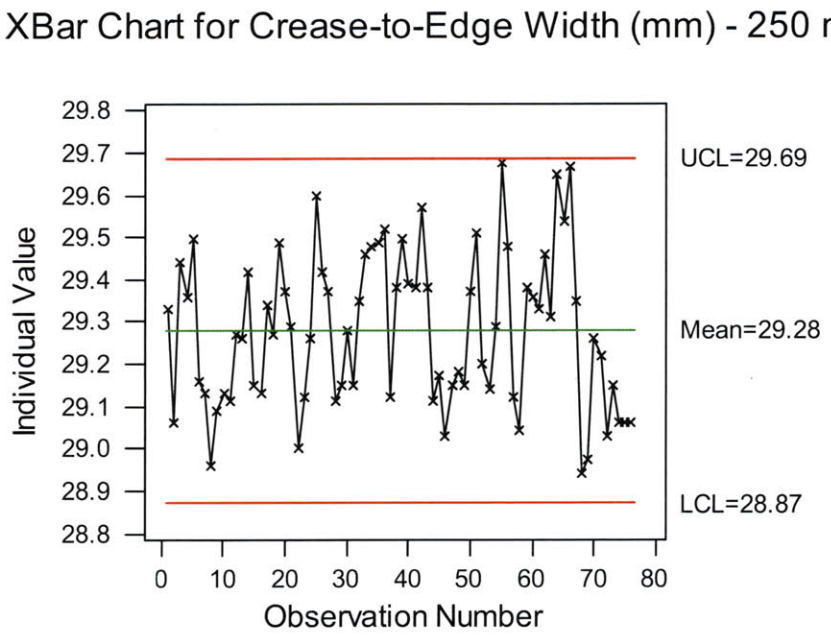


Figure 5.3 XBar Control Chart for 250 mL Slim

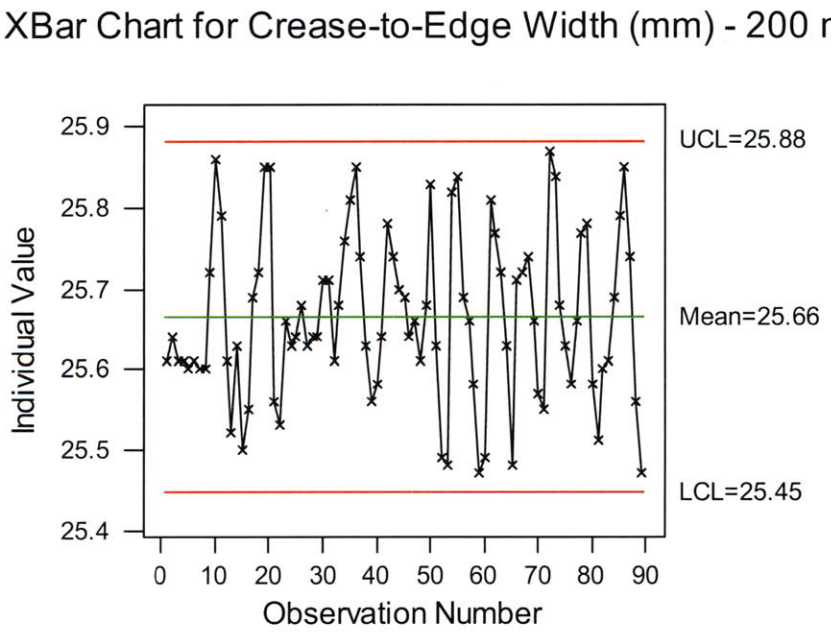


Figure 5.4 XBar Control Chart for 200 mL Slim

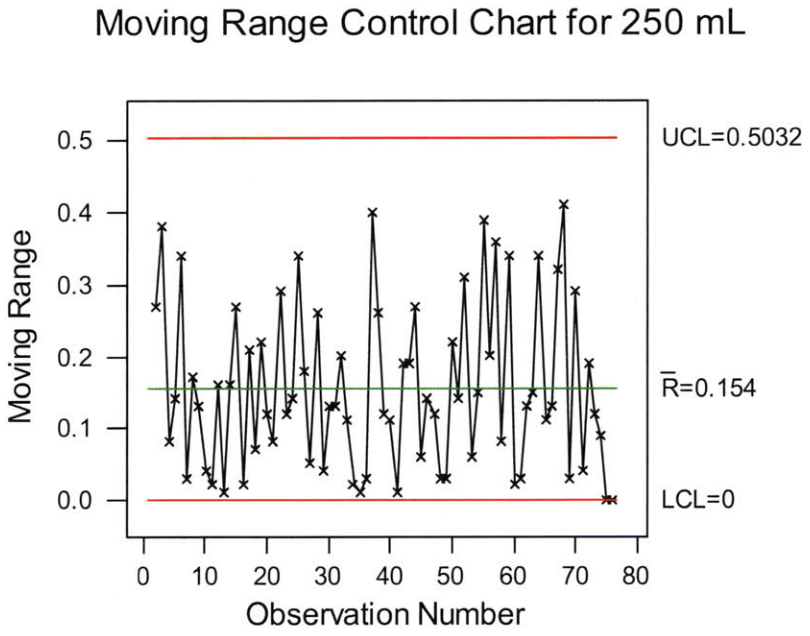


Figure 5.5 Moving Range Control Chart for 250 mL Slim

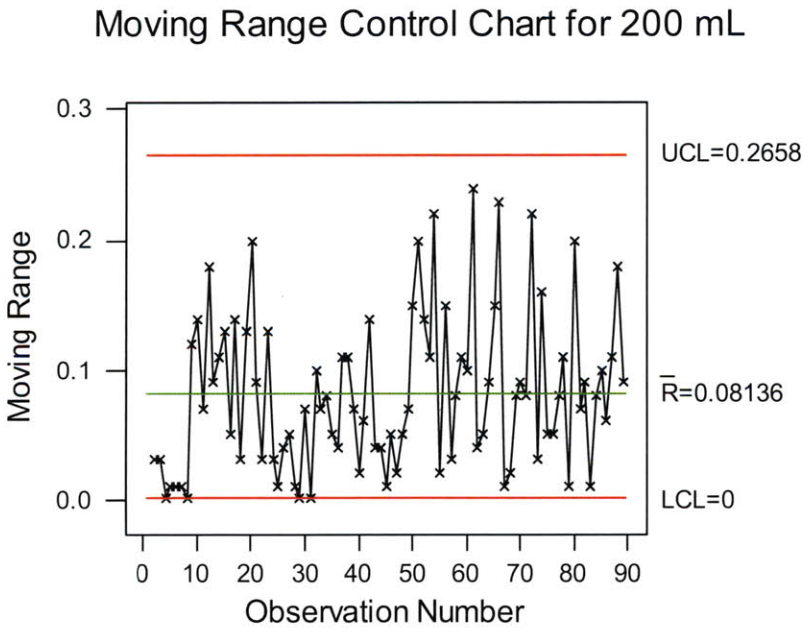


Figure 5.6 Moving Range Control Chart for 200 mL Slim

In practice, what we observe is an estimate of process capability. This estimate is subject to error in estimation since it depends on sample statistics. Hence, it is a useful idea to report the estimate in terms of a confidence interval. The process capability estimation for current process performance at CXJ is shown in Figure 5.7 and 5.8 below for 250 mL and 200 mL respectively. Using the Anderson-Darling normality test, with 99% confidence interval (i.e. $A^2 < 1.029$), it can be seen from Figure 5.9 and 5.10 below that both could be assumed to have normal distributions for 250 mL slim ($A^2 = 0.936$) and 250 mL slim ($A^2 = 0.75$) respectively.

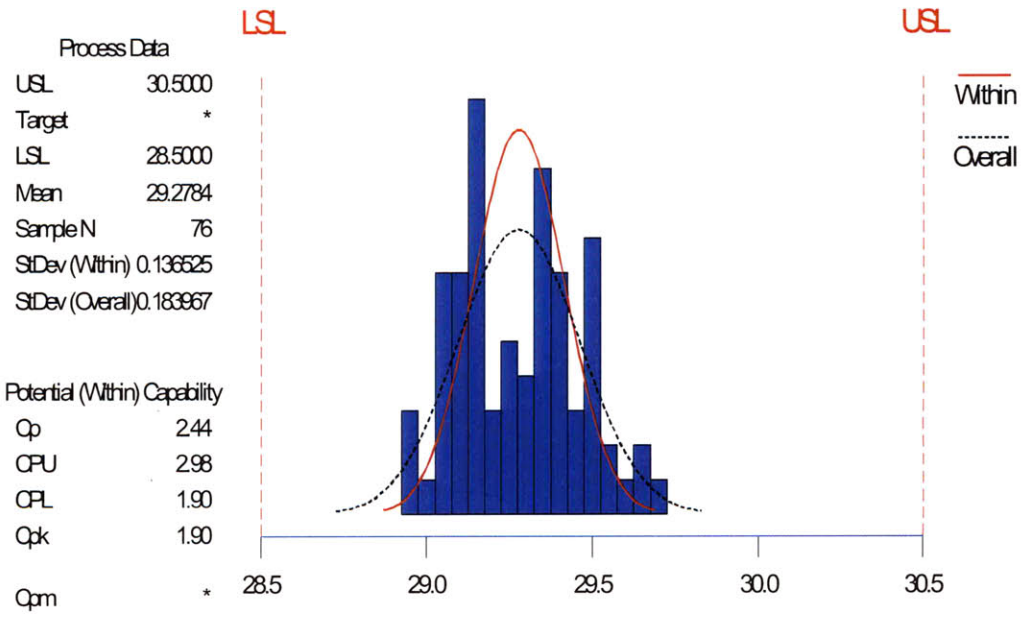


Figure 5.7 Process Capability Analysis for 250 mL Slim

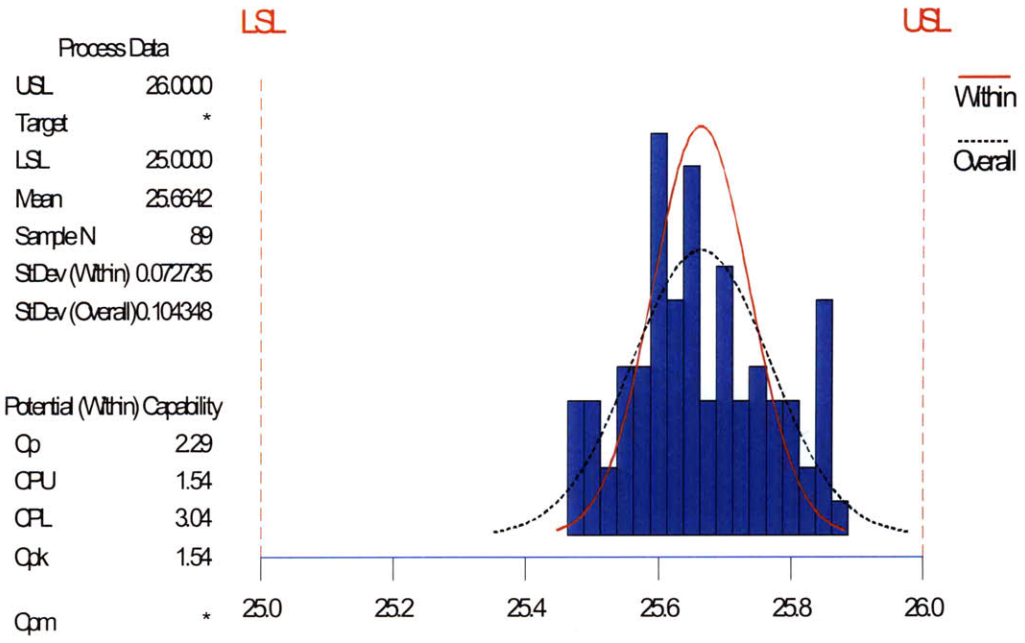


Figure 5.8 Process Capability Analysis for 200 mL Slim

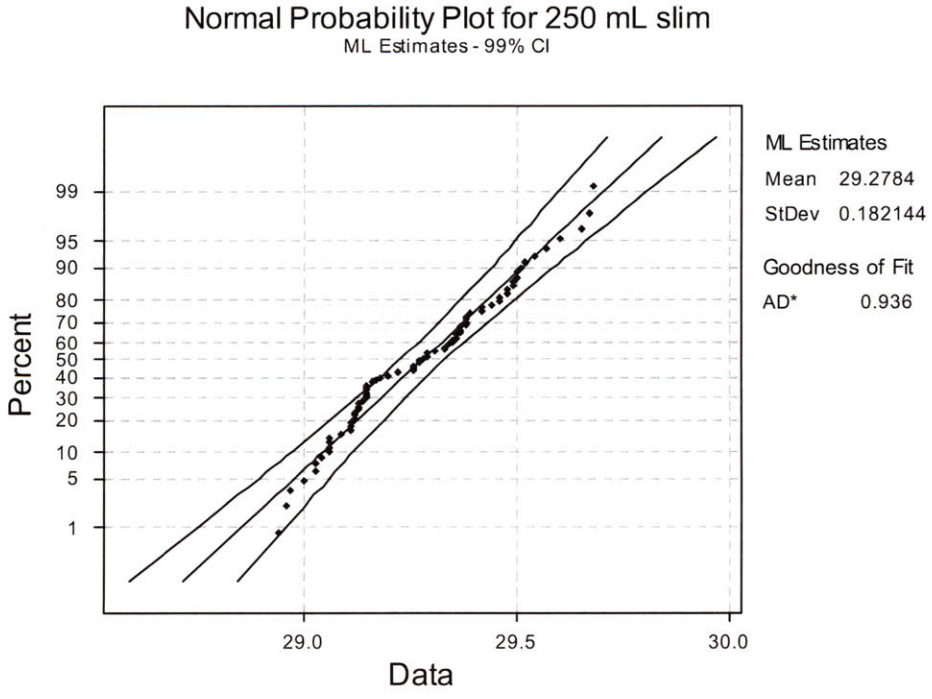


Figure 5.9 Anderson-Darling Normality Test for 250 mL Slim

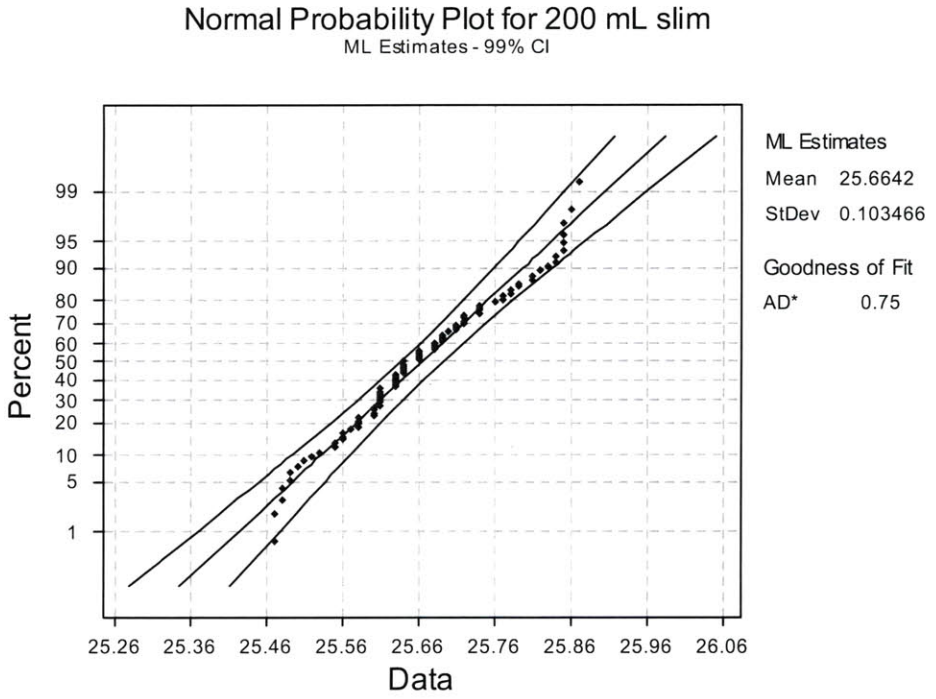


Figure 5.10 Anderson-Darling Normality Test for 200 mL Slim

From an industrial perspective, the process capability would be more often described in terms of an interval rather than a point estimate. This is because point estimates are subject to statistical fluctuation and therefore are not stable and not accurate at all times. The alternative is preferred and it has already become standard practice to report confidence intervals for process capability ratios. The Chi-Square distribution (χ^2) is used to find the intervals, since C_p is a measurement of variance.

If the quality characteristic follows a normal distribution, according to Montgomery's book on Statistical Quality Control [5], then a 100 (1-α)% confidence interval on C_p, where $\alpha = 0.05$, is as follows:

For 250 mL slim,

$$C_p\sqrt{\frac{\chi^2_{1-0.025,n-1}}{n-1}} \le C_p \le C_p\sqrt{\frac{\chi^2_{0.025,n-1}}{n-1}}$$

$$2.44\sqrt{\frac{52.9419}{76-1}} \le C_p \le 2.44\sqrt{\frac{100.8393}{76-1}}$$

$$2.05 \le C_p \le 2.82927$$

For 200 mL slim,

$$C_p\sqrt{\frac{\chi^2_{1-0.025,n-1}}{n-1}} \le C_p \le C_p\sqrt{\frac{\chi^2_{0.025,n-1}}{n-1}}$$

$$2.29\sqrt{\frac{63.9409}{89-1}} \le C_p \le 2.29\sqrt{\frac{115.8414}{89-1}}$$

$$1.952 \le C_p \le 2.6274$$

Generally, the process capability ratios for 200 mL slim are smaller as compared to 250 mL due to a tighter tolerance range being specified for 200 mL (± 0.5 mm) as compared to 250 mL (± 1 mm). Also, it can be seen that the current process capability is already good, but there is still a problem associated with the current process, i.e. the off-centered process for both sizes; i.e. 200 mL and 250 mL slim. Note that this off-centered process could potentially contribute to fluctuating occurrence of defect waste caused by incorrect slitting.

5.2 Shewhart Control Charts

Figure 5.11 and 5.12 show the run charts at default settings for both sizes; i.e. 250 mL and 200 mL slim respectively. Both run charts have been divided into two sections, i.e. ramp-up period and constant speed period at 800 m/min. For 250 mL slim, the mean values for ramp-up and constant speed period are 29.17 mm and 29.28 mm. The standard deviations are 0.21 mm and 0.18 mm for ramp-up and constant speed period respectively. For 200 mL slim, the mean value and the standard deviation at ramp-up period are 25.34 mm and 0.12 mm. At constant speed, the mean value and standard deviation are 25.31 mm and 0.11 mm. It is observed for both pack sizes, that there are some "adjustments" being made as the speed stabilizes; i.e. there is a mean shift in the process possibly caused by the transition from non steady-state to steady state condition. Another observation found for both pack sizes, 250 mL and 200 mL slim, is that the variation less fluctuates (smaller standard deviation value) at steady-state (constant speed) period. At steady-state, the process is stationary, and all state variables in the system (process) are constant; therefore less variation is observed.

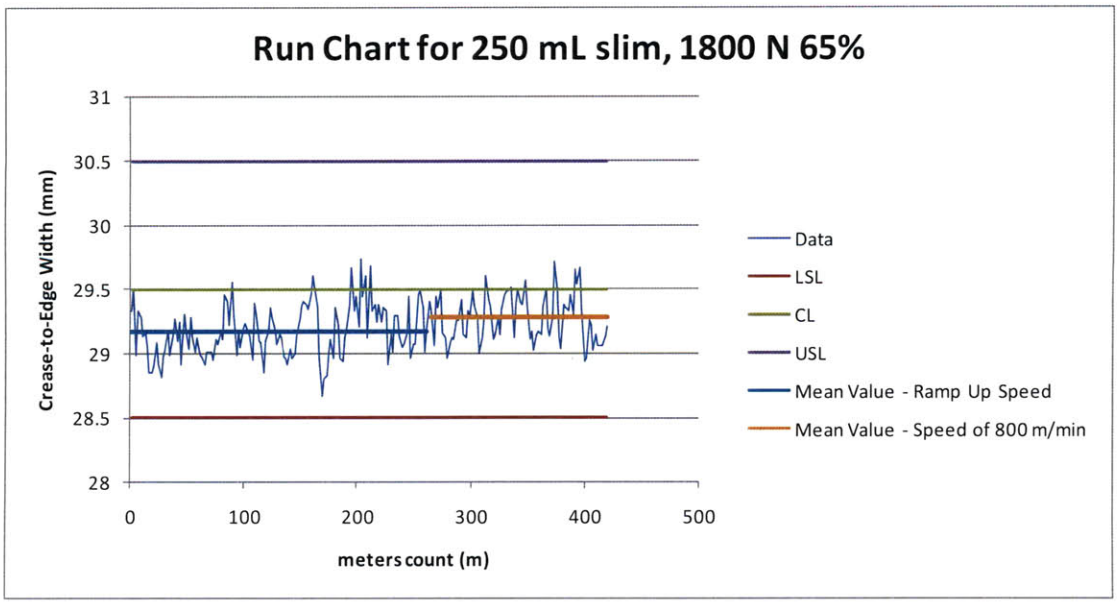


Figure 5.11 Run Chart for 250 mL Slim – Default Settings (1800 N, 65%)

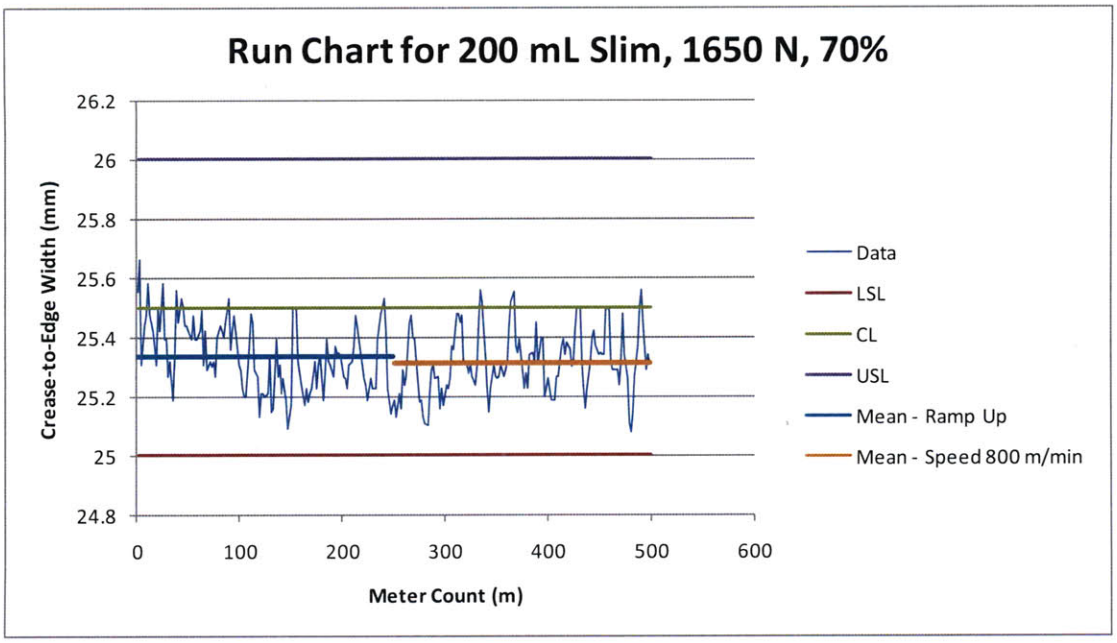


Figure 5.12 Run Chart for 200 mL Slim – Default Settings (1650 N, 70%)

In the Design of Experiments (DoE) being conducted, there are a total of 5 design points for each pack size; i.e. 2^2 + center point. The next step is to check whether the process remains stationary for all five design points in the experiments being conducted using control charts. And from here onwards, the further analysis on the experimental data is based on the steady-state period (constant speed of 800 m/min) where the process is stationary. Control limits of $\pm 3\sigma$ are selected to decrease to decrease the risk of type I error. Type I error is a false alarm concluding the process is out of control when it is in fact in control.

For 250 mL slim, at default setting, both control charts (X-Bar and Moving Range) have already been presented earlier in Figure 5.3 and 5.5 respectively and both show that the process is in control. For the 2nd design point, at pull unit web tension of 1650 N and rewinder tension of 65%, the control charts are shown in Figure 5.13 (XBar) and 5.14 (Moving Range) respectively. The mean value is 28.81 mm and its standard deviation is 0.20 mm. As we can observe from the two figures (Figure 5.13 and 5.14), the process is not in the state of statistical control because of the out-of-control points. This could be possibly caused by lateral shift of the paper which is then being re-adjusted back using

the auto feedback control from the guiding line camera system – steering roller alignment.

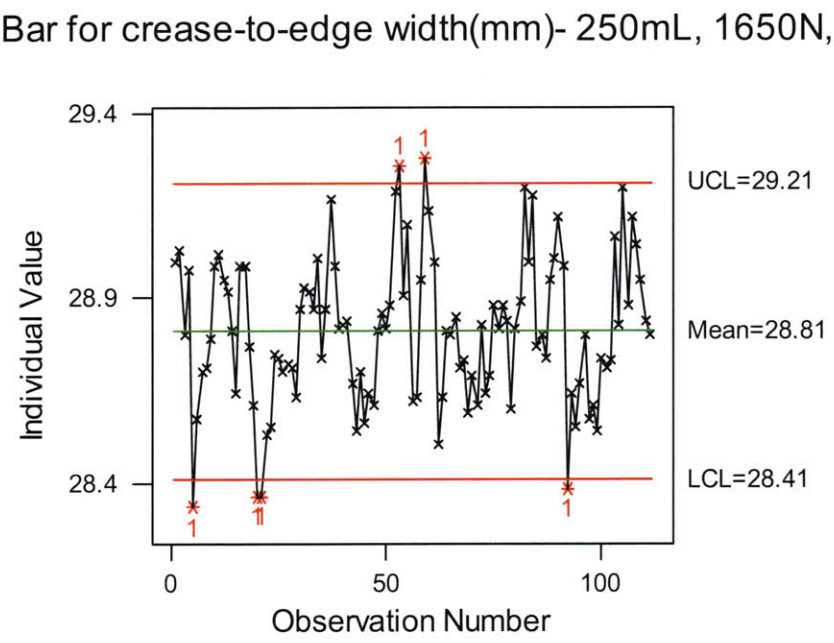


Figure 5.13 XBar Chart for 250 mL Slim – 1650 N, 65%

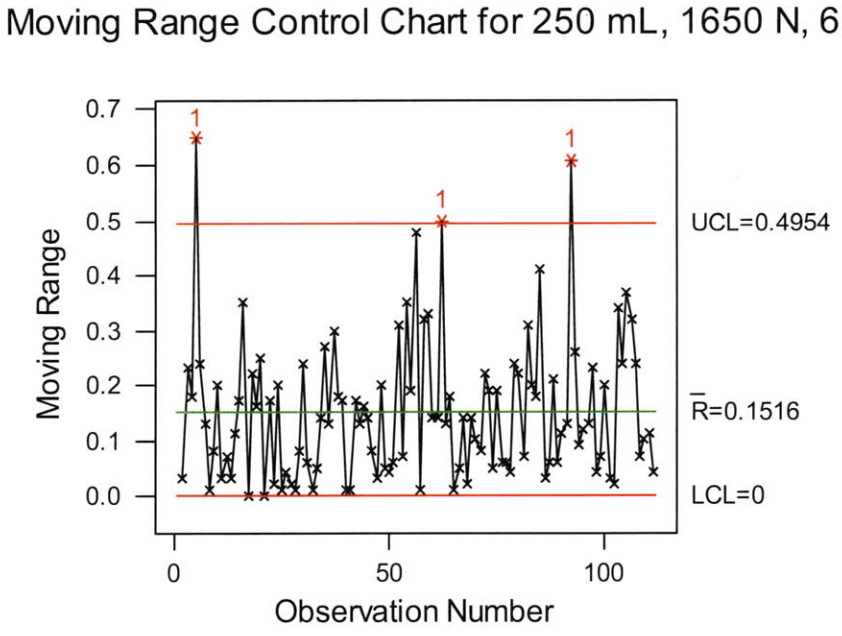


Figure 5.14 Moving Range Chart for 250 mL Slim – 1650 N, 65%

When the out-of-control points are removed, the new control charts (as shown in Figure 5.15 and 5.16) for this setting show that the process is in control.

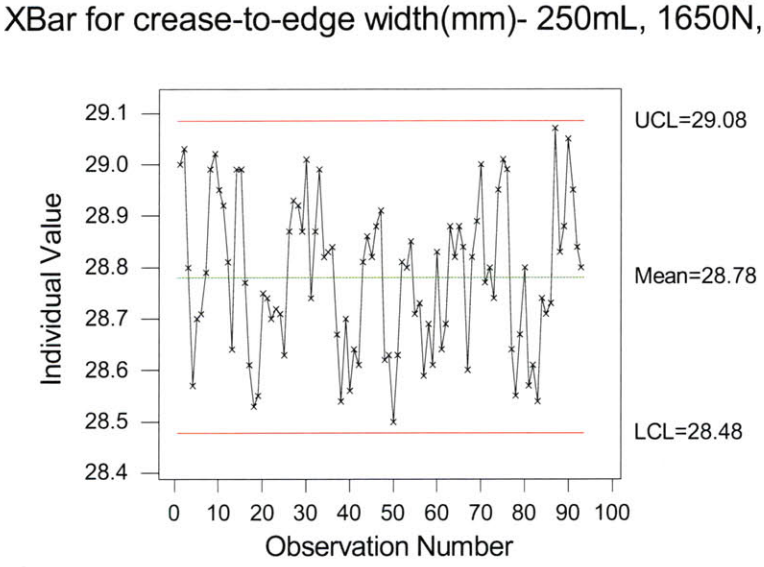


Figure 5.15 Corrected XBar Chart for 250 mL Slim – 1650 N, 65%

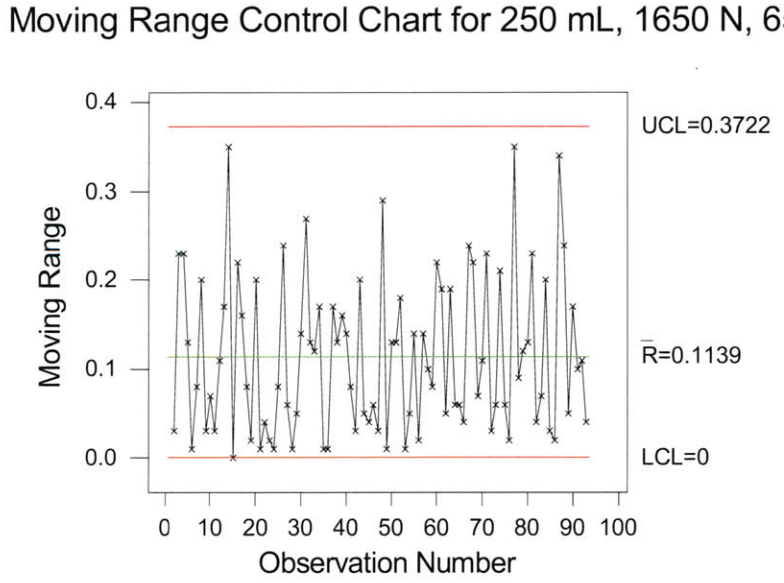


Figure 5.16 Corrected Moving Range Chart for 250 mL Slim – 1650 N, 65%

The corrected mean value and its standard deviation are 28.78 mm and 0.15 mm. These steps were repeated for the rest of design points for both pack sizes in order to assure the reliability of analysis and to ensure that the process is stationary.

At the 3rd design point, which has the settings of main pull-unit web tension of 1800 N and rewinder tension of 80%, the control charts are shown in Figure 5.17 for X-Bar chart and Figure 5.18 for Moving Range chart. The calculated mean value and standard deviation are 28.75 mm and 0.13 mm respectively.

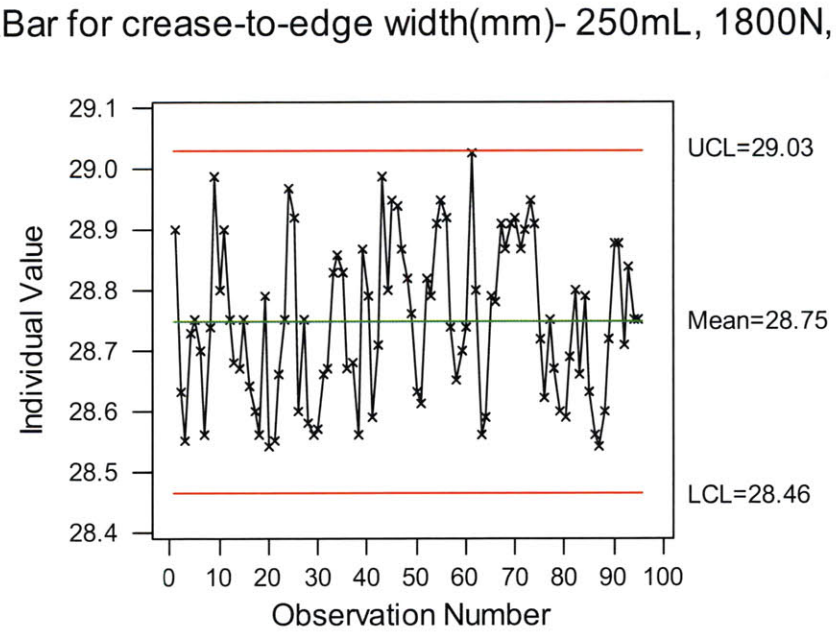


Figure 5.17 XBar Chart for 250 mL Slim – 1800 N, 80%

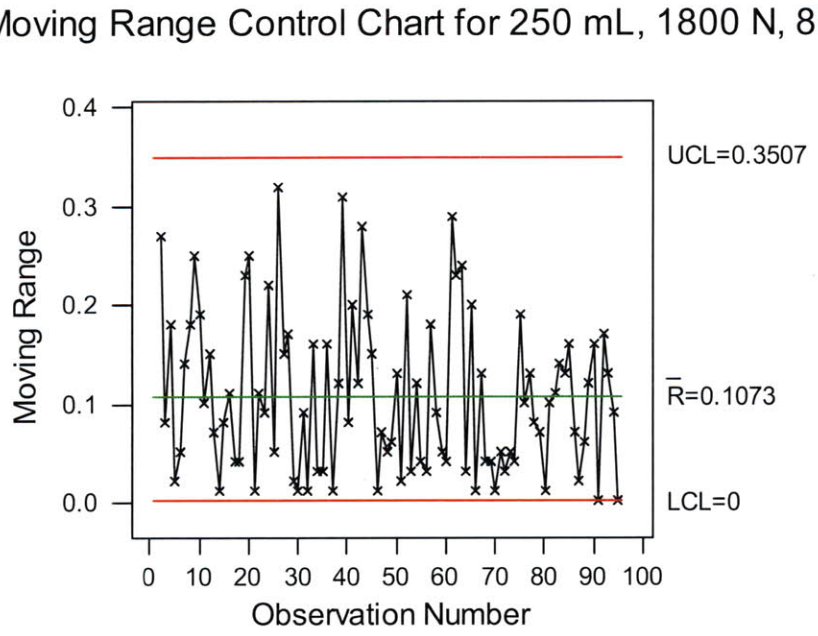


Figure 5.18 Moving Range Chart for 250 mL Slim – 1800 N, 80%

At the 4th design point, which has the settings of main pull-unit web tension of 1650 N and rewinder tension of 80%, the control charts are shown in Figure 5.19 for X-Bar chart and Figure 5.20 for Moving Range chart. Its mean value and standard deviation are 28.88 mm and 0.17 mm respectively.

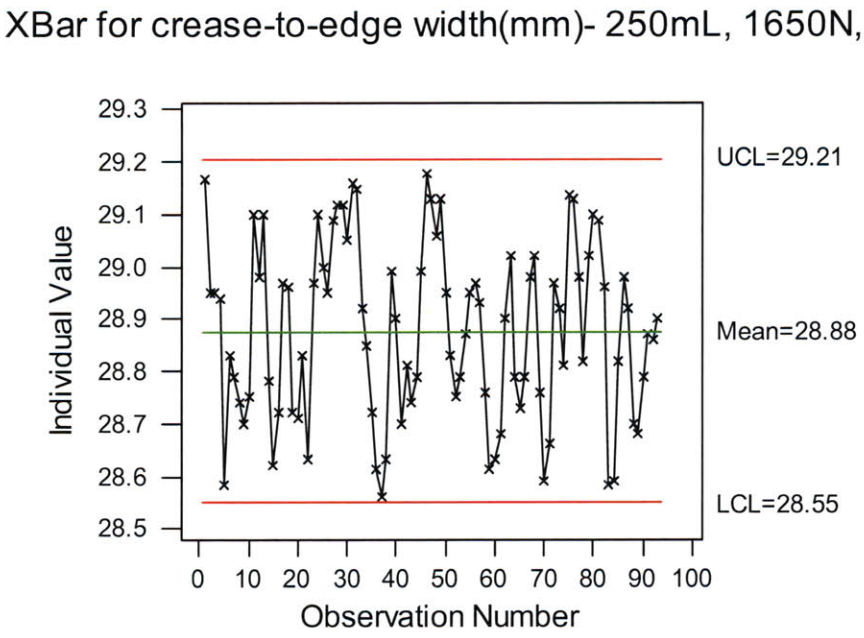


Figure 5.19 XBar Chart for 250 mL Slim – 1650 N, 80%

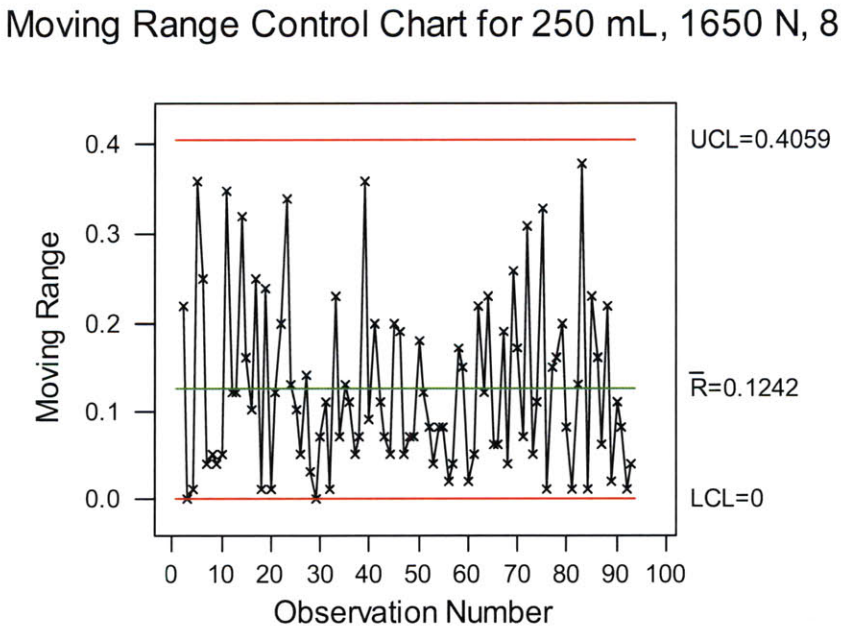


Figure 5.20 Moving Range Chart for 250 mL Slim – 1650 N, 80%

At the 5th design point, which has the settings of main pull-unit web tension of 1650 N and rewinder tension of 80%, the control charts are shown in Figure 5.21 for X-Bar chart and Figure 5.22 for Moving Range chart. Its mean value and standard deviation are 29.02 mm and 0.21 mm respectively.

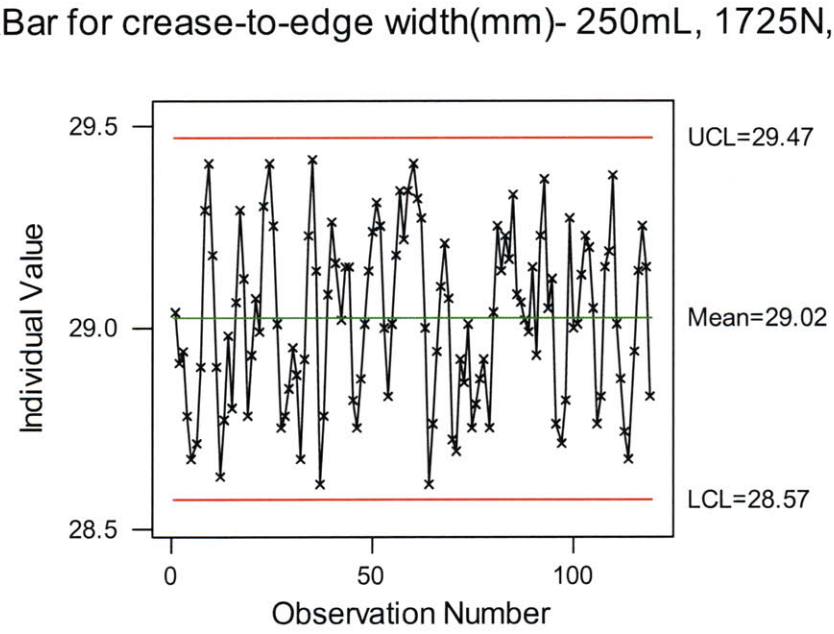


Figure 5.21 XBar Chart for 250 mL Slim – 1725 N, 73%

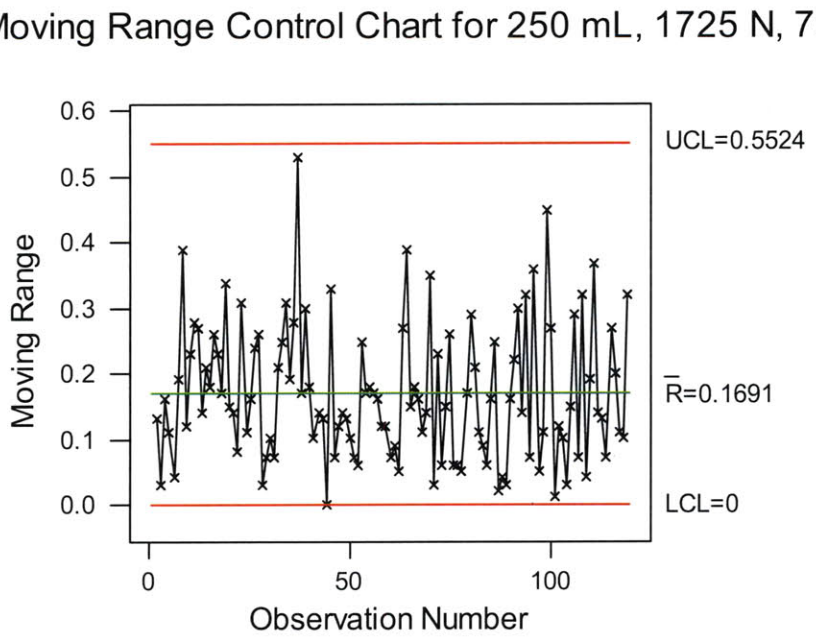


Figure 5.22 Moving Range Chart for 250 mL Slim – 1725 N, 73%

The same procedure applies for 200 mL pack size, and the result is tabulated in Table 5.2 below. As it can be observed from the data points being collected, the mean value for each design point keeps changing. This could be due to the manual setting of the knives by the operator, and the setting differs from one operator to another operator. The knives' positioning is currently subjectively decided by the operators who were taking the manual measurements using measuring tape for adjustment. This could contribute to variability and assignable causes (identifiable factors that cause the variation) in the system. Also, the paper shrinkage inherited from the upstream processes could also contribute to the mean shift in the process. When splicing from one roll to another, it might also affect the variability in the mean value of crease-to-edge width being measured. If the knives' positioning is accurately calibrated with a proper measurement system, the process could be re-centered. Hence, the focus of this analysis will be on the variance model of the data.

Table 5.2 Mean and Standard Deviation for 200 mL Slim at 5 Design Points

200 mL slim	Mean (mm)	Std Dev (mm)
1650 N 70%	25.31	0.11
1800 N 70%	25.29	0.16
1800 N 85%	25.39	0.12
1650 N 85%	25.25	0.14
1725 N 78%	25.34	0.11

After verifying that all of the design points at each particular setting are stationary, the next steps are the Design of Experiments (DoE) and ANOVA (Analysis of Variance). The objective is to find the sensitivity of tension towards the output, i.e. crease-to-edge width.

5.3 Design of Experiments

At each slitter setting, a 2^2 full factorial design with a center point is used to study the significance of tension on the crease-to-edge width variance (output variance). The two input factors are the pull-unit web tension and rewinder tension and their ranges were scaled to [-1, 1], which is standard for regression analysis. Table 5.3 and 5.4 show the output of the DoE for 200 mL and 250 mL respectively. Note that x1 is used to represent main pull-unit web tension and x2 is used to represent the rewinder tension percentage.

Table 5.3 Experimental Data for 200 mL Slim at 5 Design Points

Actual Values	Pull Unit Tension (x1)	Rewinder Tension (x2)	x1 . x2	Std Dev (mm)	Variance
1650 N 70%	-1	-1	1	0.11	0.011
1800 N 70%	1	-1	-1	0.16	0.024
1800 N 85%	1	1	1	0.12	0.015
1650 N 85%	-1	1	-1	0.14	0.020
1725 N 78%	0	0	0	0.11	0.012

Table 5.4 Experimental Data for 250 mL Slim at 5 Design Points

Actual Values	Pull Unit Tension (x1)	Rewinder Tension (x2)	x1 . x2	Std Dev (mm)	Variance
1800 N 65%	1	-1	-1	0.18	0.033
1650 N 65%	-1	-1	1	0.15	0.021
1800 N 80%	1	1	1	0.13	0.017
1650 N 80%	-1	1	-1	0.17	0.029
1725 N 73%	0	0	0	0.21	0.045

The variance was calculated by averaging the output values (about 100 data points) at each of the five design points for both pack sizes. The models chosen to represent the variance for 200 mL, σ^2_{200mL} and 250 mL, σ^2_{250mL}, are of the form:

$$\hat{\sigma}^2_{200mL} = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_{12} x_1 x_2$$

$$\hat{\sigma}^2_{250mL} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2$$

The ANOVA outputs based on the above models are shown in Table 5.5 and 5.6 for 200 mL and 250 mL respectively.

Table 5.5 ANOVA Output of Variance Model for 200 mL Slim with 5 Design Points

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.90
R Square	0.81
Adjusted R Square	0.23
Standard Error	0.00
Observations	5.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.00010	0.00003	1.39	0.54
Residual	1	0.00002	0.00002		
Total	4	0.00012			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.0166	0.002	7.65	0.08	-0.01	0.04
Pull Unit Tension (x1)	0.0018	0.002	0.74	0.60	-0.03	0.03
Rewinder Tension (x2)	-0.0001	0.002	-0.05	0.97	-0.03	0.03
x1 . x2	-0.0046	0.002	-1.91	0.31	-0.04	0.03

Table 5.6 ANOVA Output of Variance Model for 250 mL Slim with 5 Design Points

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.59
R Square	0.35
Adjusted R Square	-1.60
Standard Error	0.02
Observations	5.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.00016	0.00005	0.18	0.90
Residual	1	0.00031	0.00031		
Total	4	0.00047			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.0290	0.008	3.69	0.17	-0.07	0.13
Pull Unit Tension (x1)	0.0001	0.009	0.02	0.99	-0.11	0.11
Rewinder Tension (x2)	-0.0022	0.009	-0.25	0.85	-0.11	0.11
x1 . x2	-0.0060	0.009	-0.69	0.62	-0.12	0.11

From Table 5.5, for 200 mL size, the intercept is the only significant coefficient since its p-value is less than 0.1, thus the variance could be assumed constant at the desired operating range with different combination of tension settings. The surface model is somewhat "flat" around this allowable specified operating range. Therefore, the response model for 200 mL size variance is:

$$\hat{\sigma}^2_{200mL} = 0.017 \text{ mm}^2$$

$$\hat{\sigma}_{200mL} = 0.13 \text{ mm}$$

From Table 5.6, the output shows that none of the four coefficients is significant to a 90% confidence level (i.e. the center point is contained in the 90% confidence interval for the coefficient estimates). Therefore, it was determined that the above model form

would not fit the variance data more significantly than would the overall average of the variance. Therefore, it was determined that:

$$\hat{\sigma}^2_{250mL} = 0.029 \text{ mm}^2$$

$$\hat{\sigma}_{250mL} = 0.17 \text{ mm}$$

This variance model implies that the variance of the response is uniform across all points in the desired setting range. Therefore, it can be concluded that the variance of the response is not too sensitive to the different pull-unit and rewinder tension settings. Any operating point defined in the remaining design space is just as likely to produce "good" outputs as any other point.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

It was determined that current process capability for slitting process has the value of $2.05 \leq C_p \leq 2.83$ for 250 mL slim size and $1.95 \leq C_p \leq 2.63$ for 200 mL slim size. This is considered to be satisfactorily for the current production goals. The process capability for 200 mL is lower due to tighter tolerance range specified (± 1mm) as compared to 250 mL (± 2mm). The company is working towards the Six Sigma processes, which can be achieved if one has six standard deviations between the process mean and the nearest specification limit, i.e. it has C_{pk} of 2.00. But there is still a caveat that the process is frequently off-centered, which could potentially contribute fluctuating occurrence of defect waste caused by incorrect slitting. Several modifications to the existing process could improve the process such as by accurate calibration of knives' positioning, using a proper measurement system.

Design of Experiments (DoE) was conducted at five web tension operating points which spanned the "allowable" range specified by the production team, particularly the slitting team at CXJ. This experiment is used to study the significance of tension towards the crease-to-edge width variance (output variance). The inputs are the main pull-unit web tension and rewinder tension. The output being measured is crease-to-edge width. The experiments were conducted at two pack sizes; i.e. 200 mL slim and 250 mL slim. The variance response model for 200 mL pack size is a constant (i.e. $\hat{\sigma}^2_{200mL} = 0.017 \text{ mm}^2$), from which it can be concluded that any point in the defined operating region gives an output just as good as any other operating point. Based on this calculated variance, C_{pk} = 1.28 for 200 mL slim size if it is a centered process. The output shows that none of the four coefficients in the model is significant to a 90% confidence level. The overall average of the variance would then best represents the variance model for 250 mL pack

size, i.e. $\hat{\sigma}^2_{250mL} = 0.029\ \text{mm}^2$. This implies that the variance response model for 250 mL is uniform across all points in the desired setting range. Based on this calculated variance, $C_{pk} = 1.96$ for 250 mL slim size if it is a centered process. From these results, it can be observed that a greater care should be imposed when dealing with 200 mL size. There is a high probability that of out-of-tolerance points might occur during the slitting process, especially if the process is off-centered. Process centering is necessary and needs to be done during the setup before running into the production. This can be done through proper calibration of knives' positioning, which currently is being done through subjective manual decisions by the operators, which may differ from shift to shift.

In case there is an event of out-of-control happens in the future, the out-of-control plan is also provided for corrective measures, as it is shown in Figure 6.1 below.

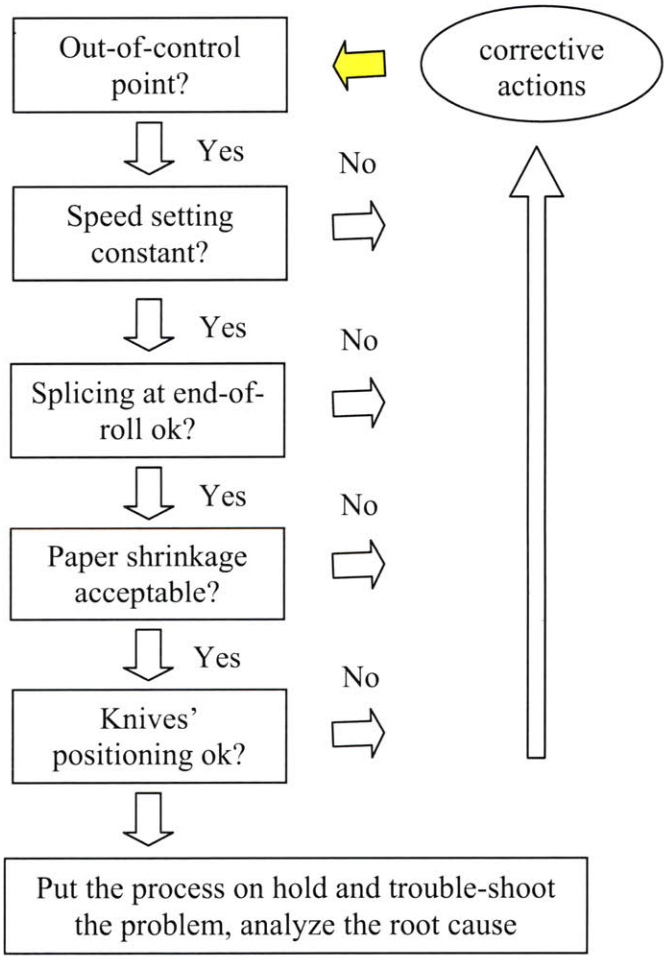


Figure 6.1 Out-of-Control Action Plan

6.2. Recommendations

Two factors are affecting the output quality of slitting process; i.e. the disturbance to the process (i.e. assignable causes, such as knives' positioning) and non-optimized setting of process (machine) parameters (i.e. common causes, such as tension parameter). Based on these conclusions, the recommendation is to remove the assignable causes in the process to achieve a centered process, which could be done by conducting proper training to the operators on how to use the real-time camera measurement system to measure the output (crease-to-edge width) and to detect any mean shift happening in the process during the setup. The trade-off is a longer setup time, but as the learning curve starts to build up, it will become more and more efficient in the future. The process parameters such as tension settings are found to be uniform across all points within the allowable range; therefore any point within the range is likely to produce "good" outputs as any other points.

CHAPTER 7

FUTURE WORK

This project covers only up to a specified allowable operating range in which the experiments are based upon. There is an opportunity to do some analyses beyond the specified allowable range, in which it could be beneficial to improve the current production process. Further research to conduct the stress-strain behavior test of different papers being used in the production to study the elastic region of the materials and the significance of Poisson effect (tension in axial direction vs. shrinkage in lateral direction) will be valuable inputs to the future improvement work.

The line speed setting with a different set of values would be part of future work that could be analyzed further. The trade-off by having a slower line production speed with less variance is to be expected. The significance of varying this line speed parameter is yet to be observed and studied. The detailed implementation plans need to be worked out.

The expansion of analysis to a broader pack sizes and different incoming paper materials will also be of a great interest in the future. Due to time limitation, the current work is still based on the same type of incoming paper materials and two pack sizes under analysis. The constant line speed setting is being set at 800 meters per minute.

Finally, there is another future opportunity to expand this project horizontally across different slitters machine and it would be of a great objective to see whether or not each machine performing the slitting process at the same level of performance with the other, provided the conditions applied across are exactly the same.

Appendix A – Standard Operating Procedure for CCD Line Guider

One Point Lesson (OPL) was established [2], which has the objective of standardizing the procedure of material set up for the Charge-Coupled Device (CCD) line guider. The Standard Operating Procedure (SOP) for this particular lesson is as follows:

1. Switch the controller to the 'Manual' mode (See Figure A.1 for illustration)

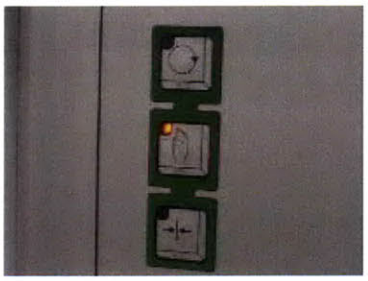


Figure A.1 CCD Line Guider Controller [2]

2. Cut one piece of web with black guiding line. Figure A.2 below shows the example of the piece of web being cut.

Figure A.2 A Piece of Web with Black Guiding Line [2]

3. Paste white labels on both sides of the line as close as possible, as it is shown in Figure A.2 above.
4. Place the line vertical in front of the camera, pressed against the roller. Figure A.3 illustrates this step.

Figure A.3 Placement of Web Piece with Black Guiding Line [2]

5. Press the line button shorter than 1 second.
6. Light-Emitting Diode (LED) array will show 3-3 or 3-2, depending on the line width under observation. It is demonstrated in Figure A.4 below.

Figure A.4 CCD Line Guider LED Array [2]

7. Switch the controller back to the 'Automatic' mode.

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