Quality Improvement and Control Based on Defect Reduction

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN MANUFACTURING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2010

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Submitted to the Department of Mechanical Engineering
on August 18, 2010 in partial fulfillment of the
requirements for the Degree of Master of Engineering in
Manufacturing

Abstract

This thesis addresses the quality improvement in a printing process at a food packaging company now experiencing hundreds of printing defects. Methodologies of Define, Measure, Analyze, Improve, and Control (DMAIC), and Response Surface Model were introduced to reduce the defect rate and control the process. As a result, critical inputs were identified, and a statistical regression model was constructed to predict the flaw size by knowing the critical inputs of the process. The mathematical optimal settings were determined to minimize the flaw size. Moreover, advanced control charts were developed to monitor and control the process.

Keywords:
Defect Reduction, Process Control, Quality Improvement, DMAIC, Response Surface Model

Thesis Supervisor: David E. Hardt
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Table of Content

List of Figures

List of Tables

CHAPTER 1

Introduction

1.1 Overview

This thesis is based on a group project in a food-packaging company X to help control and improve the product quality. The manufacturer operates a continuous-flow production line to fabricate beverage cartons. The whole line can be divided into three main manufacturing processes: printing, laminating and slitting. Figure 1.1 presents the general manufacturing processes of producing packaging materials. The particular focus of the thesis is on the printing portion of the manufacturing, and how to reduce defects in this process.

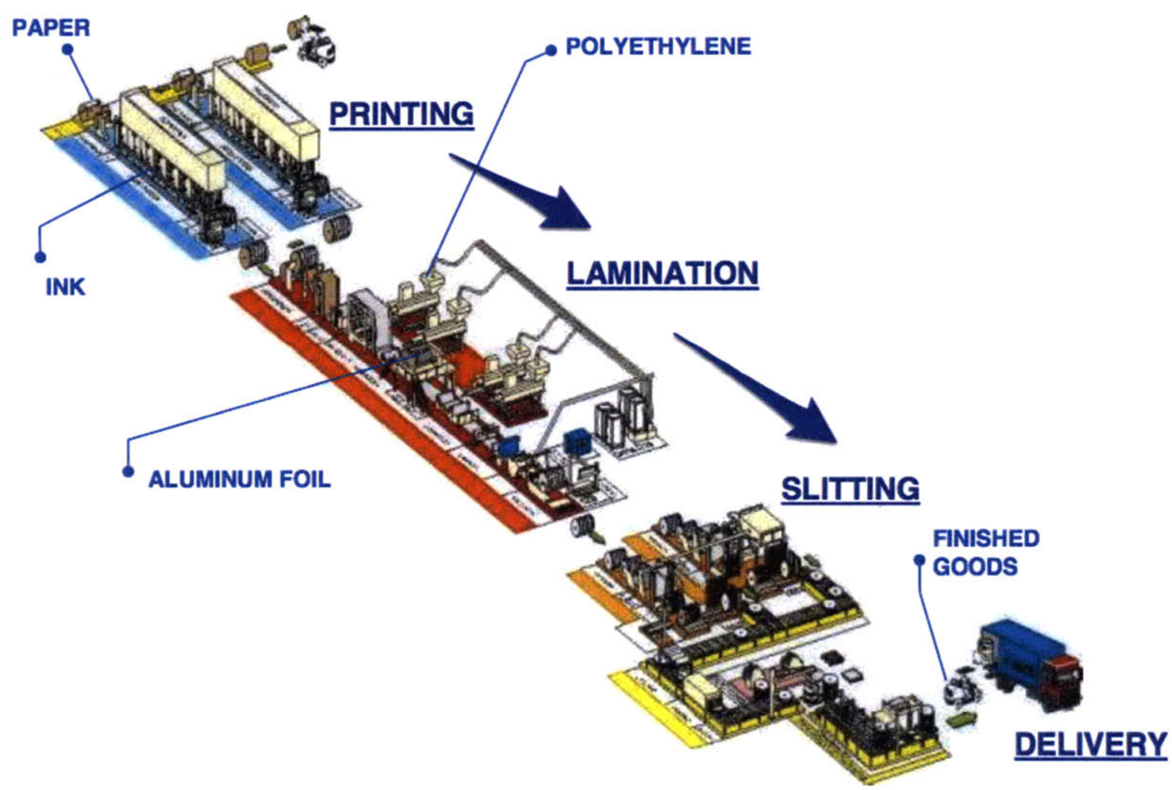

Figure 1.1 General Manufacturing Processes [1]

1.2 Company Background

Company X is a multinational food processing and packaging company of Swedish origin. Currently it is one of the larger suppliers of packaging systems for milk, fruit juices and many other products in this industry. It also provides the integrated processing, packaging, distribution lines, and plant solutions for food manufacturing. It regionalizes its production in four regions: Europe, Central Asia (Middle East) & Africa, Asia Pacific and America. Among its global network, the manufacturing plant in the South East Asia cluster located in Jurong, Singapore serves customers from more than 17 countries.[1]

Compared to company's other plants, the Jurong Plant is distinctive in that it operates on smaller and more customized orders. Thus frequent setups are needed, and close monitoring and careful scheduling are required to ensure continuous improvements and quality maintenance. Moreover the lead-time for delivery to customers is minimized. In 2007, this plant was honored to receive the Manufacturing Excellence Award (MAXA) for its overall excellence in innovations, operations and sustainability.[1]

To satisfy the needs of high flexibility with uncompromising performances, the new principles of production – World Class Manufacturing (WCM) are introduced to ensure flexibility with maximum performance. The production will be in small batches to satisfy the variations and the volatility in the demands. The inventories will be organized on a "Just-In-Time"(JIT) basis. The attention is focused on the 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. The work organization becomes more flexible. For instance, the boundaries between unskilled and skilled workers are narrowed. The major tasks implemented are learning and continuous improvements that involve all of the work forces rather than just skilled engineers and managers.

The WCM recognition will help the plant continue to enjoy a high reputation and establish a high-end brand to stand out in the packaging industry and have a larger market share. World Class Manufacturers are those who demonstrate industry best practices. To achieve this prestigious label, the Jurong Plant attempts to be the best in the field in quality, price, delivery speed, delivery reliability, flexibility and innovation. The aim is to maximize performance in these areas to ensure competitiveness. Achieving the standard of WCM is an essential step to firm restructuring. The prime step is to develop a business strategy to match its core competences with the opportunities in the market. One of the key critical factors in developing the business strategy is quality where the emphasis will be given to the use of more advanced and sophisticated tools delivering the best quality at low costs. Statistical Process Control is the most commonly used tool for quality improvement that meets the WCM standards.

1.3 Evolution of Total Productive Maintenance from Quality Perspective

Over the past ten years, the Jurong Plant has been undergoing three typical Total Productive Maintenance (TPM) development phases. From 2001 to 2004, the plant was engaged in the pilot phase of TPM. During that phase, the main target was to improve the basic quality problems since the defect rate was high. By introducing the basic quality control tools like the Five Whys, Root Cause Analysis and other basic quality control toolkits, the plant expanded fast. It reached TPM level two, TPM Excellence, in 2005. In that phase, the defect rates had been reduced significantly, and it remained at that level by standardizing the process with the use of high-level quality control tools. From 2007 until now, the plant has achieved TPM Advance - TPM level three. In this phase, defect waste was further reduced to 1.37%.[2] However hundreds of defects remain, each of them rare, random and difficult to eliminate. For instance, the most frequent defect in the printing process was only 0.011% in 2009.[2] Therefore, more advanced tools like daily quality maintenance and Statistical Process Control (SPC) should be introduced to achieve the goal of defect-free.

Through defect free manufacturing, quality maintenance aims to achieve customer satisfaction by achieving the highest quality possible. Its focus is on eliminating non-conformance in a systematic manner, much like Focused Improvement.[3] The plant has gained understanding of what parts of the equipment affect product quality and has begun to eliminate current quality concerns, and to move to potential quality concerns. The transition is from Quality Control to Quality Assurance, namely from reactive to proactive.[3]

Quality maintenance activities are the art of setting equipment conditions that preclude quality defects, based on the basic concept of maintaining perfect equipment to maintain perfect quality of products. The condition is checked and measured in a time series to verify that measured values are within standard values. The transition pattern of measured values is watched to predict the possibility of defects occurring and to take counter measures beforehand.[3]

1.4 Printing Portion of the Production

1.4.1 Pre-press

In the pre-press stage, the clichés for printing are prepared from the negatives. The clichés are polymeric stamps with elevated portions for the areas to be printed. One cliché is prepared for each color used for printing. A number of clichés are then mounted on a sleeve that is a rotating spindle fitted into the printer. According to different designs, a number of clichés are then mounted on the sleeve and called webs. A cliché used for printing is shown in figure 1.2, and the mounted sleeve is shown in figure 1.3.

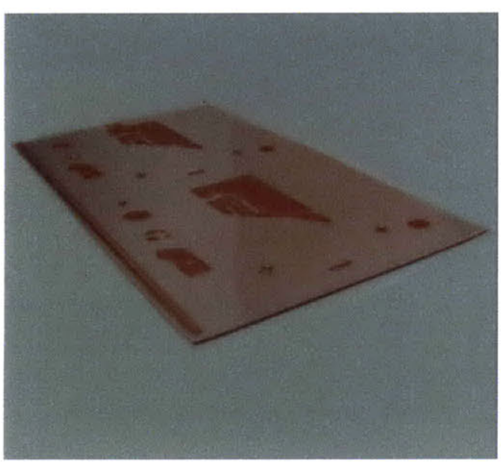

Figure 1.2 Cliché

Figure 1.3 Mounted Sleeve

1.4.2 Printing

In the printing stage, there are three printers. Two of them use flexographic (flexo) printing technology that processes more than 90 percent of orders in the company, while the third machine applies offset printing technology which is used for special, high resolution orders only.

In this thesis, only flexo is to be introduced and discussed.

Flexo, is a direct rotary printing using flexible raised image printing plates (cliché) used especially in the packaging industry. It is suitable for printing on coated and uncoated paper and board, and non-porous substrates including metallised and paper foils, and plastic film.[4]

There are three cylinders needed to process the flexo shown in Figure 1.4. The first one is called the anilox cylinder. It is engraved with a cell pattern whose surface contains millions of very fine cells so that it functions as an ink-meter to enable an even and fast ink transfer to the printing plate. The second one is a cliché cylinder prepared by the previous pre-press stage. The last cylinder is an impression cylinder that puts the paper in contact with the cliché so that they come in contact. The impression cylinder loads the paper against the cliché and then the image is transferred to the paper.

A doctor-blade mechanism is used between the anilox cylinder and the ink chamber. It scrapes off excess ink so as to control the amount of ink retained in the anilox cylinder and therefore available to be transferred to the cliché. The doctor-blade mechanism is illustrated in Figure 1.5.

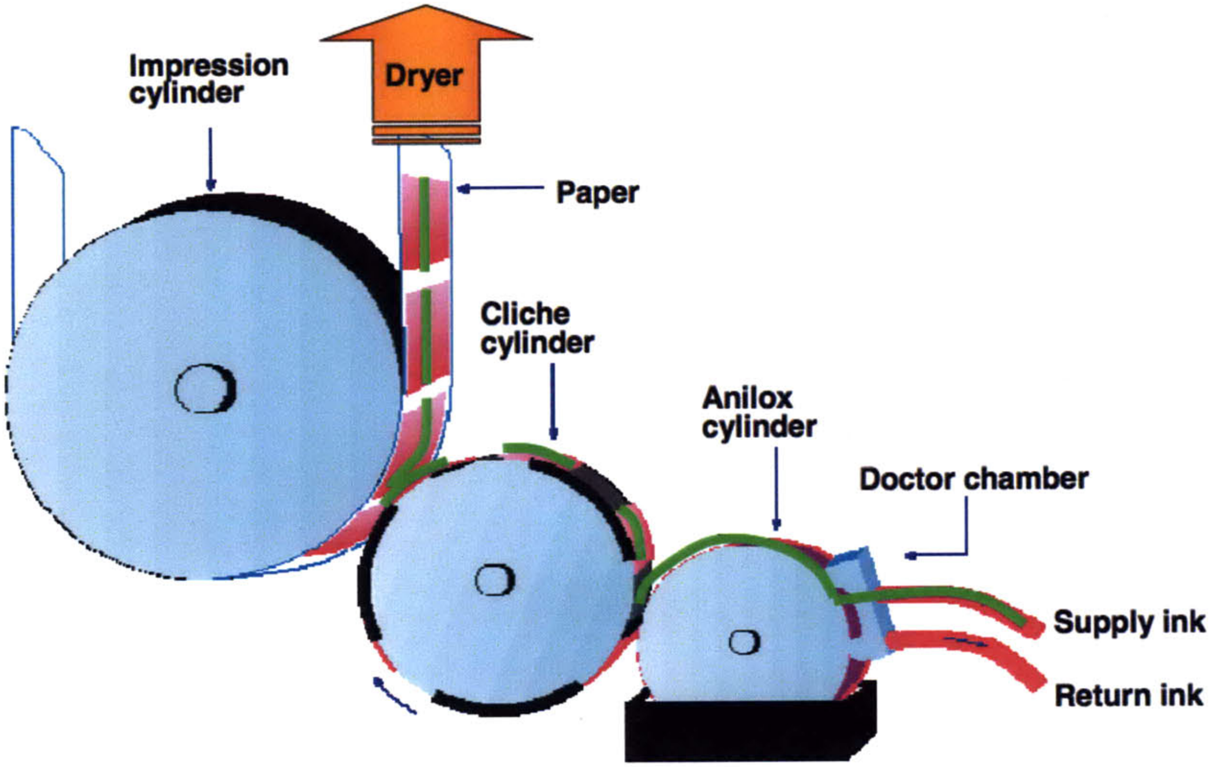

Figure 1.4 Flexography Printing Process [5]

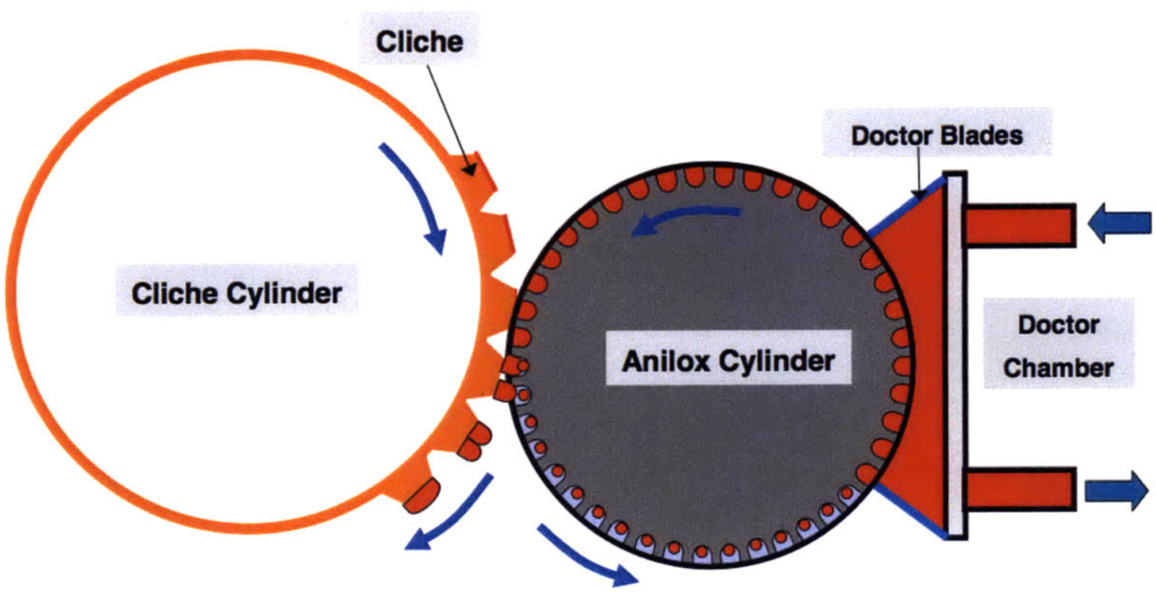

Figure 1.5 Doctor-Blade Mechanism [5]

The whole printing operation process is shown in Figure 1.6. The incoming paper roll is loaded on the unwinder that opens it up and feeds it to the printing stations. There are seven substations in the process. Each printing station holds one set of clichés designed for one color only. Depending on the color scheme, some of the substations might be left idle, however, the paper will go through all the seven substations. Once the paper is printed, it is creased into the appropriate shape in the creasing station. The purpose of creasing is to enable proper folding of the paper during the filling stage at the customer site. The creasing tool also punches holes for the straws. Then the paper will go through the inspection room to be checked for defects. There are two inspection systems, FUTEC and Eltromat, installed in this room, which identify defects like dirty print, missing print and registration cross misalignment and trigger alarms. The printed and creased paper is then rolled back on the rewinder.

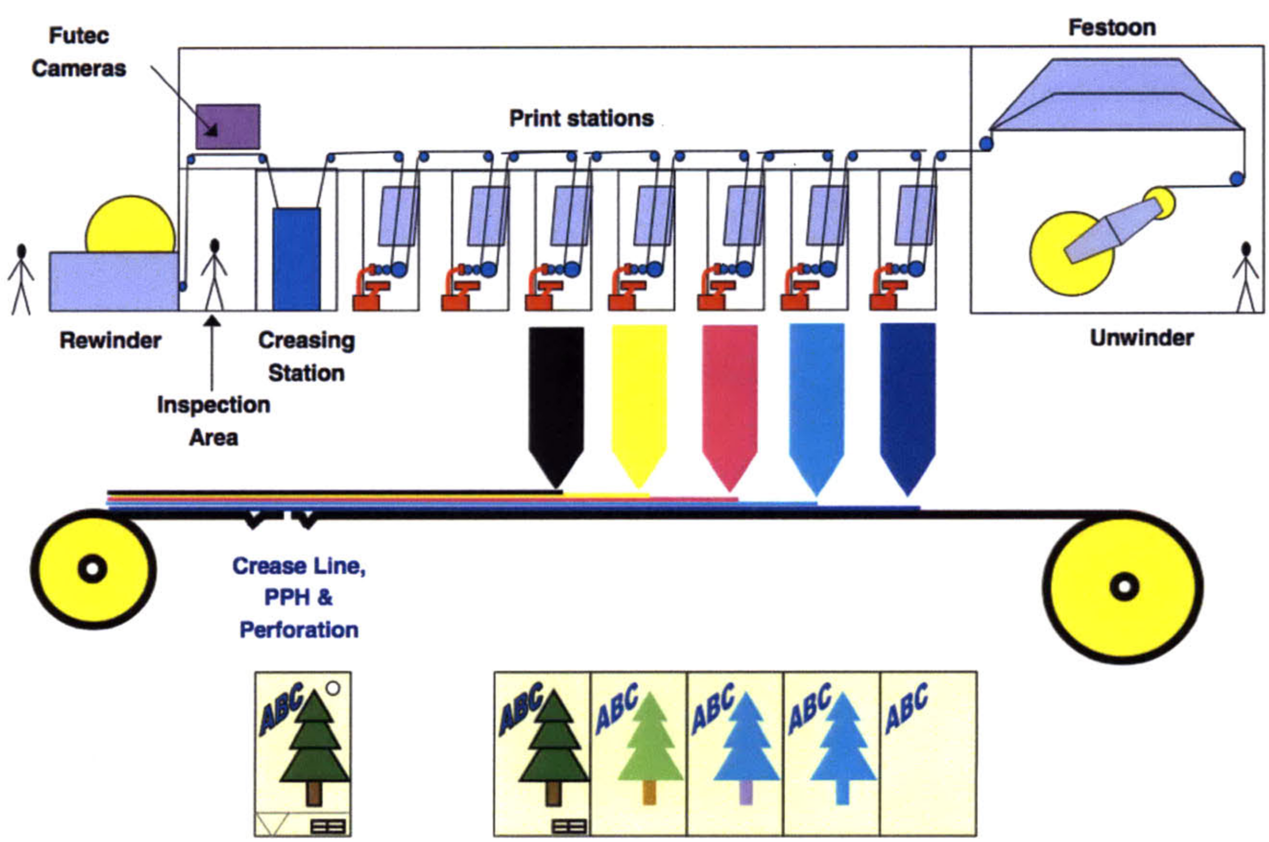

Figure 1.6 Printing Operation Processes [5]

1.4.2 FUTEC Inspection System

This system provides real-time inspection for flaws on continuously fed material at high speeds by 100% scanning with CCD cameras. The system is also an in-line flaw detection system that evaluates the conformance or non-conformance of the items to be inspected, based on the results of the inspection. In addition, the system has a multi-level sorting function, allowing the operator to perform quality control, including quality checks and the analysis of the causes for flaws, without reducing yields. This system consists of an image pickup section and a control section. The image pickup section includes a high-precision CCD cameras (photo detector), fluorescent lights, a labeler and a rotary encoder. The control section consists of a signal processing unit, a monitor, a printer, and a specified keyboard. The signal-processing unit performs all the controls including the execution of the flaw detection inspection, the registration of the patterns to be inspected for any possible flaws, and the checking of the flaw detection conditions.[6] The overall structure of the system is shown in Figure 1.7.

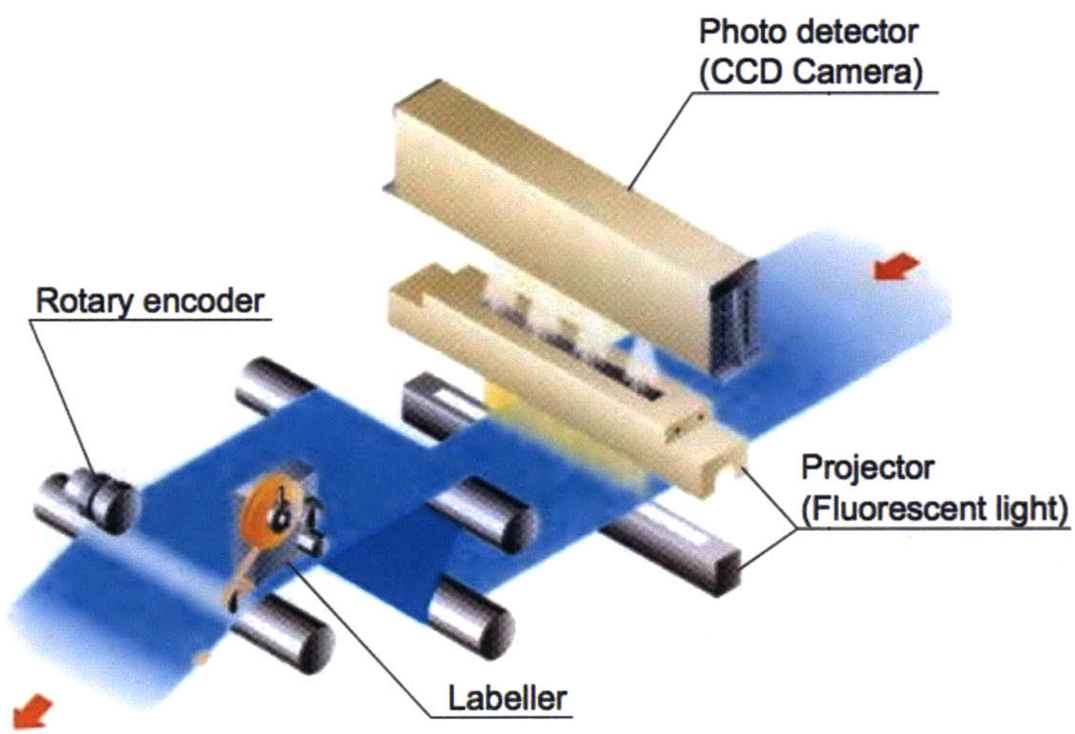

Figure 1.7 Overall Structure of FUTEC Inspection System [6]

The photo detector takes images of the item to be inspected and converts the data into electrical signals.[6] Once the printer starts to produce, it will capture the first defect-free package as a master to compare the following packages. Since different color shades have different light reflection, the system will trigger an alarm and record the flaw size once the color or printing pattern is different, i.e. there is a “defect”. It is this type of defect that is the focus of this thesis.

1.5 Organization of Thesis

The thesis consists of seven chapters. Chapter 1 introduces the background of the Company X, its Total Productive Maintenance and the printing process. Chapter 2 defines the current problem and scope of the project. Chapter 3 presents a literature review of studies on process control and methodology of Define, Measure, Measure, Analyze, Improve and Control (DMAIC). Chapter 4 details the methodology of DMAIC applied to identify and analyze the problem. Data and results are discussed in Chapter 5. Chapter 6 summarizes some recommendations for the Company X. Chapter 7 concludes the paper with findings, and future opportunities for further research.

CHAPTER 2

Problem Statement

2.1 Project Motivation

Due to the increasingly competitive business atmosphere around the world, the company is struggling with the increasing costs of raw materials, labor forces and R&D, shorter product life cycle, higher expectations from customers, and the reverse-engineering industry. In addition, the plant wants to achieve WCM in the near future. Currently the plant is on TPM third level, which has a low defect waste at 1.37% only. However the waste causes variability within the process. Moreover, the waste involves the company in more than 100 external customer claims each year. The plant's goal is to achieve defect free manufacturing, zero claims, and consistent and reliable equipment and processes.

2.2 Problem Description

For the printing process itself, the total defect waste was 0.688% in 2009. Among all the printing defects, Dirty Print (Spot) and Missing Print (Bad Ink Transfer) were top two of the contributors to the defect and claim losses: 0.076% and 0.04% respectively for defect waste and more than 20% in total for clam losses. Company-wide, they were also the highest contributor to claims, and fifth and tenth highest contributors to defect wastes.[7]

Flaw size is the measure of difference between the master (defect free package) with the real product given by FUTEC inspection system. The problem is to reduce the flaw size and variance so as to reduce the occurrence of these two defects from the current level to a much lower level. Samples of Dirty Print (Spot) and Missing Print (Bad Ink Transfer) are illustrated in Figure 2.1 and Figure 2.2.

Figure 2.1 Sample of Dirty Print (Spot) [8]

Figure 2.2 Sample of Missing Print (BIT) [8]

Dirty Print (Spot), contaminating the printed paper, derives from unwanted excess ink transferring to the anilox roller or cliché roller. Missing Print (Bad Ink Transfer) is when the printed paper misses part of printing pattern design during the ink transfer. Both defects will result in difference between the original design and finished products. It is unacceptable for customers since the two defects will damage the visual appearance of the products and spoil the company's brand.

2.3 Project Objective

In this project, improving and further controlling the printing process and equipment are to be achieved through the following means:

I. Map out the process of printing and identify the critical inputs and outputs;
II. Build the response surface;
III. Reduce the pooling of Dirty Print (Spot) and Missing Print (Bad Ink Transfer) defect waste by 50%;

IV. Make Out of Control Action Plan (OCAP)

2.4 Project Scope

This project only concerns the specific printing process in the Jurong Plant Company X. Since there are hundreds of defect modes in the plant, and other constraints and limitations of the project, only Dirty Print and Missing Print are selected and investigated. In addition, the project only focuses on the flaws of product family XBA happening during stable production.

CHAPTER 3

Literature Review

3.1 Overview

The Section 3.2 and 3.3 is a summary of manufacturing processes and methods to reduce the variance of the process based on Professor David E. Hardt's paper, "Manufacturing Processes and Process Control". The Section 3.4 presents a brief introduction of methodology of Define, Measure, Analyze, Improve, and Control.

3.2 General Process Model [9]

A manufacturing process can be defined as an interaction of equipment with material to transform it into a 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, height, etc. Properties characterize those constitutive and intrinsic attributes of the part, like stiffness, strength and the like. Figure 3.1 illustrates the schematic diagram of this model.

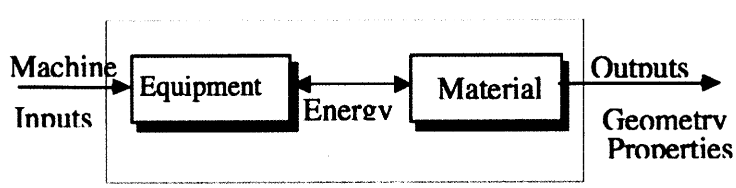

Figure 3.1 Schematic Diagram of a Process Model [9]

As noted, the manufacturing is all about two objects: equipment and material. They 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 the Young's modulus. They could be either of the equipment or of the material. It is noted that there are always disturbances to 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 (Equation 1) is presented to characterize the causality. The schematic diagram of this model is given in Figure 3.2. It is noted that the controllable inputs are the subset of the process parameters that are accessible and manipulable in a reasonable time frame relative to the process execution time.

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

(Eq. 1) [9]

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

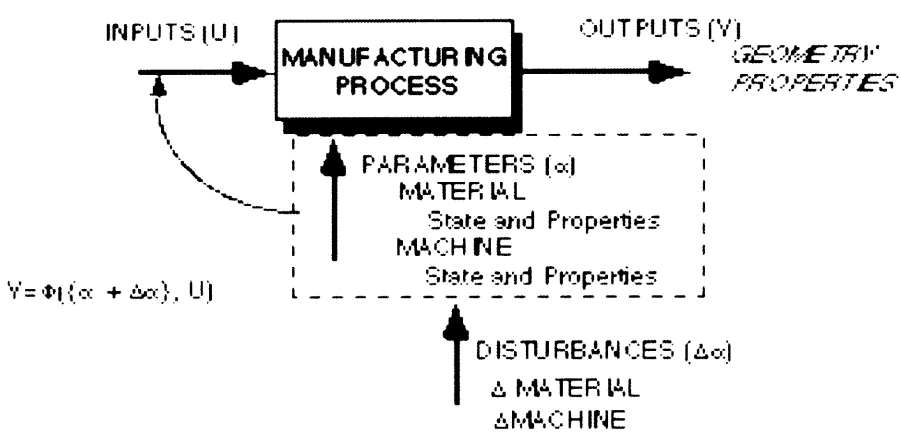

Figure 3.2 Schematic Diagram of a Process Causality Model [9]

3.3 Hierarchy of Control Methodology [9]

Based on the process model given in Equation 1, we further take the partial differentiation and then derive the first-order variation equation as shown in Equation 2.

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

(Eq. 2) [9]

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

There are three distinctive methods from different aspects shown as follows to minimize ΔY.

I. Reduce sensitivity
   - Design of experiment
II. Reduce Disturbance
   - Standard operating procedure
   - Statistical process control
III. Measure outputs and manipulate inputs
   - Feedback control of outputs

3.3.1 Reduce Sensitivity - Design of Experiment (DOE)

This method is to minimize the term ∂Y/∂α such that the variation in outputs is minimized. It would be helpful if we could derive the quantitative form of this partial differentiation characterizing the process. However, in most cases, the physics of the process are too complicated for us to obtain the insight of this level. Therefore, we could use the design of experiment instead to calculate the variation at different operating point and select the one with the minimal variation as our robust operating point. This robust 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.

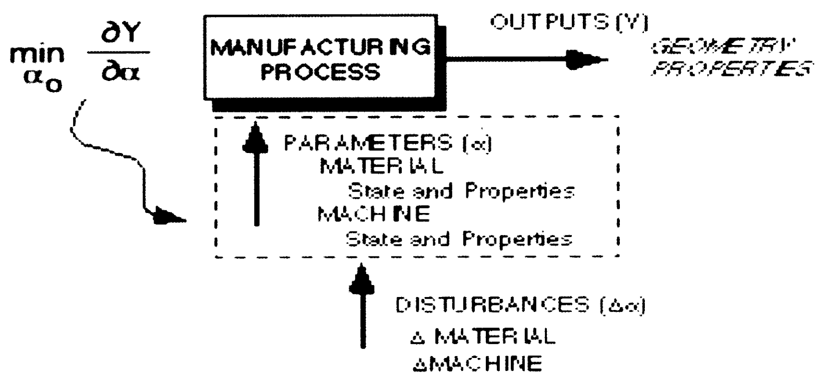

Figure 3.3 Schematic Diagram of a Robustness Design [9]

3.3.2 Reduce Disturbance - Statistical Process Control (SPC)

This method is to reduce the disturbance term of Δα so that the variation in outputs is minimized. Statistical process control is a monitoring tool in nature. Once an out-of-control point is detected on the control chart, it provides no prescription for action but implies that the disturbance exists and should be eradicated immediately before it leads to large changes or mean shift in outputs like defects. Therefore, except establishing 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 disturbance. The schematic diagram of this method is shown in Figure 3.4.

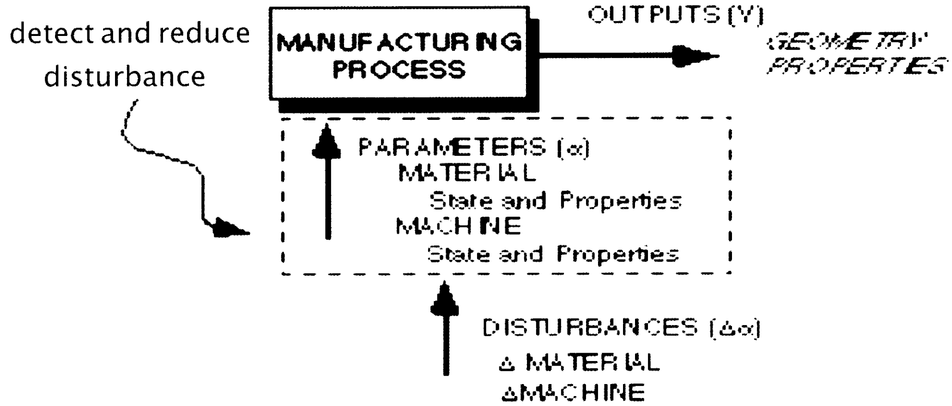

Figure 3.4 Schematic Diagram of Statistical Process Control [9]

3.3.3 Measure Outputs and Manipulate Inputs

This method is to measure the outputs and in turn constantly tune the inputs to ensure the minimal change in outputs. It is the most straightforward and powerful way of controlling the process to yield conforming outputs since this strategy encompasses all influences on the processes. However, special attention should be paid to the issues in time delays and accuracy of measurement system. The schematic diagram of this method is illustrated in Figure 3.5.

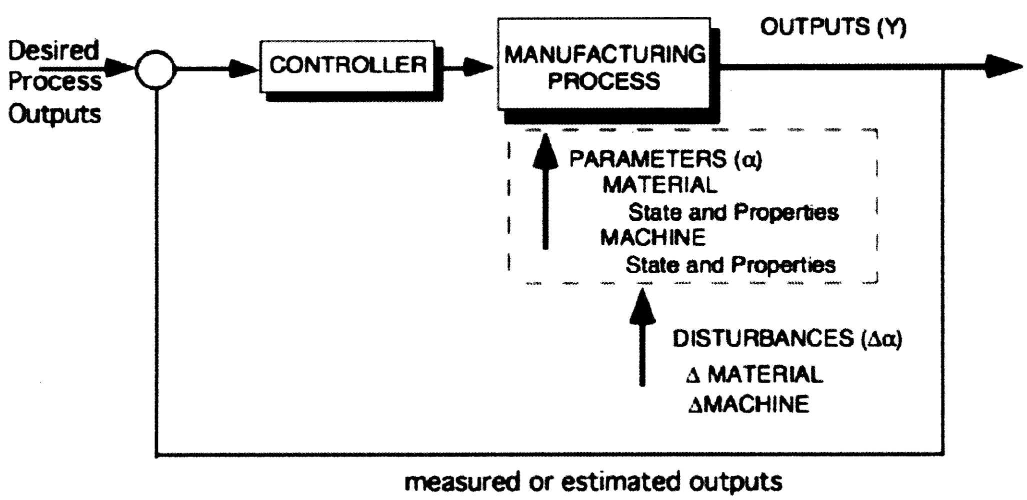

Figure 3.5 Schematic Diagram of Direct Feedback Control of Outputs [9]

3.4 Methodology of Define, Measure, Analyze, Improve, and Control

Define, Measure, Analyze, Improve and Control (DMAIC) 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 root causes of quality and process problems.”[10] The basic target for each phase is shown as follows.

I. Define the problem, and the objective of the project.
II. Measure the key aspects of the current process and collect the relevant data.
III. Analyze the data to investigate and verify cause and effect relationships. Identify what the relationships are, and attempt to ensure all factors have been considered. Then seek out the root causes of the defect under investigation.
IV. Improve the current process based on the data analysis applying methodologies to create a new and better future state process.
V. Control the future state process to make sure that any deviations from the target are corrected before they result in final defects.

CHAPTER 4

Methodology

4.1 Project Roadmap

The entire project was divided into five phases, following the "Define - Measure - Analyze - Improve and Control" methodology of total quality management, as illustrated in Figure 4.1.

Figure 4.1 Methodology Flowchart [11]

4.2 Define Phase

During the define phase of a DMAIC project, "the project leaders should take responsibility for clarifying the purpose and scope of the project, for getting a basic understanding of the process to be improved, and for determining the customers' perceptions and expectations for quality".[12] Establishing realistic estimates for the project timeline and costs should be taken into consideration as well. The charter for this project is presented in Table 4.1. This will ensure that all the project members agree with what is to be done, and also provide a way to evaluate the project process and objective.[12]

Table 4.1 Project Charter

Project Name		Process Control for Print On Defect Mode Dirty Print and Missing Print					
Sponsor		AAA	**Date, Version #**				
Team Leader		BBB	**Supporting Staff (BB/MBB)**				
Core Team members		CCC, DDD, EEE, FFF					
Start Date		WK 51 '09	**Target Completion Date**			Wk 16 '10	
Element		**Description**	**Team Charter**				
1	Process/System Definition	The work process or system in which opportunity exists.	Printing Process, printing unit				
2	Business Critical Y	Describe the opportunity as it relates to strategic business goals	Company priority is claim and waste. Dirty Print and Missing Print are the highest contributor to claims, and fifth and tenth highest contributor to defect wastes.				
3	Project Y	State the significant issue the team wants to improve. Problem statement.	Reduce Flaw Size of Dirty Print and MIssing				
4	Project Objective		**Baseline**	**Goal**	**Entitlement**		**Comment**
		Primary Ys	Flaw size	Reduce by 50%	0		50% reduction on this defect waste
5	Financial Benefit Estimated (Annual)	What is the improvement in business performance anticipated and when?	26K worth of defects. accreditation; market share; consulting service				
8	Benefit to Customers or Delivery Partners	Who are the customers or delivery partners, what benefit will they see and what are their most critical requirements?	The end customers are our customer (i.e HHH). They require our packages to be visually presentable and acceptable for sale in market. Dirty print and missing print affect the visual appearance of the package and should be reduced to meet customer's expectation.				

4.3 Measure Phase

During the measure phase, process mapping, cause and effect analysis, and measurement system analysis are conducted, and process capabilities are calculated to learn the current level of the process. In this phase, the focus is on collecting data to describe the current process situation. It is important to identify the appropriate process measures and gather sufficient baseline data, so that once improvements are made the impact can be verified empirically.[12]

4.3.1 Process Mapping

Process mapping is a workflow diagram to bring forth a clearer understanding of a process. [13] Depending on the type of process, a process map may be created using direct inputs from the individuals involved in the process, by an observer who monitors and records information about the process, or a combination of the two.[14]

In this project, only steps during the production are considered. The set-up (ramp up) phase is neglected due to its instability.

A detailed process map is created shown in Table 4.2, including documentation of variations in how the process is carried out. With this information, the technicians and engineers can identify some of the factors that may be affecting process performance.

Seen in Table 4.2, the first two columns show all the inputs and their specifications during production. The output column has two main outputs: formation of dry ink particulates and ink leakage at sides that are considered as the two root causes for dirty print and missing print. The reason to put root causes as outputs instead of the original flaw size is that it will help to find out the detailed causality in further analysis, like the cause and effect matrix in the next step.

Table 4.2 Supplier Inputs Process Outputs Customer (SIPOC)

Inputs (X)	Specs	Process	Output (Y)
pH of ink	8.6 ± 0.4	Ink Reservoir (during production)	Formation of dry ink particulates
Viscosity of ink	14 - 18 s		Ink leakage at sides
Temperature of ink (reservoir)	24 - 28 degrees		Formation of dry ink particulates
Flow rate of chill water	NA		Formation of dry ink particulates
Temperature of chill water	18 degrees		Formation of dry ink particulates
Contact pressure (ink chamber)	6 bar	Printing (during production)	Ink leakage at sides
Vibration (ink chamber)	NA		Ink leakage at sides
Vibration (anilox)	NA		Ink leakage at sides
Temperature (anilox shaft)	35 - 50 degrees		Formation of dry ink particulates
Temperature (anilox surface)	NA		Formation of dry ink particulates
Temperature (sleeve bearing block)	35 - 50 degrees		Formation of dry ink particulates
Doctor blade condition	NA		Ink leakage at sides
Rubber seal condition	NA		Ink leakage at sides
Pump flow capacity	~ 30 - 40%		Ink leakage at sides

4.3.2 Cause and Effect Analysis

A cause and effect matrix is designed to check the importance of all the inputs mapped in the previous stage. According to the importance of the outputs to customers, each output is assigned one rate. Then one score is rated to the crossover between an input and an output to present the relationship. Each input will have a total score by multiplying the importance rate and the score. The higher score it has, the more it affects the outputs.

After rounds of discussions among printing process engineers and technicians, a detailed Cause and Effect Matrix was developed and shown in Table 4.3. According to the process mapping done previously and process engineers' know-how, ink leakage at sides and formation of dry ink particulates are assigned 10 marks and 8 marks respectively. Rating each relationship between input and output, and multiplying them to the importance rate, we will have the total score of each input.

Table 4.3 Cause and Effect Matrix

Rating of Importance to Customer			**10**	**8**	**Total**
Process Step		Process Inputs	Ink leakage at sides	Formation of dry ink particulates	
1	Ink Reservoir (during production)	pH of ink	1	6	58
		Viscosity of ink	3	6	78
		Temperature of ink (reservoir)	1	9	82
		Flow rate of chill water	1	9	82
		Temperature of chill water	1	6	58
2	Printing (during production)	Contact pressure (ink chamber)	6	0	60
		Vibration (ink chamber)	6	0	60
		Vibration (anilox)	6	0	60
		Temperature (anilox shaft)	1	6	58
		Temperature (anilox surface)	3	9	102
		Pump flow capacity	9	1	98

Rating of Importance to Customer			10	8	Total
Process Step		Process Inputs	Ink leakage at sides	Formation of dry ink particulates	
2	Printing (during production)	Temperature (sleeve bearing block)	0	1	8
Total			380	424	

Based on the cause and effect matrix, the four inputs, the temperature of the ink in the reservoir, the flow rate of the chill water, the temperature of the anilox surface and the pump flow capacity, are deemed to be the most important parameters. SInce the plant does not have measurement tools to measure the flow rate of the chill water now, further work will be focused on the other three inputs.

4.3.3 Measurement System Analysis - Gauge R&R

Gauge Repeatability & Reproducibility (Gauge R&R) is a measurement systems analysis technique investigating two components of measurement error: the repeatability and the reproducibility. The repeatability stands for the measurement system capability that whether the same observed value will be gained if the same unit is measured several times under same conditions.[15] The reproducibility means how much difference in observed values is induced when units are measured under different conditions, such as different operators.[15]

In this case, the output is directly measured and recorded by the FUTEC inspection system, and the four inputs can be directly read from the monitor or the temperature gun. (The temperature gun is set in a permanent position.) Based on the assumption that the FUTEC inspection system and the temperature gun are effective to measure the outputs and inputs, no further Gauge R&R study was conducted.

4.3.4 Process Capability

A process consists of men, machines, materials, methods, and environment engaged in producing a measurable output; for instance, a manufacturing line for machine parts. All processes have inherent statistical variability that can be evaluated by statistical methods. The Process Capability is a measurable quality characteristic of a process to the specification, expressed as a process capability ratio (e.g., C_p or C_{pk}). The output of this measurement can be illustrated by a histogram and calculations that predict how many parts will be produced out of the quality specification limit.[16]

According to the data achieved, the process capability of flaw size can be calculated. There is no lower specification line (LSL) since flaw sizes are nonnegative values. The upper specification line is 8, which is a boundary level sitting between defect alarm and negligible level. As shown in the Figure 4.2, the process capability (C_{pk}) for the process is 1.24 now, which suggests that the process is in between three-sigma (1.00) and four-sigma level (1.33).

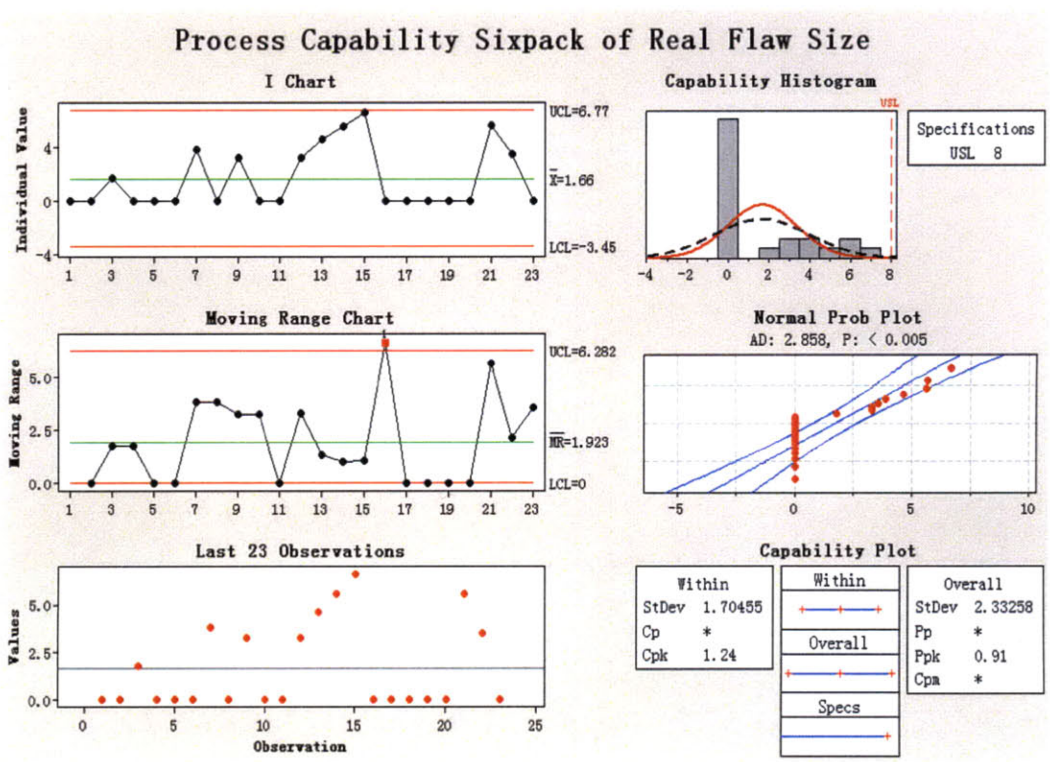

Figure 4.2 Process Capability of Flaw Size

A C_{pk} value of one means that if the process is stationary and normally distributed, the output can be expected to fall between the specification limits 99.7% of the time. This corresponds to a ±3 sigma interval on the normally distributed output data. At a C_{pk} of 1, the process will have defects at the rate of 1 part in 370. For a customer-focused business, C_{pk} 1.33 is a practical minimum target, which implies that 99.9937% of the outputs will fall in the specification limits or 1 part in 16,000 will have a defect.

4.4 Analyze Phase

During the analyze phase, the main purpose is to identify the root causes of the process problems. A variety of methods are applied to identify potential root causes, narrow down the possibilities, and prove the cause and effect relationship between the suspected inputs and the outputs of the process.[17] Statistical analysis, such as Analysis of Variance (ANOVA), will be conducted to quantify the potential relationships.

4.5 Improve Phase

The main target in the improve phase for this project is to build a response surface model that will give a global image of the process and quantify the relationship between inputs and outputs. Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes.[18] The application of RSM is most widely-used in the industrial, where several inputs potentially influence some performance measure of the quality characteristic of the product or process.[18]

The quality characteristic is called the response.[18] In this case, the response is the flaw size, while the potential inputs are the four decided in the previous phase. The relationship between the inputs and the response will be presented by a regression model.

The first step is to build up the regression model in terms of the inputs and the outputs. A first-order model shown in Equation 3 will be the approximating function if the response is well modeled by a linear function of the independent variables.[19] If there exists curvature in the system, then a polynomial of higher degree should be used, such as a second-order model shown in Equation 4.[19]

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

(Eq. 3) [19]

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j=2} \sum^{k} \beta_{ij} x_i x_j + \varepsilon$$

(Eq. 4) [19]

where:

X = input/variable

β = coefficient/constant

ε = the noise or error observed in the response y

The method of least squares* is used to estimate the coefficients in the above regression models. The t-test statistics† is applied to determine whether each input is statistically significant to the output. If the fitted regression model is an adequate approximation of the real response function, the fitted regression model can be treated as equivalent to the actual system.[19]

After achieving the regression model, the second step is to determine the optimal settings for the system. In this case, the objective is to minimize the flaw size.

Due to the limitation of the project, a formal Design of Experiment (DOE) with full factorial changes was not conducted. Instead historical data was used to create a regression model for the response surface.

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* The method of least squares chooses the estimates of the β's in equations in Eq. 3 and Eq. 4. The estimates are those values of the parameters that minimize the sum of squares of the model errors.[19]

† The hypotheses for testing the significance of any individual regression coefficient β_i are H_0: $\beta_i = 0$ and H_1: $\beta_i \neq 0$. If H_0: $\beta_i = 0$ is not rejected, then this indicates that X_j is not statistically significant to the output and can be deleted from the model.[20]

4.6 Control Phase

In the final step control phase, steps are taken to ensure that the gains obtained during the improve phase are institutionalized and maintained.[21] A set of advanced control charts will be applied to monitor the quality characteristic of the process. Moreover, a detailed process control plan including each operator's responsibilities and how to check and control each parameter's setting should be carried out.

CHAPTER 5

Results and Discussion

5.1 Response Surface Model

The four inputs, the pump flow rate, the temperature of the anilox surface on operator side and drive side, and the temperature of the ink in the reservoir, are recorded by operators on the shop-floor. The pump flow rate can be read from the control monitor, the temperature of anilox surface for both sides and ink reservoir can be read from the temperature gun. The detailed data used to build the response surface model are shown in Table 5.1.

Table 5.1 Data for RSM

Pump Flow Rate	Anilox surface temp OP side	Anilox surface temp DR side	Ink reservoir temp	Flaw Size
34.98	28.78	29.17	27.4	0.00
35.00	28.83	29.22	27.4	0.00
35.00	29.00	29.32	27.6	1.76
35.00	29.17	29.42	27.7	0.00
35.00	29.17	29.42	27.7	0.00
35.00	29.17	29.42	27.7	0.00
35.00	29.67	29.72	28.1	3.85
35.00	29.67	29.72	28.1	0.00
35.00	29.77	29.66	28.1	3.25
35.00	29.75	29.57	28.1	0.00
35.00	29.75	29.57	28.1	0.00
35.00	29.69	29.23	27.9	3.29

Pump Flow Rate	Anilox surface temp OP side	Anilox surface temp DR side	Ink reservoir temp	Flaw Size
35.00	29.66	29.09	27.8	4.60
35.00	29.63	28.94	27.7	5.60
35.00	29.60	28.80	27.6	6.65
34.75	29.32	28.59	27.4	0.00
34.75	29.32	28.59	27.4	0.00
33.60	28.06	27.61	26.6	0.00
33.45	27.89	27.48	26.5	0.00
33.45	27.89	27.48	26.5	0.00
32.00	26.30	26.25	25.5	5.64
31.50	25.75	25.82	25.1	3.54
31.00	25.20	25.40	24.8	0.00

In this case, the first-order polynomial model is not considered due to two main reasons. On one hand, the four inputs are not independent. For instance, the ink transferred to the anilox roller will affect the temperature of the anilox roller surface and vice versa, and the pump flow rate might also have effects on the temperature of the ink. On the other hand, the process now is already sitting in between three-sigma level and four-sigma level, which suggests that the current settings are close to the optimal solutions and a first-order model might not precise enough to model the real process. Therefore, the regression model is to be built in terms of a second-order polynomial model shown in Equation 5.

The method of least squares was applied to determine the coefficients for the parameters. Moreover, statistically significant terms in the model can be tested by the t-test statistics. The combination of the least squares and the t-test can be realized by the RSM function in MINITAB. The regression equation achieved from MINITAB is presented in Equation 5. The detailed results of estimated regression coefficients and analysis of variance are shown in Table 5.2 and Table 5.3 respectively.

$$Y = -4611.6A + 6314.9B + 9259.2A^2 - 7552.6AB + 10179.9AC + 15874.2BC$$

(Eq. 5)

Where:

Y = flaw size

A = pump flow rate

B = anilox surface temperature (operation side)

C = anilox surface temperature (drive side)

D = temperature of ink in the reservoir

Table 5.2 Estimated Regression Coefficients for Flaw Size

Term	Coef	SE Coef	T	P
Constant	-124.1	217.4	-0.571	0.584
A	-4611.6	1209.2	-3.814	0.005
B	6314.9	1271.7	4.966	0.001
C	-1567.7	1225.4	-1.279	0.237
D	-128.3	182.4	-0.703	0.502
A*A	9259.2	2088.8	4.433	0.002
B*B	-5899.2	2659.6	-2.218	0.057
C*C	1731.9	2656.6	0.652	0.533
D*D	2794.4	5408.5	0.517	0.619
A*B	-7552.6	2387.8	-3.163	0.013
A*C	10179.9	4159.4	-2.447	0.04
A*D	4044.7	3814.7	1.06	0.32
B*C	15874.2	6365.4	2.494	0.037
B*D	-2810.2	7211.7	-0.39	0.707
C*D	-7131	7656.4	-0.931	0.379
S = 0.9747 R-Sq = 93.5% R-Sq(adj) = 82.1%				

Table 5.3 Analysis of Variance for Flaw Size

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	109.412	109.412	7.8151	8.23	0.003
Linear	4	19.266	28.4669	7.1167	7.49	0.008
Square	4	9.332	60.6241	15.156	15.95	0.001
Interaction	6	80.813	80.8134	13.4689	14.18	0.001
Residual Error	8	7.6	7.5996	0.95		
Lack-of-Fit	2	0.188	0.1884	0.0942	0.08	0.927
Pure Error	6	7.411	7.4113	1.2352		
Total	22	117.012				

Seen in Table 5.2, those inputs, with a P-value‡ smaller than the significant level (alpha=0.05), are statistically significant to the output. Namely, there are five parameters contribute most to the flaw size: A, B, A*A, A*B, and B*C. The others, which have P-values bigger than the significant level, are not statistically significant to the flaw size. Therefore, they can be eliminated in the final response surface model.

In addition, R-squared (R-Sq) is calculated to determine how well the regression line approximates real data points. An R-Sq of 100% indicates a perfect fit. In this case, the R-Sq shown in Table 5.2 is 93.5%, which means the regression model is effective.

The analysis of variance shown in Table 5.3 further proves that the regression model is effective. The P-values of the regression including linear, square and interaction are all smaller than the significant level (alpha=0.05). The lack-of fit P-value of 0.972 suggests that the second-order polynomial model fit the physical process very well. Therefore, the response surface model equation achieved previously is effective.

‡ The P-value is the smallest level of significance that would lead to rejection of the null hypothesis H_0.[22]

5.2 Discussion

5.2.1 Optimal Settings

Based on the regression model achieved in section 5.1, the optimal settings for the smallest flaw size can be determined as follows: the pump flow rate is 35%, the temperature of the anilox surface on the operator side and the drive side are 28.8 and 29.2 degrees Celsius respectively, and the temperature of ink in the reservoir is 27.4 degrees Celsius. This will result a predicted mean flaw size of 0.006 cm^2.

5.2.2 Control Plan

Advanced statistical control charts, such as the Exponentially Weighted Moving-Average (EWMA) Control Chart, and the Cumulative Sum (CUSUM) Control Chart will be introduced to monitor the slight mean shift of the process in this phase.

An Exponentially Weighted Moving-Average Control Chart is a good alternative to the conventional control charts when detecting small shifts is of interest.[23] It plots exponentially weighted moving average values. A weighting factor is chosen by the user to determine how older data points affect the mean value compared to more recent ones.[24] Because the EWMA Control Chart uses a weighted average of all past and current samples, usually it can detect the small process shift a bit faster than a conventional control chart.

A Cumulative Sum Control Chart plots the cumulative sums of the deviations of the sample values from a target value.[25] It is usually used in high volume continuous processes. Since the CUSUM Control Chart presents both position and spread on the charts, it can pick up small persistent mean shifts.

5.2.3 Advantages and Risks of the Response Surface Model

The first advantage of the RSM method is that the response surface model can quantify the relationship between inputs and outputs. With the regression equation achieved previously, flaw size can be predicted by knowing pump flow rate, temperature of anilox surface, and temperature of ink. Therefore technicians might avoid dirty print (spot) and missing print (bad ink transfer) defects by keeping and controlling the inputs consistently in a certain range.

Secondly, the response surface model can provide a global image of the printing process instead of local focus. Though the printing process is complicated and it has hundreds of different defects, the response surface model can simplify the problem at an overall level since the output of the model is flaw size, a direct and final defect measure of the printed paper. In addition, it establishes the foundation for further research. By understanding the whole process, engineers and technicians can dig deeper into a specific root cause of defects.

On the other hand, the response surface model might also involve some risks during the printing production.

Statistically speaking, because some parameters have bigger P-values (bigger than the significant level alpha, 0.05), they are considered as not statistically significant or not significantly sensitive ones and are eliminated in the final mathematical regression models. However they cannot be ignored or released in the real production since the coefficients of the model are much larger than the parameters themselves. For instance, with even a small change in the temperature of the ink in the reservoir (e.g. 0.1 degree Celsius), the flaw size will become large after multiplying the coefficient 128.

In addition, if technicians and operators on the shop floor only focus on the response model and neglect to check other qualities of the product, they may discover other problems. The regression model is achieved by analyzing past data during a certain period for one product family only, so that analysis might not work for other products. The different products might introduce some new inputs or disturbance into the process.

Moreover, due to the limitation of the work, replicates of each treatment are not available, Thus the regression model only describes how large the flaw size will be. It does not show the variance model. If the area near the optimal solution is sensitive and the variance is big, the process might be in danger. For example, if the process is not under controlled or kept consistent, the process will shift from the target, resulting in bigger flaw size.

In sum, the response surface model can effectively predict the flaw size and it will work better with the help of a variance model. However, it might not be the optimal solution for the real production process due to the trade-off between flaw size and cost/ability of control.

5.2.4 Problems of ANOVA in the Analysis Phase

During the Analyze Phase of DMAIC, one-way ANOVA was conducted to test and prove the Cause and Effect Matrix done in the Measure Phase, and to quantify the relationship between each individual input and the flaw size. The four tables of results are shown in Table 5.4, Table 5.5, Table 5.6, and Table 5.7 respectively.

Table 5.4 One-way ANOVA: Flaw Size Versus Pump Flow Rate

Source	DF	SS	MS	F	P
Pump Flow Rate	7	41.03	5.86	1.16	0.381
Error	15	75.98	5.07		
Total	22	117.01			
S = 2.251 R-Sq = 35.07% R-Sq(adj) = 4.77%					

Table 5.5 One-way ANOVA: Flaw Size Versus Anilox Surface Temperature (OP Side)

Source	DF	SS	MS	F	P
Anilox Surface T (OP)	16	109.6	6.85	5.55	0.022
Error	6	7.41	1.24		
Total	22	117.01			
S = 1.111 R-Sq = 93.67% R-Sq(adj) = 76.78%					

Table 5.6 One-way ANOVA: Flaw Size Versus Anilox Surface Temperature (DR Side)

Source	DF	SS	MS	F	P
Anilox Surface T (DR)	13	101.21	7.79	4.44	0.016
Error	9	15.8	1.76		
Total	22	117.01			
S = 1.325 R-Sq = 86.50% R-Sq(adj) = 67.00%					

Table 5.7 One-way ANOVA: Flaw Size Versus Ink Reservoir Temperature

Source	DF	SS	MS	F	P
Ink Reservoir T	10	66.23	6.62	1.57	0.229
Error	12	50.78	4.23		
Total	22	117.01			
S = 2.057 R-Sq = 56.60% R-Sq(adj) = 20.44%					

As seen in the four tables above, P-values of the pump flow rate and the temperature of the ink in the reservoir are greater than the significant level (alpha 0.05). They were initially eliminated from further consideration for not being "statistically significant" to the output. However, that is incorrect from two aspects. One is that the R-square values for the pump flow rate and the temperature of the ink in the reservoir were not considered. They are 35.07% and 56.60% respectively. An R-Sq of 100% indicates a perfect fit. That means the two regression models do not fit the original data at all. The second mistake is that the assumption, the variables (inputs) must be independent, of doing a one-way ANOVA is neglected. Before the regression model is achieved, whether interactions exists between parameters is unknown. Thus the one-way ANOVA cannot be used in this case.

CHAPTER 6

Recommendations

6.1 Further Develop the Response Surface Model

More replicates and data are needed to further develop the response surface model. The response surface model achieved in the previous section can only predict the potential flaw size instead of the variance. After the variance model of the process is built, the variance of the predicted values of flaw size can be presented. The variance model can help technicians and engineers to identify the sensitivity around the settings they want to set. The mathematically optimal solution is not necessarily an optimal one for the real production. If the variance model shows that the area around the optimal settings has a large variance, it might be not good to set the machines at the mathematically optimal point since the process varying by itself will result in bigger flaw size. Trade-off between the flaw size and the variance should be taken into consideration.

In addition, further designed experiments should be conducted to present a more detailed global image of the process. Due to the constraints of this project, all the data were collected for one product family during certain period from the data backup system. Conducting real experiments according to the matrix of experiment design is needed.

6.2 Control of the Process

The trade-off between the mathematical optimal solutions and the practical production settings should be taken into account. Practical production is involved in many other factors beyond the process inputs, like costs of control, and ability of control. Indeed, careful discussions on the trade-offs are required to determine the most practical production settings.

In addition, EWMA and CUSUM control charts can be applied to plot the flaw size on the spot. Therefore the two advanced control charts can help the technicians and operators on the production floor to monitor the production process directly. If they find one red point on the chart (an out of control point), checking whether inputs are at their setting values is required immediately. With the help of the EWMA and the CUSUM control charts, large flaw size or serious defect alarms can be precluded in advance.

Furthermore, purchasing an improved temperature control system is recommended. After the optimal production settings are decided, the temperature of the ink should be monitored and controlled by a precise measuring and controlling system. The new system will help the technicians and operators to monitor and control the temperature of the ink in the reservoir.

6.3 Foundations and Reference of Other Further Projects

The regression model together with the variance model could be the foundation for the company's further projects dealing with more specific single root cause of printing defects. The more specific project is considered to improve the portion of the process into local optimal. When doing the more specific project, technicians and engineers should take the flaw size into consideration as a reference. Moreover, the local optimal solutions cannot conflict with the global optimal, the one achieved in the global regression model. If some loss of global quality is inevitable to improve and achieve the local optimal, detailed and further analysis of the trade-off should be taken into consideration.

CHAPTER 7

Conclusions and Future Work

7.1 Conclusions

This project demonstrates the application of the DMAIC in the printing process control. For a practical production process control project, the work can be conducted by following the roadmap of DMAIC.

The response surface model achieved in the section 5.1 presents and quantifies a global image of the process. The regression model can help to predict the value of potential flaw size. Therefore, operators and technicians on the shop floor can avoid large flaw size with the guide of the regression model. Special focus should be given to the pump flow rate, and the temperature of the anilox cylinder on both sides due to their statistical significant importance to the output.

In addition, the mathematical optimal solutions are not necessary to be the optimal for the practical production. Since costs, abilities of control, and other important business factors are involved in the practical production, loss of quality or trade-off is inevitable.

7.2 Future Work

The variance model can be developed by running more experiments to have sufficient replicates and data. The combination of the regression model achieved previously and the variance model could improve the real production in the future, where the variance of the flaw size can be achieved as well as the value of the flaw size.

Two factors, the viscosity of ink and the flow rate of chill water, could be added into the matrix for further experiment design. Due to the limitation of the project and the slight smaller importance scores they are rated in the Cause and Effect Matrix, the two factors are eliminated in the previous regression model. The further experiment could give a more detailed and better understanding of the whole process. Moreover, it will provide a foundation and reference for the future projects focusing on more specific root causes of each single printing defect.

References

1. Company X WCM for New Hires, September 2009, Singapore, unpublished material.
2. Company X Quality Presentation, February 2010, Singapore, unpublished material.
3. Venkatesh J., May 2009, "The Planned State of TPM (Part Two)", J. Fabricating & Metalworking.
4. Rentzhog, Maria, 2006, "Water-Based Flexographic Printing on Polymer-Coated Board", Doctoral Thesis, Royal Institute of Technology, Stockholm, Sweden.
5. Company X Printing Process Presentation, October 2008, Singapore, unpublished material.
6. FUTEC EasyMax.MC Operation Manual, 2006, Japan, unpublished material.
7. Company X Quality Presentation, February 2010, Singapore, unpublished material.
8. Company X Printing Defect Booklet, January 2009, Singapore, unpublished material.
9. Hardt, David, E., "Manufacturing Processes and Process Control", February 1996, LMP, Massachusetts Institute of Technology, Cambridge, MA.
10. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 2.
11. Company X Process Control Training Material, January 2010, Singapore, unpublished material.
12. Wiesenfelder, Heidi, "An Introduction to the Six Sigma DMAIC Process: The 5 Phases of DMAIC", http://www.brighthub.com/office/project-management/articles/23736.aspx, accessed July 29, 2010.
13. Ahoy, Chris, September 1999, *Facility News*, Iowa State University, Ames, Iowa.
14. Wiesenfelder, Heidi, "An Introduction to the Six Sigma DMAIC Process: The 5 Phases of DMAIC", http://www.brighthub.com/office/project-management/articles/23736.aspx, accessed July 29, 2010.
15. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 8, P368.
16. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 6.

17. Wiesenfelder, Heidi, "An Introduction to the Six Sigma DMAIC Process: The 5 Phases of DMAIC", http://www.brighthub.com/office/project-management/articles/23736.aspx, accessed July 29, 2010.

18. Myers, Raymond H., Montgomery, Douglas, C., Anderson-Cook, Christine M., 2009, *Response Surface Methodology*, 3rd Edition, John Wiley and Sons, TX.

19. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 14.

20. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 4, P160.

21. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 2.

22. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 4, P117.

23. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 9, P419.

24. Gad, Shayne, C., 2008, *Pharmaceutical Manufacturing Handbook*, John Wiley & Sons, TX, Ch. 3, P302.

25. Montgomery, Douglas, C., 2009, *Introduction to Statistical Quality Control,* 6th Edition, John Wiley & Sons, TX, Ch. 9, P402.