Resin	a hydrocarbon (an organic compound of hydrogen and carbon) secretion of many plants used as a raw material for industry
Response variable	is a measurable output of a process or quality characteristic of a part also called output variable such as part dimension, number of defects, processing time, etc.
Standard deviation	a measure of the spread (variability) of the process output, or the spread of a sampling statistic from the process
Sum of squares	the differences between the average values for the blocks and the overall mean. Commonly abbreviated, as SS
Vacuum	a state of being sealed off from external / environmental influences; state of emptiness; a perfect vacuum is 14.5 psi or 29.5 Hg.
Vacuum bagging film	an air tight flexible sheet placed over a lay-up and sealed along its edges
Voids	air or gas that has been trapped and cured into a laminate not exposed on the part surface (an empty space within the resin and fiber)

ABSTRAK

Pengurangan kecacatan adalah isu kritikal dalam operasi pembuatan. Dengan berkurangnya kecacatan, kos pengeluaran juga berkurangan, dan ini seterusnya membawa kepada peningkatan keuntungan bagi sesebuah organisasi. Syarikat A adalah pengeluar bahan komposit berteknologi tinggi. Sejak kebelakangan ini, ia mengalami banyak kecacatan dalam proses manual ‘hand lay-up’ dan ‘autoclave’ nya yang menjana produk yang dikodkan sebagai produk “L’ dan produk ‘T’ dalam tesis ini. Dari itu, sebuah kajian yang mengintegrasikan ‘rekabentuk ujikaji berstatistik’ (RUB), analisis kesan mod kegagalan’ (AKMK), beberapa ujikaji pinggiran, carta kawalan, dan aktiviti kawalan proses dijalankan. Kajian ini menggabungkan kaedah penyelesaian masalah dan penambahbaikan proses industri yang telah lama digunapakai dalam satu cara yang terkawal serta fleksibel, selaras dengan keadaan ketidak-tentuan yang sering dihadapi dalam persekitaran pembuatan yang sebenar. Ini menghasilkan pembangunan sebuah ’rangka penyelidikan’ yang generik, yang mana aplikasinya dapat menentukan *set-up* proses yang terbaik, yang memberikan bilangan kecacatan yang minimum pada produk akhir. Setelah mengambil kira keadaan di mana proses ini beroperasi, rekabentuk ‘fractional factorial’ ($2\wedge^{(4-1)}$ resolusi IV) digunakan untuk talian pengeluaran ‘L’, dan rekabentuk ‘blocked factorial dua-aras’ dengan 24 larian dan lapan titik tengah digunakan pada talian pengeluaran ’T’. Rekabentuk ini memberikan maklumat tentang pembolehubah yang mempengaruhi penghasilan kecacatan produk, dan membolehkan parameter penting proses seperti bentuk ‘core’, suhu, tekanan, dan kadar penyejukan, diperiksa. Setelah keseluruhan penyelidikan dijalankan, adalah didapati bilangan kecacatan dikurangkan dengan banyaknya, (iaitu dari 30 panel/bulan kepada 3

panel/bulan bagi kecacatan kedutan, dari 18 panel/bulan kepada 4 panel/bulan bagi kecacatan *delamination* pada talian pengeluaran ’L’, dan dari 25 panel/bulan kepada 5 panel/bulan bagi kecacatan *delamination* pada talian pengeluaran ’T’), dan ini menghasilkan penjimatan kos yang tinggi pada lantai bengkel. Selain itu, beberapa pengajaran telah dipelajari, dan kawalan proses diaplikasikan dengan sewajarnya. Selain aspek teknikal yang membawa kepada pengurangan kecacatan produk, sudut tertentu dalam perancangan, pemilihan pendekatan eksperimental, penglibatan pengurusan, dan pelaksanaan pendekatan penyelesaian masalah berstatistik juga dipelajari dalam kajian ini.

ABSTRACT

Reduction of defects is a critical issue in manufacturing operations. It goes without saying that defect reduction leads to manufacturing cost reduction, and this translates to increased profitability for the organization. Company A is a manufacturer of high technology composite materials. Of late, it has been experiencing high levels of defects from its manual hand lay-up and autoclave processes that generate products coded 'L' and 'T' in this thesis. Thus, a study that integrates the use of 'statistical design of experiments' (SDE), 'failure mode and effect analysis' (FMEA), several side experiments, control charts, and certain process controls is carried out. The study combines time-tested industrial problem-solving and process-improvement methods in a way that is both regimented as well as flexible, in line with the numerous uncertainties that inevitably present themselves in any live manufacturing environment. This culminates to the development of a generic framework, of which its execution enables the determination of the best process set-up that gives the minimum number of defects in the final product. Taking into account the circumstances under which the processes operate, fractional factorial design (2^ $^{(4\text{-}1)}$ resolution IV design) is used in production line 'L', and , a two-level factorial blocked design with 24 runs and eight center points is used in production line 'T'. These designs give much insight into this line's defect-causing variables, and enables the examination of important process parameters such as geometry of core, temperature, pressure, and cooling rates, to name a few. Consequently, after the entire research process is carried out, it is seen that the number of defects is greatly reduced (from 30 panels/month to 3 panels/month for wrinkles, 18 panels/ month to 4 panels/month for delamination in production line 'L', and from 25

panels/month to 5 panels/month for delamination in production line ‘T’), leading to tremendous cost savings on the shop floor.

To all my respectful and dear rests……

Chapter 1

Introduction

1.1 Background

Composite sandwich panels are widely used in aerospace, marine, automotive, rail and recreational industries because of their high specific strength, stiffness, corrosion resistance, stability, and ease of use in simple manufacturing methods (Vignjevic & Marengo, 2005; Antonio & David, 2005; Campbell, 2004; Reinhold, 2005). Bader (2002) discussed five different technologies used in the process of manufacturing composite panels, namely ‘hand lay-up & autoclaving’, ‘resin transfer molding’ (RTM), ‘resin film infusion’ (RFI), ‘pultrusion’, and ‘compression molded sheeting’. Some authors categorize the process into two groups, namely (a) those that are currently used in production and (b) those that are primarily under development.

The first category includes (a) manual hand lay-up, machine assisted hand lay-up, followed by autoclave curing, filament winding, and pultrusion and (b) resin transfer molding, deformation forming, and automated tow placement. It should be noted that the technologies in group (b) are in actual fact variants of the technologies in group (a). However, the production is usually small-scale compared to the first three processes in group (a). *Hand lay-up & autoclaving* is the most widely used method of composite production in the aerospace industry. Autoclaves are extremely versatile pieces of equipment, whereby pressure, temperature, heat-up-rate, and cool down rates are the main parameters involved. Since gas pressure is applied isostatically into the autoclave chamber, panels of almost any shape can be cured in it. The only limitation is the size of the autoclave itself (Gutowski, 1997). *Resin transfer molding* (RTM) is a closed mold pressure injection process to manufacture fiberglass composites. The advantages of this process include faster gel time, faster cure times, less waste, less environmental impact, and more constant part size/material usage as compared to alternative types of molding.

Resin film infusion (RFI) is a cost effective fabrication technique for producing textile composites. Dry textile pre-forms are resin impregnated, consolidated and cured in a single step, eliminating costly prepreg tape manufacture and ply-by-ply lay-up (Gutowski, 1997). *Pultrusion and compression molding* are widely used to shape composite materials into parts characterized by constant cross sections. In pultrusion molding, fibers are impregnated into a resin bath and the wetted reinforcement is then pulled through a heated die to be correctedly shaped and cured.

Pultrusion is a continuous process characterized by high automation, and is increasingly used to obtain complex parts for aeronautical, spacial and civil applications (Bader, 2002; Gutowski, 1997; Carlone et al, 2007). In contrast to pultrusion molding, compression molding typically employs two matched steel mold halves mounted in a hydraulic press with movement limited to the axis normal to the plane of the mold. This process can be used with a variety of materials. The mold may be heated or the composite may be preheated and formed in relatively cool molds. Regardless of the composite fabrication technique used to produce the parts, there are still several possible failures of the composite panels. Wrinkles, edge delamination, cracks, warpage, and edge effects are the most common manufacturing defects in composite materials.

Although composite manufacturing process has been undergoing constant technical changes and improvements, the hand lay-up & autoclaving process still persists as the method in use in the manufacture of more than half of all advanced aerospace composite structures. Its large use results from the extreme flexibility this method affords, allowing the construction of a large variety of panels in flat as well as highly contoured shapes. Additionally, because hand lay-up is a labour intensive process, it does not require large capital investments.

In the last two decades, most researchers focused on improvement of the composite's mechanical, physical and chemical properties. Manufacturing process improvement received very little attention. The mold process and the cure process are considered too simple to warrant further research. However, interest in this field is changing owing to composite materials' growing importance in the daily lives of most people in industrialized societies. Each year, composites find their way into hundreds of new applications, from golf clubs and tennis rackets to jet skis, aircraft, missiles and aircraft (Shokrieh & Taheri, 2006; Ahmad & Ahmad, 2006; Sanjay, 2001). Therefore, to improve the overall performance of composite materials, one must not only consider the mechanical, physical and chemical properties of the materials, but also the manufacturing process improvement and optimization, with a view to minimize process defects and to make the process more cost effective.

1.2 Problem Statement

The hand lay-up and autoclaving processes that composite sandwich panels undergo carry with them many variables and process settings that contribute to the formation of wrinkles, delamination, and warpage. These defects show up in the final product, which, if detected, will cause the product to be rejected. This adds up to the total manufacturing cost of producing the part. On the other hand, if not detected, the defects will contribute to the early failure of the part when used in the field. Given that the product is used in commercial aircrafts, early failure of it can be detrimental. In order to minimize the formation of these defects, the best process variable settings should be used during the manufacturing process of the parts.

1.3 Research Objectives

The main objective of this research is development of a *framework* to identify the best process settings for process lines coded ‘L’ and ‘T’ in a certain facility that manufactures composite sandwich panels used in commercial aircrafts. The ‘best’ process settings should enable the formation of the least number of defects in the final product. In order to achieve this main objective, several sub-objectives are targeted, as listed below:

(i) to apply a combination of process improvement methods, namely Statistical Design of Experiments (SDE), Failure Mode Effects Analysis (FMEA), and several side experiments in a unified way that results in the reduction of defects in the final product.

(ii) to use control charts to determine the state of the process before and after improvement methods have been undertaken.

(iii) to employ new and improved process settings that result in the least number of defects in the manufacturing line.

(iv) to incorporate and implement certain standard operating procedures (SOPs) in order to maintain the improved state of the process.

The attainment of sub-objective (i) above entails the use of a framework that can be used to study similar types of problems in other production lines within the facility. The generic nature of this framework also means it can be used in all cases of composite manufacturing processes, serving as a guide in a systematic manner through different stages of process improvement.

1.4 Research Methodology

This is an applied research carried out in a ‘live’ and dynamic manufacturing environment of a highly regulated industry. As such, the methodology used in the research is both preplanned as well as reactive to the circumstances the researcher finds himself to be in. After many discussions that provide insights into the engineering basis of the processes, the author develops a framework that integrates Statistical Design of Experiment (SDE), Failure Mode and Effects Analysis (FMEA), several side experiments, control charts, and certain process controls in a way that is both regimented as well as flexible, in line with the numerous uncertainties that inevitably present themselves in any live manufacturing environment. The general structure of the framework and what makes this framework original are discussed in detail in Chapter 3. In the course of running the research, the softwares ‘Minitab’ and ‘Design Expert’ are used to perform data mining, to set up the experimental designs, and to analyze data of selected process parameters.

1.5 Research Subject

The research focuses on two main processes, namely the hand lay-up process and the autoclaving process. The author selects two manufacturing lines that subscribe to these two processes, namely the ‘L’ production line and the ‘T’ production line. Both lines do not differ much from one another. The difference between the two is that the panels manufactured on production line ‘L’ are used on the front side of certain aircraft models, while the panels produced on the ‘T’ production line are affixed on the rear side of the aircraft.

The manufacturing specifications and procedures of both productions lines are almost identical. The study is conducted on the shop floor plant of a Malaysian composite manufacturing facility, referred to as “Company A” in this thesis. It is noted since January 2005 (for ‘L’ line) and March 2006 (for ‘T’ lines) that these lines are producing a large number of defective parts. Hence, the two lines catch the attention and focus of the top management of Company A.

The photograph of the panel which is produced on the said productions lines is shown in *Figure 1.1*. The panel with dimensional specifications which are 25.5x 17.5x 0.15 inches in dimension, and is manufactured using preimpregnated fiberglass; honeycomb core materials, aluminum alloy rub-strip, tedlar and adhesive film - a bonding material which is used to bond core and prepregs.

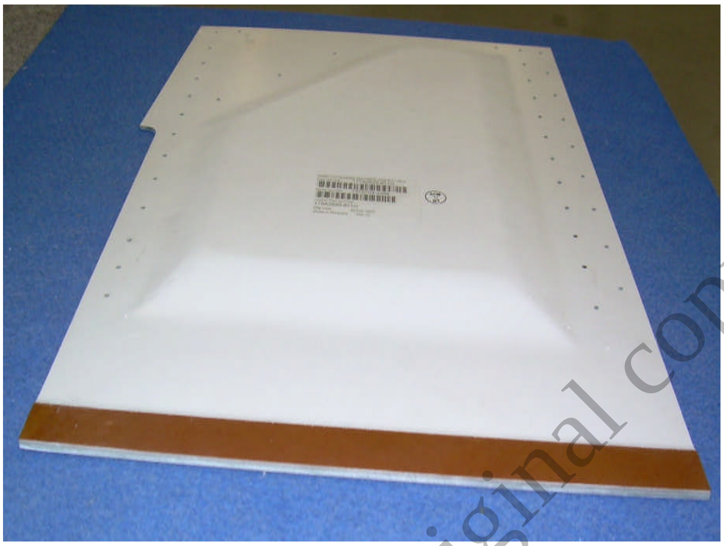

Figure 1.1: Photograph of the panel

1.6 Organization of Thesis

In this section, a brief description of each chapter in the thesis is given. Chapter 1 presents the different technologies used in the process of manufacturing of composite panels, most common defects, motivations, problem statement, objectives, research methodology, research subject and organization of the thesis and a brief description of each chapter is given.

Chapter 2 provides a survey of the research literature in the area of composite manufacturing defects, particularly wrinkles, delamination and warpage.

In addition, statistical design of experiments (SDE), failure mode effects analysis (FMEA), control charts, process capability, and process performance are incorporated. This chapter also reviews the integration of SDE, FMEA, control charts, process controls, and process monitoring approaches that lead to process improvement.

Chapter 3 describes the research methodology, which involves the development of a generic framework for manufacturing process improvement, which includes control and monitoring plans.

Chapter 4 presents the experiments carried out, data mining analysis done prior to SDE, and the use of FMEA for process improvement of production line ‘L’. This chapter also describes some process controls which are developed and implemented in making the process robust.

Chapter 5 reports the application, results and analysis of SDE, and several actions items which are taken for the improvement of production line ‘T’.

Chapter 6 provides an overall discussion of the entire research work.

Chapter 7 gives a summary and concludes the project with some suggestions for future work. In addition, some comments are made on the combinational use of the process improvement methods carried out in this research.

Chapter 2

Literature Review

2.1 Introduction

As stated in Chapter 1, wrinkles, delamination, and warpage are very common in the manufacturing of composite panels used in the aerospace industry. Much research has been carried out to improve the mechanical, chemical and physical properties of the composite materials, but relatively less research can be found in the area of composite manufacturing *process* improvement. As a result, strategies for the optimal manufacturing of composite panels with desired quality are difficult to find. Therefore, when this research began in 2005, there is little in the way of specific literature on studies to improve the manufacturing process of composite materials.

This chapter gives some background to the research available in the literature. It discusses the manufacturing of composite sandwich and laminate panels with the aim of showing how ideas from the literature review and from the real shop floor have influenced the direction of the research. Due to the sheer volume of literature in the general field of composite rejects, this chapter is not meant to cover the whole range of the literature. The broader literature relevant to the thesis is referred to throughout Chapters 1 – 7.

The relevant research in this area can be traced from 1947. A variety of work has been conducted to understand the causes of wrinkles, delamination and warpage, which are the three prevalent defects found in the manufacturing of composite panels for use in the aerospace industry (Gutowski et al; 1995; Bradaigh et al; 1990; Fraccihia & Bohlmann, 1994; Pagano, 1989; Tay, 2003; Aymerich et al; 2008; Parlevliet et al; 2007).

2.2 Composite Manufacturing Process and Defects

2.2.1 Wrinkles

Wrinkles are surface defects that commonly occur in a ridge or fold form on the surface of composite panels. It is the most common defect occurring in composite materials. In their study on wrinkles, Bradaigh et al (1990) writes that wrinkles are “lines of maximum shear to the laminate”, whilst Gutowski et al (1995) says that wrinkles are “the maximum interlaminar slip”. The scaling results reported by Gutowski et al. show that interlaminar shear forces produce the dominant loads that lead to wrinkling. Minimizing the shear forces between the laminates is the most important factor to reduce wrinkling.

Material-induced defects are caused by ‘bulk factor’ and the ‘tooling materials’ used. Bulk factor is a spatial gap between plies (a ply is a layer of thin material used to maintain laminate thickness) because of the rough and uneven surfaces of the plies. Bulk should be removed from the raw material before use. After the completion of ply collation on the mold, the lay-up is sealed in a plastic bag for autoclave curing. This is called ‘bagging’, and is detailed out in Chapter 4. If the bagging carry the bulk into the autoclave, there would be an approximately 30 % chance that wrinkles would form immediately after the panels are taken out of the autoclave.

After the completion of lay-up, panels are placed on a rack before they are inserted into the autoclave for curing. The mold used in this process is simply called the ‘tooling material’.

Besides serving as a ‘container’ to house the panels when they (the panels) are inserted into the autoclave, the function of the tooling material is to provide uniform temperature to the panel. At present, there are two types of tooling materials used on the shop floor, namely aluminum tooling material, and steel tooling material. The panels are placed on either one of these tool types, the selection of which depends on the availability of the tool. In the autoclave, the panels and the tool expand differently because of the difference in their density and their coefficient of thermal expansion (CTE).

The lay-up process, described in *Appendix A in note A.1*, provides the source of wrinkles cause. By far, the most important process in the current composite parts production is the hand lay-up process. In spite of steady progress to replace hand lay-up with automated processes, the hand-lay up provides still continues to be used because it is flexible and capable of making a wide variety of shapes. Unfortunately, the literature indicates that this process induces many possible wrinkle causes, including (a) improper squeeging around the radius areas of the sandwich panels, (b) improper lay down of prepreg on tool, (c) excessive ply movement during lay-up, (d) low viscosity of resin, (e) excessive resin movement, (f) improper tooling application during lay-up, and (g) inconsistent compound and contour areas of the panel.

Daniel and Abot, (2000) laid an emphasis on the improvement of composite manufacturing processes, and described in much detail their advantages and limitations. They linked the process operations by taking into account the problem of wrinkle formation on laminated sandwich composites (according to them, wrinkles can be formed by air entrapment, broken fibers, air pockets, node bond damage of core, and blisters created during the lay –up process).

As recognized by Mallick & Newman, (1988) wrinkle formation causes stiffness and strength reduction of the composite material. They further tried to correlate the formation of wrinkles, to the manufacturing process parameters such as fiber volume fraction, resin viscosity, geometry of honeycomb core, dryness of the core, prepregs surface character, core surface depression, aluminum foil properties, temperature, moisture, and many more.

The third wrinkle-inducer is the autoclave itself. Non-homogeneous CTE of the parts that are in contact with one another results in non-homogeneous expansion during temperature ramp-up, when the panels are in the autoclave. The part is stretched due to the expansion of the tool. In addition, thermal expansion generally increases with ply angle. For example, at 0°, a ply shows no expansion during cure, while at 90°, the ply exhibits large expansion during autoclave. This results in wrinkle formation on the panels. Because higher temperatures cause more thermal stress to be imposed on the panels, the number of wrinkles subsequently increases. This thermal expansion phenomenon can be controlled by optimizing the autoclave curing temperature ramp-ups.

Contrary to the dearth of literature on studies to improve the manufacturing process of composite materials, there is a fair amount of theoretical literature available regarding the formation of wrinkles in the panels. These studies are basically theoretical in nature and there are still too few experimental studies in the existing literature. A study by Hadi & Mathews (2000) found that many theoretical papers concerning wrinkling of sandwich panels have been published from 1940 onward, and most of them lead to substantially the same results, namely that the mechanisms involved in their formation are yet to be defined. For detailed information on wrinkling, the reader is referred to some of these earlier works which are presented and compiled by (Plantema, 1966; Allen, 1969; Mautner; 1948).

A study by Victor (2005) showed that wrinkling is induced by thermal bending of the panels. Victor analyzed the thermal bending phenomenon and obtained a solution using Levinson theory. In this theory, he proposed that facings and core material degrade due to non-uniform elevated temperatures, causing possible wrinkling. In opposition to this view, considered that wrinkling in the panels is not subjected to the non-uniform temperature. Rather, uniform temperature causes the formation of wrinkles.

Another approach to wrinkle occurrence is presented by Pandey & Son (1999), who discussed two different approaches: a layer-by-layer, LBL approach, and second a single-layer large-deflection SLLD approach. The first approach stated that during the lay-up process, resin-rich layers at the interfaces become relatively weak compared to the plies themselves. The differences in the stiffness of plies and the resin-rich layers at elevated temperatures enable plies to slip relative to each other during the curing process. In the second approach, wrinkle is started by the first layer lying towards the mold side; remaining layers through compressive load provide support to the first layer.

The stresses generated in the plies during the deformation are functions of time, temperature and processing rate. A processing condition could exist which would cause ply stresses to become high enough to cause wrinkles in the composite laminate. The researchers later observed that wrinkling starts on the first layer lying towards the tool side. Remaining layers provides support to the entire length of the above-mentioned inner layers.

2.2.2 Delamination

Delamination is essentially a separation of laminate layers within the panel. This type of defect can occur during part fabrication, assembly and during service. Campbell (2004) describes the possible causes of delamination, which include foreign materials, prepreg backing paper, improper part handling, incorrectly installed fasteners, and several others. Mallick & Newman (1990) note that "delamination or separation of layers is usually observed near the center line of thick parts". Contrary to Campbell, Mallick and Newman also provide the possible causes of delamination as excessive thermal stresses, internal stresses, in-complete curing and poor fibre wetting by the resin. In Section 4.4.4 author also provide some detail on delamination which is the most common defect in composite panels.

In the last two decades, many analytical and numerical studies have been carried to investigate the variables causing delamination. For example, a complete description of delamination in composite laminates (including stacking sequence, ply orientation, ply interfaces stresses and panel thickness influence) can be found in Chapter 9 of the book by (Carl, 1998). Other studies have also shown that interlaminar stresses can cause interlaminar separation or delamination. Interlaminar stresses are a function of the laminate stacking sequence. It can be controlled by proper design of the stacking sequence. By controlling delamination, more uniform and quality parts can be made. For detailed information on delamination, the reader is referred to some of the earlier works presented and compiled by (Charentenay & Benzeggagh, 1980; Devitt et al; 1980; Wilkins et al; 1982; Brien, 1982; Street; 1985).

Byrd & Birman (2006) investigated the causes of delamination and found that elevated temperature represents a major contributing factor for delamination. Similar conclusions are reached by (Gates et al; 2006), who studied the influence of temperature on laminated composite materials. Gates also investigated other process variables such as orientation of the panels. In another study, Shu (2008) shows that delamination is induced by the thermal stresses. According to (Ural et al; 2003), delamination is a very complex phenomenon and can be induced due to manufacturing, environmental and material aging effects. Caron et al; (2006), used laminate theory to predict delamination in angle ply laminates.

Hohe et al; (2003), discussed layered composites consists of an inhomogeneous material are subject an increased delamination as compared to homogeneous material. Feraboli & Kedward, (2006), described the potential source of impact damage which lead to delamination is due to “dropped tools” during manufacturing. Yam et al; (2004) used finite element model to investigate delamination in composite material. Tafreshi & Oswald, (2003), described various methods in great detail to study delamination phenomenon in composite laminates. For example, they used finite element technique and performed a parametric study to investigate the influence of delamination of composite material.

As for research into experimental methodology to study delamination, Gresham et al; (2006) used fractional factorial experimental design to study the main effects of different factors on the process’s response variables. Other researchers who used similar design of experiment methods in their study for process improvement include Grediac, (2004); Kim & Ramulu, (2004); Guillaumat et al; (2005); Edwards, (2005); Cannillo et al; (2006); Groove et al; (2006), used Taguchi experimental designs to investigate the variables most critical to successful bonding of laminates, leading to zero delamination.

2.2.3 Warpage

Warpage is a deviation from flatness of normally flat laminates due to process-induced stresses. Warpage arises because of non-uniform properties such as fibre volume fraction gradients and tool-part interaction. Tool-part interaction is due to the tool material having a high coefficient of thermal expansion (CTE) compared to the part. Plies which are close to the tool-part interface may get stretched, causing stress through the plies when the part cures. As a result, the parts warp away from the tool after autoclaving.

Work done by Albert & Fernlund, (2002), is a comprehensive study on spring-in (a reduction of angles on angled sections of panel) and warpage of composite laminates. However, they only considered design and process parameters but not material-related variables. In contrast, Campbell (2004) gives a complete detail of warpage, where he stated that composites by their very nature are directionally dependent materials and the resulting residual stresses are due to differences in ply orientations. For example, a 0° ply expands very little during cure because it has a very low CTE, whereas a 90° ply expands significantly because it is dominated by the thermal expansion.

Similar types of residual stresses are created at all ply interfaces having different orientations, e.g., at +45° and -45° ply interfaces. If the laminate is not balanced and unsymmetric, macro warpage will certainly occur during cool-down phase. An example of a balanced laminate is 0°, +45°, -45°, 90°, -45°, +45°, 0° whereas an unbalanced laminate would be 0°, +45°, -45°, 90°, -45°, +45°, 90°. A symmetric laminate is one that is balanced at its center line and forms a mirror image on both sides of the center line. For example, a symmetric laminate would be 0°, +45°, -45°, -45°, +45°, 0°, whereas a non-symmetric laminate would be 0°, +45°, -45°, +45°, -45°, 0°. Further, small deviations in ply alignment, even a couple of degrees, can produce warpage in thin laminates. While the warpage may not show up in thicker laminates, it is still there as residual stress, albeit constrained by the thickness of the laminate.

Mallick and Newman (1988) have concluded that warpage is caused by non-uniform cooling down ramp rates. They observed that thin sections of the panels are adversely affected by warpage compared to thicker sections as the thinner section of the part gets heated-up fast and cooled-down rapidly, causing the panel to warp. They further explained that warpage could be caused by flow-induced fiber orientation as defined in Chapter 6. Because various fiber orientations (0°, 45° and 90°) behave differently against the CTE of the parts in contact, differential shrinkage in various directions of the parts occur, leading to warpage. Mallick and Newman (1988) also observed that thick sections of the panels cool slower compared to thin sections. During autoclave curing process, thin sections solidify before thicker sections. As the thick section cools, it shrinks and the material for the shrinkage comes only from the unsoldified areas, which are connected to the already solidified thin section. This builds stresses near the boundary of the thin section. Since the thin section of the panels does not yield because it is solid, the thick section, which is still liquid, must yield. Often, this leads to warping of the laminates.

However, these are not the only causes of warpage. White and Hahn (1993) have observed that by performing autoclave processing of laminates at a lower temperature for a longer time, or by utilizing an intermediate lower temperature in a three-step cure cycle, residual stresses can be reduced by as much as 30%.

The same study by White and Hahn (1993) showed that for a given cure temperature, reducing the cure cycle time can reduce residual stresses, resulting in a decrease of warpage for as much as 60%. But, reducing the cure time may have an unwanted effect on the mechanical properties of the laminate. The same researchers also reported that cooling down rates may have some effect in reducing the residual stresses. They also observed that enhancing the cool-down pressure from 0.35 to 1.0 MPa has no noticeable effect on warpage.

There have been several methods developed for the investigation of process-induced warpage, ranging from simple analytical models to large and complex finite element based process models that attempt to simulate the entire cure process. The work of Koteshwara and Raghavan (2001) among others is a good study for the understanding of process induced warpage. They observed that thermal and cure shrinkage anisotropy, tool part interaction, uneven temperature, uneven resin flow, variation in the fiber volume fraction, and CTE within the part could be responsible for process-induced warpage.

A number of authors have offered similar explanations of how tooling and process variables might induce warpage in sandwich panels and composite laminates (Twigg et al; 2001; Daniel & Ishai, 1994). The mechanisms put forth consider a low CTE laminate against a tool with a considerably higher CTE. Under the circumstances, the tool and part are forced together due to autoclave pressure, and subjected to a temperature ramp. The laminate is then stretched due to the expansion of the tool material. Plies close to the tool are stretched more than plies farther away, creating a stress gradient through the thickness of the laminate. This non-uniform stress distribution is locked-in as the resin cures, and upon removal from the tooling, the resultant bending moment warps the part away from the tool material. It has been noted that this type of dimensional change is different from part to part, and can depend on parameters such as pre-preg age and resin viscosity, as well as process variables such as the rate of application and magnitude of applied pressure and temperature.

Other studies Fernlund & Poursartip (1999), discuss the effect of tooling material, cure cycle and tool surface finish on spring-in of autoclave processed composite parts. Pagliuso (1982), investigate warpage defect and conclude warpage is process induced defect and main causes are stresses or strains. Ridgard (1993), study warpage formation with respect to the mismatch between tool and part coefficient of thermal expansion (CTE). Fernlund et al (2003), study thoroughly residual stresses effect on warpage in composite material parts.

Kim et al (1989), discuss an anisotropy of the composite materials is one of the causes of warpage. Patterson et al; 1991; and Twigg et al; 2001 study warpage with respect to tool part interaction, and also state anisotropy effect of warpage in panels. Fernlund et al (2002), show other causes and multiple mechanisms such as effect of cure cycle, tool surface geometry, hand lay-up process and autoclave curing that lead to warpage failure of composite laminates. Warpage and its checking methods are discussed in more detail in Chapter 6.

2.3 Statistical Design of Experiments (SDE)

In this section, the author discusses the use of SDE by several researchers who have employed this method in order to improve manufacturing processes. The workings of SDE, however, are rather standard, and as such are presented separately in *Appendix B* of this thesis. Because of the many different terminologies used in this area of knowledge, the author also provides a glossary of terms used in SDE in *Glossary of Terms List*.

Normally, in order to gain insight about a process so that decisions and conclusions can be made to improve the process, experiments are carried out to reduce waste, defects, and cycle time. Statistical Design of Experiments (SDE) is a branch of statistics that provides methods for selecting the best (i.e., the optimum) values of process parameters without having to run very many experiments. It is a systematic experimental approach that is said to be the most powerful tool currently available because much information about the process under study can be acquired with as little work as possible.

In carrying out SDE, a series of structured tests are performed in which changes in the input variables of a process (or system) are made in a systematic manner. The effects of these changes are then evaluated to plan for the next stage of experiments, and this continues until the researcher finds the optimum setting of the process under study. Without SDE, a researcher interested to find optimum process settings may resort to the 'one-factor-at-a-time' (OFAT) approach whereby a process factor (say, pressure) is varied while other process factors (say, temperature, curing time, humidity, etc) are held constant. This approach does not guarantee that the optimum setting can be identified since interaction affects cannot be assessed using this approach. (More on the OFAT approach is given in *Appendix B.*) Instead, with SDE, the researcher uses a structured approach capable of assessing interaction and modeling quadratic effects to achieve optimal performance with minimal resources.

Different experimental designs have different combinations of experiments in which the process variables are prescribed at specific levels. The results of these experiments will lead to the identification of the process parameters that will ultimately reduce defects; in the case of this research, the defects are wrinkles, delamination and warpage. Each of the experimental methods has some attractive properties as well as drawbacks. Chapters 4 and 5 address in more detail the requirements for planning an experiment, such as the choice of controllable factors, factor levels, noise contributors and responses that need to be identified.

The most relevant work on industrial application of SDE comes from Placket and Burman (1946) who described the construction of very economical designs. Their designs are very efficient screening designs when only main effects are of interest. Box and Hunter (1961) introduced high resolution fractional factorial experimental designs for scientific investigations, which can be used to study main effects and as well as interactions with three or more factors. Daniel (1959) used plotting techniques (half normal plots) for the interpretation of experimental data from design of experiments, and Box and Draper (1987a) discussed the use of Response Surface Methodologies (RSM) for the optimization of processes. In recent years there has been a revival of interest in experimental designs in which Genichi Taguchi has been credited for the spread of this development although his methodologies have been criticized by several authors including Box (1988), and Nair (1992). Taguchi uses signal to noise ratio, where interactions are confounded in the ratio. He does not comprehend the interactive effect of the process variables on the responses, and neither does he acknowledge that many process problems are induced due to interactions of the process variables.

In rising above the drawbacks of the methods and designs employed, many researchers, starting from Box and Jenkins (1962), attempted the use of a *combination* of methodologies, popularly referred to as 'frameworks'. In this way, the shortcomings of the original method(s) can be compensated by the strengths of other methods used in parallel. Box and Kramer (1992) presented a thorough discussion of the combined use of statistical process control (SPC) and engineering process control (EPC) for process improvement, followed by several other authors, for example Nelson (2006), who used FMEA, design of experiment (DOE) and Ishikawa cause – and – effect diagram to solve certain industry problems. Thus, the recent literature has advocated the development of improvement 'frameworks', which are essentially a systematic way of using different techniques in combination of one another, to achieve manufacturing process improvement.

2.4 Failure Mode and Effects Analysis (FMEA)

Failure Mode Effect Analysis (FMEA) is methodology for analyzing potential reliability problems early in the development cycle of the product where it is easier to take actions to overcome the potential problems. It identifies potential failure modes, determines their effect on the operation of the product, and identifies actions to mitigate the failures. In other words, it is a method whereby the designer anticipates what might go wrong with the product. There are many types of FMEAs, namely system FMEA (focuses on global system functions), design FMEA (focuses on components and subsystems), process FMEA (focuses on manufacturing and assembly processes), service FMEA (focuses on service functions), and software FMEA (focuses on software functions), (Crow, 2002).

For detailed information on FMEA, the reader is referred to some of these earlier works presented and compiled by Stamatis (1995), explain the effective use of FMEA methodology to improve product design, process design and process improvement. He uses practical examples from the automotive, semiconductor, hardware, software industries. McDermott et al (1996), state it is useful technique to identify what possible failure may occur in the design and manufacture of products, and pinpoint their sources, propose preventive actions and evaluate the risks.

Some recent researchers have also reported on the FMEA approach that is often referred to as a “bottom up” approach see for instance Brown (2007) discussed risks and their consequences and quantify them using FMEA technique. Almannai (2008) combine the two standard techniques namely, FMEA and quality function deployment (QFD) to study an industry problem. Korayem & Iravani (2008) employed the combine use of FMEA and QFD to determine the failure modes in robot design. FMEA identifies a particular cause or failure mode within a system in a fashion that traces forward the logical sequence of this condition through the system to the final effects.

2.5 Control Charts

Walter A. Shewart first developed the charts in 1924, and it is still the most used in the industry. Control charts are used to determine whether a manufacturing process is in a state of statistical control. If the chart indicates that the process being monitored is not in control, the pattern it reveals can help determine the source of variation to be eliminated so as to bring the process back into control. Harriet et al; (1999) used 'statistical process control' (SPC) for manufacturing process monitoring. He points out that SPC in the form of control charts is useful in improving product quality by continually checking the "stable-state" system. When there is a departure from the stable-state of statistical control due to certain special events, the control charts attempt to detect this departure. The engineer or analyst can then look for the assignable causes that make the system behave this way, and eliminate them. Harriet et al; 1999 concluded that control charting is a useful tool in product and process improvement.

The work of Grant & Leavenworth (1996) and Douglas (2005) provide a more detailed discussion of the various types of control chart methods which can be used for product and process improvement.

The typical control chart plots are used to measure the average quality characteristic versus time or batch number. A centerline is drawn on the chart to represent the process average of selected quality characteristic that corresponds to the in-control state. To serve the purpose of continually checking the stable-state system, the upper control limit (UCL) and lower control limit (LCL) are plotted. When a point falls outside the control limits there is statistical evidence that the process is out of control (Zarandi, 2008). Then corrective actions can be commenced to look for the assignable cause.

2.6 Process Capability

Often, the recognition of a problem begins with an assessment of the magnitude of the problem. This usually happens before either data mining or experimental design. Process capability is used to measure the magnitude of the problem at hand. It is usually measured by Cpk, which indicates the short term capability of a process to meet process specifications. The estimated Cpk is given by:

$$\hat{C}_{pk} = \min\left\{\frac{USL-\hat{\mu}}{3\hat{\sigma}}, \frac{\hat{\mu}-LSL}{3\hat{\sigma}}\right\} \tag{2.1}$$

where $\hat{\mu}$ is the estimated value of the process average, $\hat{\sigma}$ is the estimation of process standard deviation computed from short term variation, USL is the upper specification limit and LSL is the lower specification limit.

Process performance is usually measured by Ppk, which relates the long term capability of a process to meet process specifications. The estimated Ppk is defined as

$$\hat{P}_{pk} = \min\left\{\frac{USL-\hat{\mu}}{3\hat{\sigma}}, \frac{\hat{\mu}-LSL}{3\hat{\sigma}}\right\} \tag{2.2}$$

where $\hat{\mu}$ is the estimated value of the process average and $\hat{\sigma}$ is the estimation of process standard deviation computed from long term variation. Both Cpk and Ppk are common indices that measure the capability of a process to meet specification limits. The indices measure the manufacturing product quality consistency and uniformity, and these are important criteria for judging manufacturing quality (Kane, 1986). The use of the capability indices was first explored within the automotive industry. Ford Motor Company (1986) used Cp and Cpk to keep track of its process performance and to reduce process variation. Boeing (1998) also recommended the use of Cp and Cpk to measure the capability of the manufacturing processes in its plants all over the world. The literature indicates that some researchers have reported wide use of process capability indices, for instance (Pearn & Chen, 1997; Mats, 1999; Juran, 1974).

Higher Cpk and Ppk values yield lower fall out rates and, as a result, are preferable. Cpk and Ppk values are usually compared to some target value with typical target values being 1 or 1.33 or 1.5 or 1.67. A Cpk value of less than 1 implies that the process is producing products that do not conform to specifications.

Chapter 3

Framework Development

3.1 Introduction

This chapter describes the research methodology, which involves the selection of softwares and development of a generic framework that can be used on this and other process improvement initiatives on the manufacturing shop floor. The framework is essentially one of the deliverables of this research, and its successful development indicates the fulfillment of one of the sub-objectives of the research, as depicted in Section (1.3) part (i) and (ii). As will be made apparent in the subsequent sections of this chapter, the said framework concerns the joint use of statistical design of experiments (SDE), failure mode and effects analysis (FMEA), side experiments, control charts, process control and monitoring, and adjustment policies that ensure the sustained achievement of predefined process goals. Because its construction is based on general approaches to solve industry problems, the framework is generic. Hence, if fine-tuned appropriately, it provides a structured technique to solve any industry problem, and offers a general approach that can be applied to conceptual and concurrent design of products, manufacturing processes, and other business processes.

3.2 Selection of Software

3.2.1 Minitab

As discussed in Chapter 1, Minitab is one of the softwares, used in this study. Minitab is used to perform data mining of the collected data from the experiment facility. Minitab is chosen because with SDE, it has powerful graphics engine, and an extremely simple interface. Most of Minitab's graph attributes are easy to configure and can be edited after the graphs are created. Minitab supports most of the other statistical analysis and methods that most users use, including statistical process control (SPC), reliability calculations, and gauge repeatability and reproducibility (R&R). In addition, Minitab is often used in conjunction with the implementation of Six Sigma, capability maturity model integration (CMMI) and other statistics based process improvement methods. In this research the researcher is used Minitab for regression analysis, time series analysis, analysis of variance (ANOVA) and various other statistical charts and diagrams.

3.2.2 Design Expert

The researcher uses the computer software *"Design Expert" V 7.0.2 Stat* (Ease Corp, Minneapolis, USA) for the design and construction of the main experiments carried out to improve the manufacturing process. This software is one of the many that can be found in the market. Others that belong in this category are ECHIP: 6.4.1 software for design of experiments, SAS–JMP4, SYSTAT 10, STATISTICA, SPSS and ADOE. *Design Expert* has been chosen in this research on the basis that it is known to provide the most comprehensive guidance in the classification and analysis of industrial quality- related problems, from which suitable solutions can be devised for process improvement. Features available in this software include a variety of design strategies such as minimum-run resolution IV, two level factorial, central composite design (CCDs), two-level-full and fractional factorial design, and a multitude of others. The design strategies, particularly adopted in this research discussed in detail in Chapter 4 and 5. A more in-depth study of *Design Expert* shows that it compares favorably to the software *ECHIP 6.4.1* which is flexible and user-friendly for non-statistician users. Which one has step-by-step guidelines that make it very simple to use? However, *ECHIP* fares slightly better in terms of being user-friendly for non-statisticians compared to *Design Expert* in that *Design Expert* requires proper training for non-statisticians. Still, all in all, *Design Expert* is recommended by many researchers to be superior to others, particularly in terms of various design creation strategies and ANOVA tables of the analyzed results. These areas are not as clear in *ECHIP* as they are in *Design Expert*.

3.3 Development of Framework

As stated in Chapter 2, the use of 'frameworks' (which is a *combination* of methods rather than one method alone) that complement the strengths of certain methods while compensating the weaknesses of others have emerged amongst those interested in process improvement. Given the complex process flows used in Company A, it is decided that the development and use of such framework is most apt. Hence, the researcher's task now turns to that of developing the said framework. Prior to designing the framework, a thorough pre-study is performed on the production line. The pre-study involves process mapping of both production lines and studying numerous available data of the two processes. Through this intensive pre-study, the researcher is able to garner useful information about the process factors involved, including hard-to-change variables (for example the temperature and pressure used during the autoclave curing process), design-related variables (for example part shape and mold design) and other related variables to determine the process settings that would give rise to minimum defects that occur in the final product. An overview and process mapping of the manufacturing process of production lines 'L' and 'T' are given in note *A.1*, *Figure A.2* and *Table A.3* in *Appendix A*. Once the processes are thoroughly understood, a draft of the research framework is carefully developed, taking into account the current state of the processes and the options available to the researcher. All options are cautiously weighted against one another, and the most feasible one eventually selected. The framework is then put to test by the actual implementation of its steps during the course of this study. A summary of the framework is given in *Figure 3.1*, while its comprehensive development is elaborated in Sections 3.4 to 3.13 of this thesis. As can be seen in Figure 3.1, the framework comprises of process data collection (data mining to determine process defect location and process stability), evaluation planning, selection of experimental design, implementation of the designed experiments, implementation of failure mode and effect analysis (FMEA), implementation of small targeted experiments, implementation of process controls, monitoring of process performance, and assessment of process capability and performance. Intertwined within these steps is rigorous analysis of the output data. In the sections that follow, each of the steps in the framework is elaborated.

3.4 Preliminary Data Collection

The research starts with data mining analysis to gain deeper insight of the manufacturing process. As Box (1997) discusses, in-depth process data gives an efficient understanding of the process. In Company A, much data is collected on the shop floor. When performing background study of the processes selected, the researcher is inundated with a flood of data that may not necessarily be of use to this research. After much deliberation, it is decided that data on process stability is most relevant in the context of this research. As it is in any manufacturing process, variation of the process output comes from two sources – namely common cause and special cause. Data from the process needs to be monitored over a period of time, and the behavior of the process, as depicted by the data collected, process

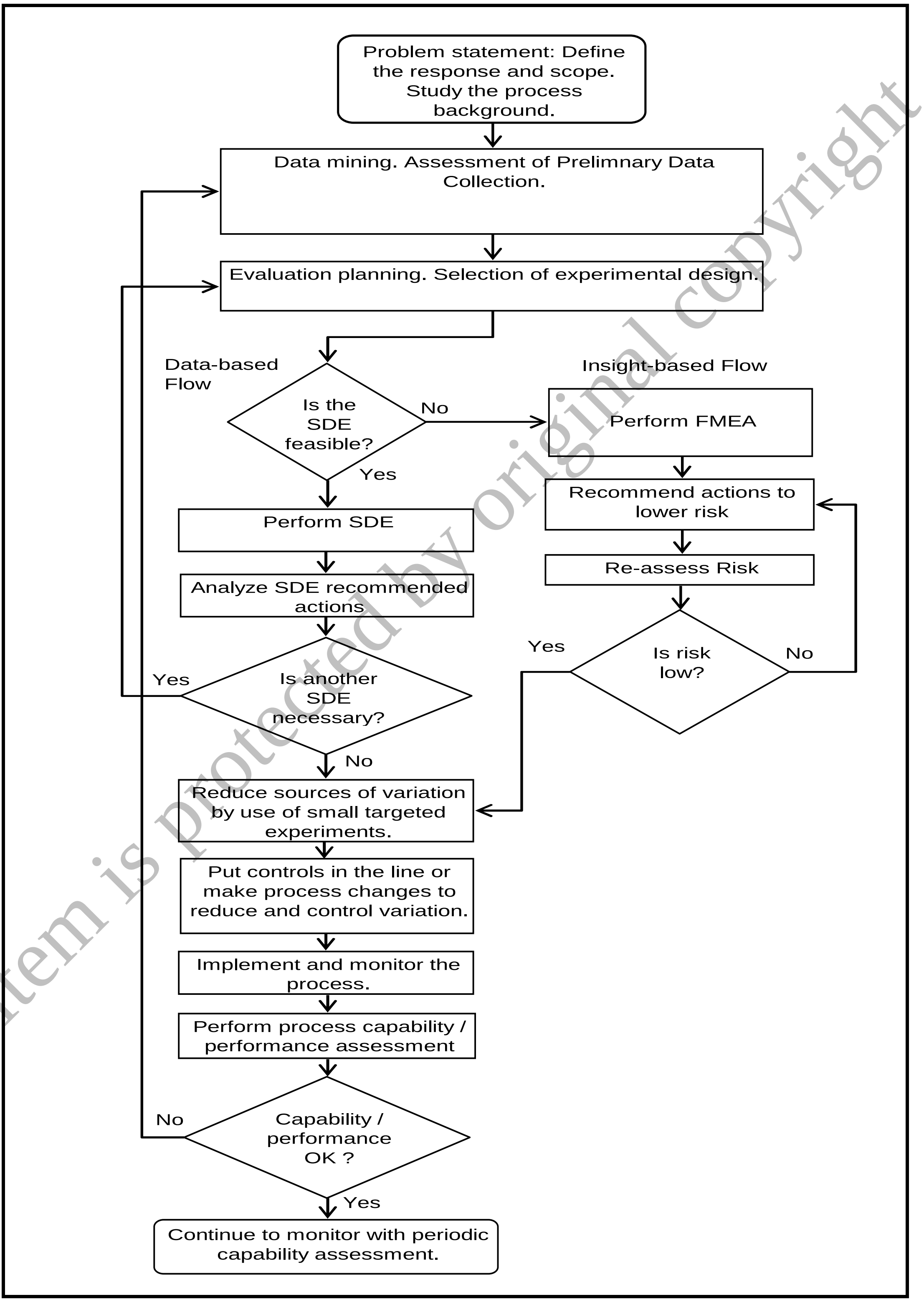

Figure 3.1: Framework development flow

stability can be gauged. From here, the existence of common causes and special causes can be identified. Special causes need to be removed before improvement on the process can be attempted, else the improvement will not last. For this, the researcher constructs controls charts, namely the individual moving range (I-MR) chart, p-chart, trend analysis plot, probability chart for data of defects collected from processes on 'L' and 'T' production lines dated January 2005 to June 2006, and March 2006 to September 2007. In Sections 4.4 and 5.4, the author discusses in detail the data mining and assessment of stability of the processes in hand.

3.5 Evaluation Planning – Selection of Experimental Design

Armed with insight information on the state of the processes, the researcher is now in a position to design experiments which can enable the output data to be used to the best advantage. With the nature of the problem already understood so some extent, the resolution of the designs and the choice of strategies are considered, taking into account the expected design performance and the estimated benefits of each design option. As all options carry potential rewards and risks, this stage of the research development is the most thought-demanding.

3.6 Feasibility Study on SDE

Once the experimental design is selected based primarily on available data and engineering knowledge of the processes, the feasibility of the design is now considered. The main feasibility criteria comprises of cost, time, and practicality. There should be enough resources to run the experiments, and there should also be correct production time to run them the correct sequence. Change of process settings may upset manufacturing schedule, and hence care is taken when planning the runs. In addition, the number of runs and the chances of success are also considered in the feasibility study. If the study on SDE implementation finds that SDE is not feasible to be carried out, the next course of action will be that of taking up failure mode effect analysis (FMEA).

This route is essentially that of 'insight-based' (as opposed to 'data-based' if SDE is to be implemented), whereby the researcher, harnessing the existing engineering knowledge of the process engineers, carries out side experiments and makes decisions that should improve the overall performance of the process.

On the other hand, if the study shows that it is feasible to carry out SDE, then the research will proceed to SDE implementation and its subsequent analysis. This is the preferred route of the research, whereby decisions on the process are made based on data collected when running the SDEs. This route is the 'data-based' route, as opposed to the 'insight-based' route of the FMEA option.

3.7 Failure Mode and Effects Analysis (FMEA)

As depicted in *Figure 3.1*, if the feasibility study on SDE shows that it is not feasible to carry out SDE, the research branches out to implementing failure mode and effects analysis (FMEA). Hence, FMEA functions as the alternative plan to SDE. FMEA has a worldwide recognition across many industries. It anticipates, evaluates and reduces risks in the manufacturing process, and makes the process in stable condition. Sections 4.8 to 4.8.8 describe in some detail a series of action items carried out to reduce risks in the manufacturing process as a result of the FMEA

3.8 SDE Implementation and Data Analysis

The next step in the research, should feasibility study on SDE proves viable, is that of full SDE implementation. Because the research is carried out on ‘live’ process producing ‘live’ and saleable parts, this step requires much planning and coordination. The movement of parts and the work schedules of operators and technicians alike are studied in order to run the SDEs without causing much disruption on an already busy and complicated process flow.

In addition, because the SDEs are to be implemented without compromising on the rigorous features embedded within the design, operators’ and technicians’ full support and involvement are most needed. Should operators and technicians ‘skim’ or ‘skip’ some of the SDE procedure planned (for example, not performing the runs according to pre-determined sequence), the results of the SDEs may not be valid.

Knowing full well that the risk of ‘skimming’ and ‘skipping’ may lead to dire consequences, the researcher spends most of his time on the shop floor during the time when the SDEs take place.

In addition, the researcher also spends much time cajoling and convincing members of the shop floor to appreciate the risks of skimming and skipping, and join the researcher in ensuring that the SDE plan is complied even to the smallest and minutest details. After the SDEs are performed, analysis of the data collected is carried out. The analysis will show which SDE yields the best results. Analysis is carried out in the software ‘Design Expert’. SDE implementation and data analysis are given in Sections 5.6 and 5.7 in this thesis.

3.9 Running of Small Targeted Experiments

Next in the framework is that of performing small targeted experiments that aim to resolve specific problems encountered in the process. The problems are resolved by focusing on how variation can be controlled and reduced. The experiments are identified and performed by the researcher with the support of technicians and engineers within the company. The researcher would know that the small targeted experiments are successful or otherwise by studying the results of the experiments.

Results that are desired should be further studied, and the experiments should be repeated if necessary, to ensure that the results are genuine, and not merely coincidences that may not be repeated in the future. Once the researcher is satisfied that the results are genuine, process improvements based on the results can now be proposed.

In this thesis, the running of small targeted experiments is described in Sections 4.9.1 to 4.9.5, and 5.8.1 to 5.8.4.

3.10 Incorporation of Controls onto the Process

Process improvement is not good enough if it happens only once. Hence, whatever measures taken that produces good and desirable results should be incorporated into the shop floor’s standard operating procedures (SOPs). This becomes the next step of the research framework – that of consciously incorporating improvement plans so that they become part of the daily routine of the operators and technicians. Incorporation of the plans is done via addition of equipment, putting up the appropriate signage, operator and technician training, and several other means.

3.11 Implementation and Monitoring of Process

Once controls are in place, the researcher must ensure that they are acted upon, and not merely fixtures that seem to be part of the process. For this, monitoring of the process is carried out appropriately. Process monitoring is best done with the help of suitable documentations and records made and filed accordingly. These become objective evidence that the improvement plans are carried out not just during the time when the researcher is around, but also way after the research 'proper' is completed.

3.12 Process Capability and Performance

A certain amount of time is needed before one can be very sure of the effectiveness of the changes and controls incorporated in the process. In other words, the process must be very stable before the success of the improvement efforts can be gauged for sure. In this regard, the next step of the framework involves the running of process capability and process performance studies. This is essentially a 'yes' and 'no' juncture of the research process, whereby should the results of process capability and process performance studies show that the improvement seen previously do not continue, then the researcher should go back to the beginning of the work where data mining is carried out, and brand new experiments be designed all over again. On the other hand, should the studies show affirmative results, the researcher will continue to the next step – that of continuing with the improved process, and at the same time perform process monitor and make capability assessments of the process from time to time.

Process capability and process performance are described in some detail in Sections 6.4 and 6.5 of the thesis.

3.13 Continued Process Monitor and Capability Assessment

Even if data from process capability and process performance studies show that the process is stable and that the previous improvement efforts are genuine, one can be sure that the process starts to drift the moment it starts to operate. Process drifts may be very small and slow, but the result of such drift might show up earlier than one thinks, and often at the expense of product quality and manufacturing cost. That is why after improvement efforts have been carried out, shop floor engineers should continue to monitor the process and make periodic capability assessments. The results of such assessments may warrant shop floor engineers to revamp the whole manufacturing process. Should the engineers decide to do this, the research framework developed in this study comes in handy.

3.14 Discussion

Development of the research framework involves many aspects. For starters, it requires a thorough knowledge of the research subjects – in this case – the hand lay-up process, the autoclaving process, the 'L' production line, and the 'T' production line. Apart from process set-ups and equipments used, knowledge of the research subjects extends to that of acceptance and rejection criteria of the parts as they go through the process in its entirety.

Next come knowledge of the tools used in carrying out this research. The researcher studies the methods of statistical design of experiments, failure mode and effects analysis and numerous statistical tools such as ANOVA, residual analysis, main effect plots, interaction plots, contour plots, surface plots, or optimization with desirability functions. Apart from understanding the methods, the correct application of the methods under real industry circumstances are also required.

Once knowledge of research subjects (the processes and the production lines) and research tools (SDE, FMEA, other statistical tools) are mastered, the research framework is appropriately developed. It is developed taking into account all possible outcomes of the research process. For example, the original intention of the research is to carry out SDE on an important sub-process, and data collected during this time is to be used to determine the best process setting. However, it is argued during the development phase that the experiment may not yield desirable results, and because the work is not carried out in a lab but rather in a 'live' industry with a profit-making motive, alternative routes should be thought of in the event that the management, for whatever reason, decide to halt the project carried out on a particular production line.

The framework is developed by combining data-based and insight-based sources. The coordinated efforts of the author, process engineers, process managers, and process technicians refine the framework and make it a feasible and effective methodology that can be applied in other similar industrial situations, with some adjustments which depends on the industry situation. The framework integrates several problem-solving schemes in a way that makes it both unique and generic.

Upon greater scrutiny, the framework is rather general in nature. For example, SDE is a well known approach to problem solving and process improvement, and many organizations use it on a regular basis. Similarly, FMEA has world wide recognition across many industries. Control charts are also quite prevalent in industry, as observed in the literature. Process controls are the norm in any industry for the purpose of process monitoring. Experimental knowledge, which forms the basis for carrying out side experiments, is considered to be of high value, and hence side experiments are commonly carried out in the industry.

Hence, all in all, it is obvious that this framework rests on well established ideas in the industry. Hence, it may be disputed that this framework is not original. While the author agrees that the components of the framework are not original, the *combination* of methods is. Here, SDE, FMEA, control charts, side experiments and engineering process controls are combined and put in sequence in a unified and coordinated way in the form of this research framework.

If one uses only SDE, one may garner some useful information about the process variables and noises, but, as the framework suggests, one does not have any option to go through should a study on the SDE shows that it is not feasible for the SDE to be continued. Similarly, carrying out FMEA may not be sufficient to achieve effective process improvement. The use of control charts is useful to monitor output errors from process, but it still is not able to provide the full solution of an industry problem if it is not used in conjunction with other tools in a coordinated manner.

Likewise, mere monitoring of the process through the use of process controls will not be sufficient to achieve targeted goals. For instance, if the process is shifted because of the drifting of certain process variables, application of process controls cannot bring the process back to its target level (Douglas, 1994; Palm, 1969). Given all the above points, and taking into consideration the time and resource limitations on the part of the researcher, a joint use of the methodologies – combined and executed in a concerted effort – is obviously needed, and hence this framework. The originality of this framework lies in its unique combination of tools, sequence of use, and flexibility when one faces with very real industry situations. The framework is put to test when it is used in the course of this work, where it is found that expensive defects in a certain composite panel manufacturing company is, to a great extent, minimized.

3.15 Conclusion

This chapter describes the development of the research framework, which combines data-based and insight-based inputs. Construction of the framework also demands text-book knowledge of statistics to be integrated within the structure of both data- and insight-based inputs. Data-based input comes from existing databases taken from shop floor records as well as new information churned out from experiments that are deliberately run to collect the data. On the other hand, insight-based input resides in the minds of shop floor engineers who are thoroughly familiar with the manufacturing process, and hence have almost an intuitive feel of the behavior of the process. The researcher, through numerous discussions with shop floor engineers, brings out this tacit knowledge, and sieves through it to extract the portion that can be put to good use in the framework.

Culling all three information sources (text book knowledge, data-based knowledge, and insight-based knowledge), the researcher constructs the research framework that is eventually put to test during the course of running the research.

Chapter 4

Application of SDE and FMEA to Improve Production Line 'L'

4.1 Introduction

In this Chapter the selection of research sub-process 1 – the 'L' production line and the outcome of the experimental design carried out as per the experimental matrix created by the 'Design Expert' software for the said production line is presented. This chapter also discusses the data mining analysis done prior to SDE, as well as the use of Failure Mode Effects Analysis (FMEA) for process improvement. Suggested improvements to the manufacturing process and process controlled documents are also highlighted in this chapter.

4.2 Selection of Research Sub-process 1 - the 'L' Production Line

It is noted in Chapter 1, there are many ways to manufacture composite panels. Of the various composite manufacturing methods, there are five (hand lay-up & autoclaving, resin transfer molding (RTM), resin film infusion (RFI), pultrusion, and compression molded sheeting), as detailed in Chapter 1.

By far, the most important process in terms of current aerospace production is the hand lay-up and autoclaving. As noted earlier, this method is flexible and capable of making a wide variety of contour in shapes and larger in length parts. The author selects his research subjects on the basis of the priority given by Company A's top management. In the common highly-regulated but profit-oriented industrial scenario, priority is most definitely apportioned based on safety and cost issues. In the case of Company A, research sub-process 1 – the ‘L’ production line – fulfils both priority criteria. Production line ‘L’ at the research facility uses hand lay-up process techniques to produce panels for a certain aircraft model.

The panels are used in the front end of the aircraft. These panels, since Jan 2005, continuously exhibit wrinkles and delamination. Wrinkles occur on aluminum foil surface of the panel, while delamination occur at the ply interface of the panel, leading to high part rejection rates, as discussed in more detail in Section 4.4.4. Therefore, company A advised the author and the engineers within the company to study the ‘L’ production line using statistical methods to reduce the number of defects in this line. Hence, the ‘L’ production line is selected as the first research subject in this study. The entire ‘L’ production line includes about 40 individual lay-up steps. The major steps of this composite manufacturing production line are outlined in *Figure A.2 in Appendix A*.

4.3 Choice of Factors and Factor Levels in Production Line ‘L’

In this section, the selection of factors and factor levels is discussed. It has to be noted that this selection is largely a knowledge-based activity. A series of discussions with company A’s process engineers are initiated, with a view to extract as much process and engineering insights as possible from the knowledgeable engineers who run the process for many years. It is decided that a numbers of controllable factors from the hand lay-up process are critical in terms of influencing the quality of the final product. However, because it is not economical to set up an experiment to run all the factors, the list is further pared down to the five most critical factors, namely, geometry of core material, prepregs surface quality, core surface depression, aluminium foils porosity, and temperature of the lay-up room.

In addition, five controllable input factors from the autoclave curing process that are identified to influence the quality of the final product are vacuum, heat up rate, temperature tolerances, cure time and cooling rates. There are also input variables in the processes that are uncontrollable. These are humidity, incoming air quality, voltage fluctuation, operator tasks, and panel thickness. The response variables of the composite manufacturing process are wrinkles, delamination, and warpage. The probable combination of input factors, narrowed from the lists include seven factors as shown in *Table 4.1*, along with the proposed factor levels. After more discussions with the process engineers, it is decided that the number of factors needed to be reduced even further. The factors are narrowed down to those shown in the *Table 4.1*. The proposed factor levels are also given in the table.

Table 4.1: List of process factors with levels

Sr.#	***Process Factor***	***Low***	***Center Point***	***Upper***
1	Geometry of Core	19.5º	22.5º	25.5º
2	Cure Temperature	180ºF	190ºF	200ºF
3	Cure Time	15 minute(s)	37.5minute(s)	60minute(s)
4	Heat-up-rate	0.5ºF/minute(s)	3.75ºF/minute(s)	7.0ºF/minute(s)
5	Pressure	10psig	15psig	20psig
6	Cooling rates	5ºF/minute(s)	5ºF/minute(s)	5ºF/minute(s)
7	Vacuum	-22inch Hg	-26inch Hg	-30inch Hg

In order to perform the experiment, the author and the engineering team within the company again review the list of input factors. Finally, the list of seven factors in *Table 4.1* is further reduced to only four (4) so as to minimize disruption to manufacturing in the form of setting change-overs. The four factors chosen for the experiment are pressure, temperature, heat-up rate and curing time. Selection of these factors is made based on what is perceived as most influential in the formation of defects.

4.4 Data Mining on Production Line 'L' Data

This section presents the data and analysis of the data collected before composite manufacturing process improvement. Before making any process changes, it is advisable to learn as much as possible about the issues at hand by performing data analysis on the current process. The data mining analysis will enable the researcher to (1) identify the underlying problem in the process, (2) to understand the problem in more detail, and (3) to determine clues as to which inputs may be affecting the output? Thus, data mining may make the experimental design and use of FMEA more efficient. In this study, data mining is performed using Minitab V.14 computer software.

4.4.1 Assessment of Stability

Process assessment stability is normally performed to determine whether or not the process is operating in a stable condition. If the process is found to be stable, then only common cause variation is present and it will be necessary to analyze the sources of these common causes of variation which are part of the usual process operation.

If the process is unstable, then special cause variation is present, which indicates that causes which are not part of the usual process are disrupting the performance of the process. To return an unstable process to a stable condition, special causes should be found and eliminated with preventive measures employed to prevent recurrence. In order to know whether special causes are present in the process, an individual moving range (I-MR) chart is normally used. An I-MR chart is a control chart for variable data that uses individual measurements of a quality characteristic. The control charts are one of the most efficient statistical process control (SPC) tools. They are used to detect assignable causes of variation that can be responsible for the problem. This chart can also be used in situations where opportunities to obtain data are limited, such as low production volume. This chart is useful to display and manage variation in a process out-put over time.

It is also helpful to distinguish special from common causes of variation. Engineers can use this chart for process improvement. In this study, the I-MR chart is selected to be used on production line ‘L’ because the data are individual values, rather than subgroup averages. The chart is proposed to be constructed to monitor some prime uncontrollable input parameters.

After many discussions with the shop floor process engineers, the parameters selected are resin viscosity, fibre volume fraction, heat-up and cooling rates at the autoclave curing process. These parameters are selected after conducting several side experiments and considered responsible for the process defects.

This control will be applied later on the production lines by the engineers within the company. An, I-MR chart for the wrinkle data from the time period Jan 2005 to Jun 2006 is given in *Figure 4.1*, which shows that the wrinkles are due to common causes (which are present in every process and produced by the process itself, means the way the process activities are performed.

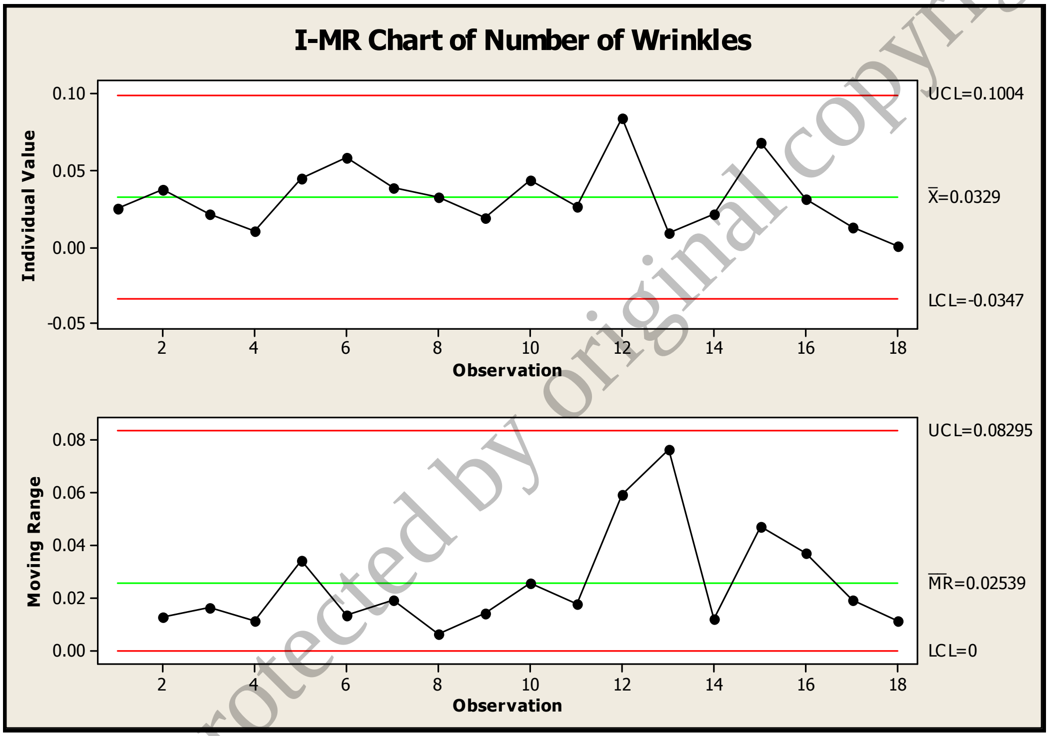

Figure 4.1: I-MR chart of wrinkle occurrence

Common causes can be removed or lessened but requires a fundamental changes in the process. A process is stable, predictable and in-control when only common cause variation exists in the process), as all points in the chart are in control. To refine the I-MR chart, a more restrictive model is applied, in this case a binomial model in which it is assumed that there is a constant probability of obtaining a wrinkle and that wrinkles occur independently (i.e., the occurrence of a wrinkle is not related to the occurrence of another wrinkle). The same type of I-MR chart which is used for wrinkles defect above to check for stability of the process is also used for delamination defects.

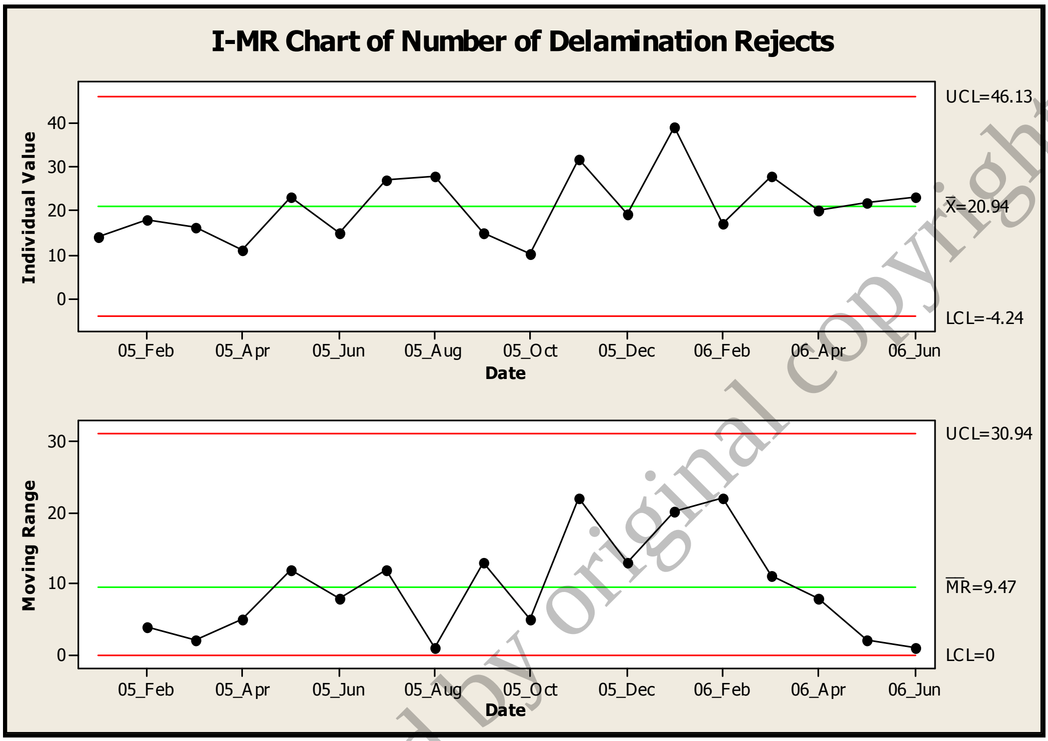

Figure 4.2: I-MR charts of number of delamination rejects

From *Figure 4.2*, it can be seen that the delamination occurrence has been stable over the time period of Jan 2005 to Jun 2006. Apart from I-MR chart, the p-chart is also proposed to be used on the manufacturing shop floor. The p-chart is an attribute control chart used primarily for the fraction defective. It is decided that p-chart is the most appropriate control chart to be used in company A because this chart is useful when variable data cannot be obtained for the quality characteristic selected.

The p-charts are equally useful to monitor the fraction defectives, for tracking the quality level of a process before any re-work is performed, to identify any sudden changes to quality levels be they positive or negative, and to assess the effects of improvements made for process improvement. The quality characteristics chosen for monitoring through p-chart are node bond damage of the core material and panel thickness and surface roughness of the mold. These parameters are chosen because they give the highest impact on the formation of wrinkles, delamination and warpage on the panels. In order to avoid these defects, the operator should not use plies with folds, scratches and core materials have node bond damage.

An example of p-chart is shown in *Figure 4.3*, where the quality characteristic used is wrinkle rejects and is plotted against time. In addition, the centerline of the plotted wrinkle rejects data, location of the data points and their trends with respect to the control limits are also shown.

Control limits are horizontal lines drawn on the control chart, usually at a distance of (±) 3 standard deviation of the plotted data. The area bracketed by the control limits will on average contains 99.73% of all the plot points on the chart as long as the process is and remain in statistical control. Control limits should not be confused with tolerance limits, which are completely independent of the distribution of the plotted sample statistic. _*Figure 4.3* indicates three possible special cause events.

This preliminary observation suggests that there is a need to determine assignable causes for Jun 2005, Dec 2005 and Mar 2006, where the data points are beyond the upper control limit. Corrective actions for these causes should be appropriately addressed. In addition, the last two months (Apr 2006 and Jun 2006) show the wrinkle reject rate falls below the usual reject level. This indicates that whatever actions taken before Apr 2006 have been demonstrated to be effective.

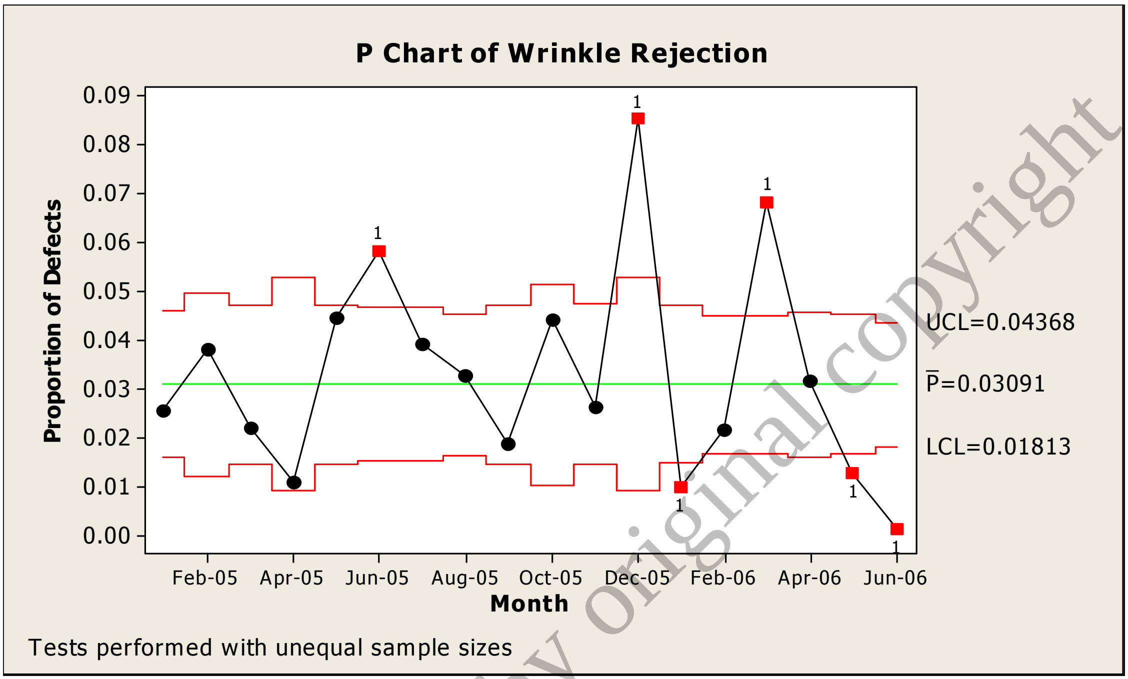

Figure 4.3: P-chart of wrinkle rejection

4.4.2 Trend Analysis of Wrinkle Rejects

Next, a trend analysis is performed using 18 months of data (Jan 2005 – Jun 2006). This analysis is carried out to determine if there has been any systematic change in the mean of the process over time. Trends upward would indicate changes occurring in the process which increase the reject proportions, while trends downward would indicate changes having a positive effect on the process. *Figure 4.4* encompasses wrinkle occurrence in an 18-month period and shows only a very slight downward trend.

This means that the improvement actions taken over the entire 18 months seem to have accounted for a very low reduction in occurrence, namely only 18*0.000350815 = 0.0063 or 0.63%. Thus, the previous 18 months of actions have been largely ineffective at making headway to reducing wrinkle occurrence. It has to be recorded that in the last three months

(Apr 2006 to Jun 2006) some small changes have been made to the process, namely that of applying dry fibre glass, use of dry honeycomb core material and adding compaction before last ply.

The results show that the process is now significantly better. If determined to be a real improvement statistically, then these changes should be made to be a part of the standard process. Hence, this is what the author carried out as part of the improvements process of this production line. In order to check the distributional shape of the wrinkle proportions, a probability plot is constructed.

A mound-shaped distribution, such as a normal distribution, may be indicative of a stable manufacturing process. In *Figure 4.5*, it can be seen that the reject proportions for wrinkles appear to be reasonably well approximated by a normal distribution as indicated by the roughly straight line appearance of the data points.

The approximation is even better if the top three highest rates (probably due to special causes which are un-predictable, typically large in comparison to common cause variation, caused by unique or a series of disturbances. Special causes can be removed / lessened by the application of basic process control and monitoring.

A process exhibiting special cause variation is said to be out-of-control and un-stable. Discontinue of compaction and the use of unfiltered pressure during compaction are the examples of special cause of problems) are deleted.

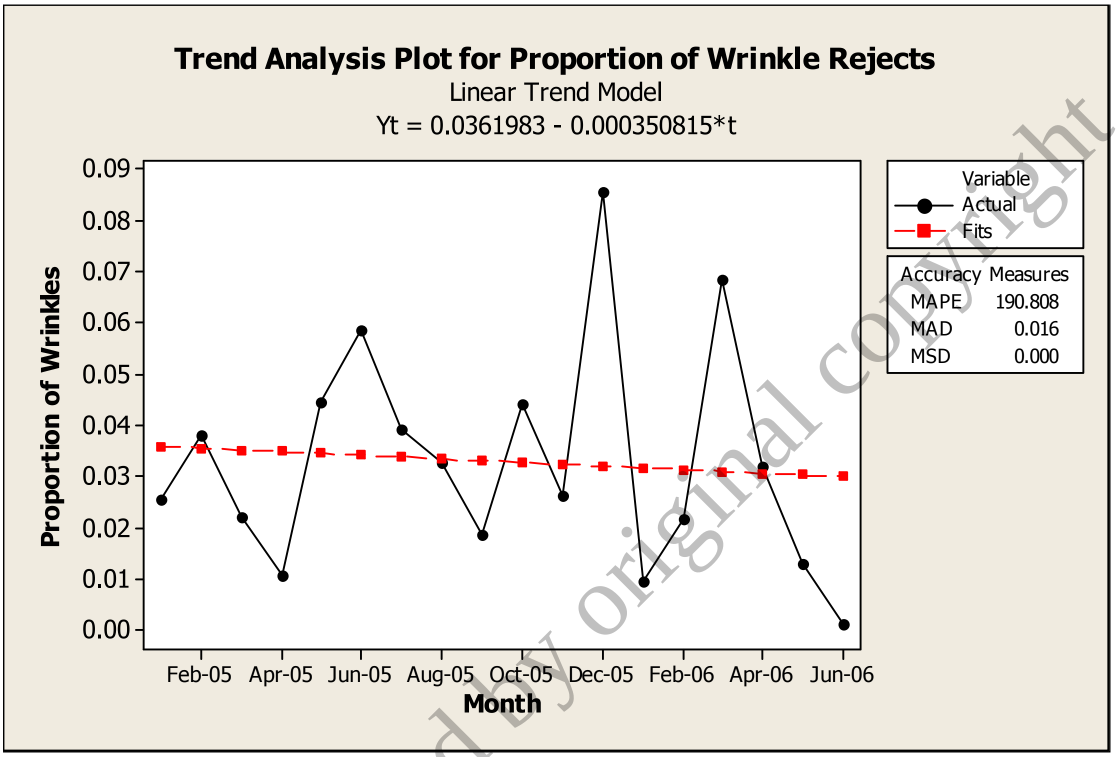

Figure 4.4: Trend analysis for wrinkle occurrence

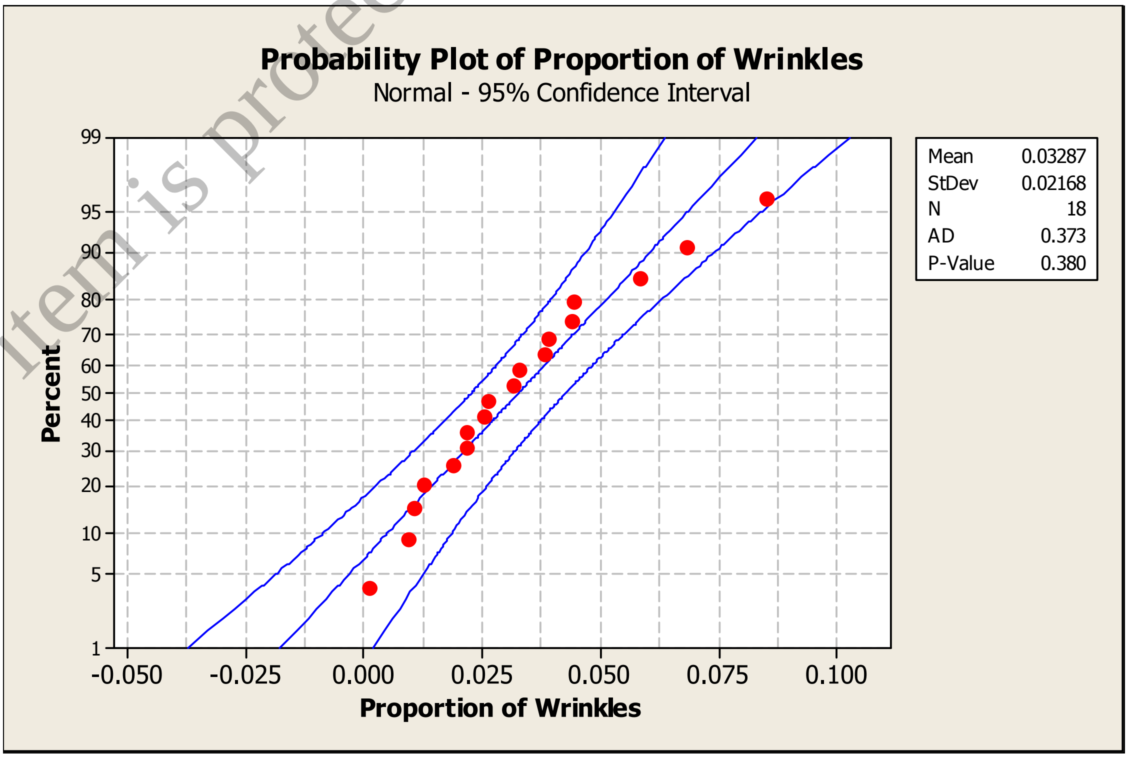

Figure 4.5: Probability plot of wrinkle occurrence

4.4.3 Correlation between Wrinkle and Delamination

It might also be instructive to know if there is any correlation between wrinkles and delamination. This may help to identify factors or to identify whether or not Failure Mode Effects Analysis (FMEA) should be performed on potential changes to see what effect they may have on any correlated issues.

In order to do this, a Time Series plot of delamination and wrinkle defect proportions is constructed, and shown in *Figure 4.6* indicating there is no correlation between delamination and wrinkle defect.

The time series plot also gives a calculation of r-value at 0.242, and a p–value of 0.334. The r-value is a number between -1 and +1 and indicates the strength of a linear relationship between X and Y variables. The r-value in the time series plot is referring to the serial correlation between successive observations in time. This means correlation between the value of X at time‘t’ and the value of X at time ‘t - 1’. It is also known as the Pearson Product Moment Correlation Coefficient. Hence, the r–value of 0.242 is not significantly different from zero, which means there is no significant correlation between delamination and wrinkles.

This lack of correlation can also be seen in the scatter plot given in *Figure 4.7* showing that these defects do not track with each other, no relationship between the two. The scatter plot also gives a calculation of r at -0.169, and a p–value of 0.717. The r–value of -0.169 is not significantly different from zero, which means there is no significant correlation between delamination and wrinkle rejects.

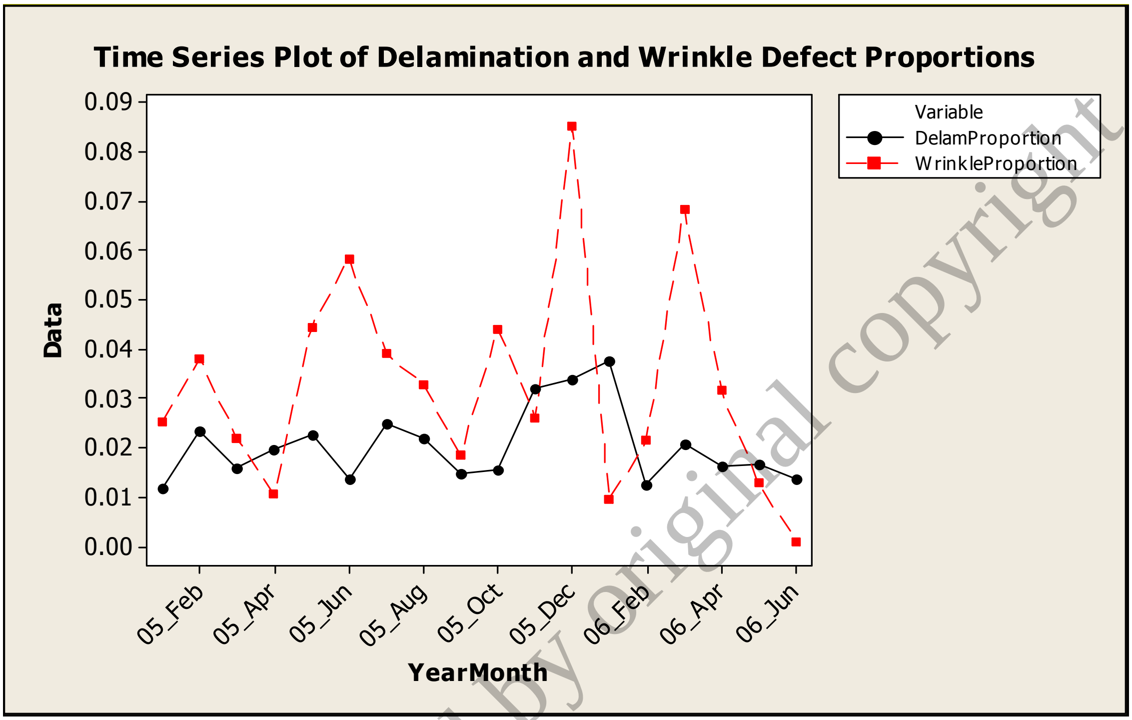

Figure 4.6: Time series plot of delamination and wrinkle defect proportions

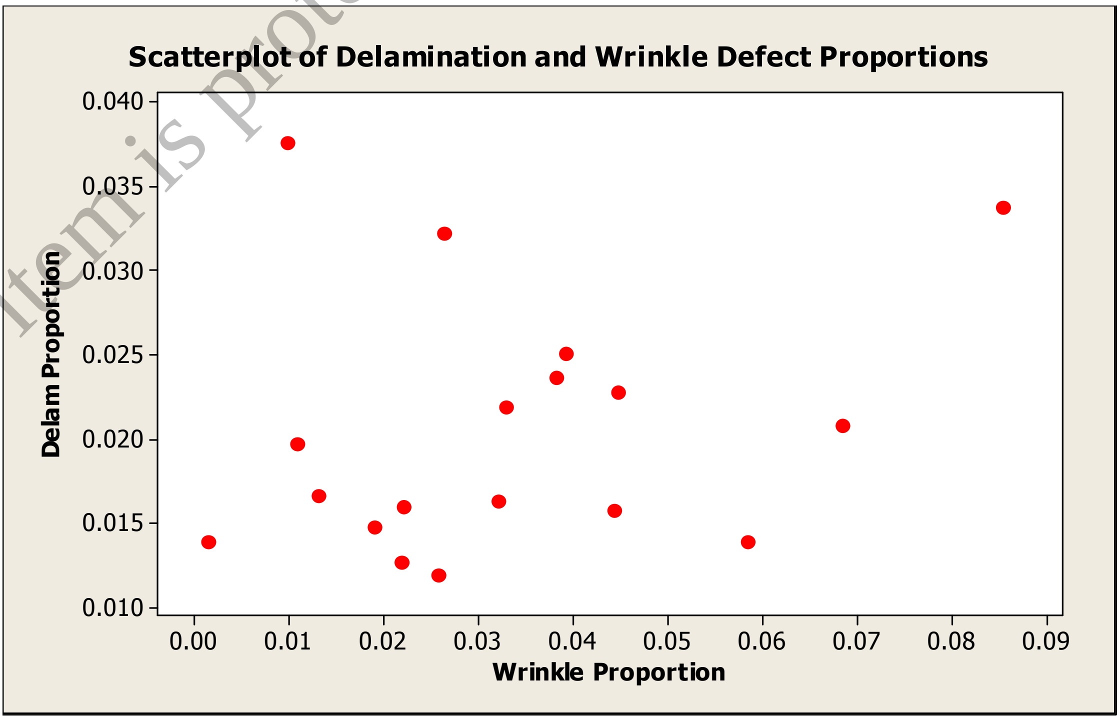

Figure 4.7: Scatter plot of delamination and wrinkle defect proportions